REPORT

Canadian Steel Industry Energy & Greenhouse Gas Emissions Intensity, Technology and Carbon Reduction Roadmap

Submitted to:

Canadian Steel Producers Association

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Executive Summary

This report is supported in part by funding from Natural Resources Canada and the Canadian Steel Producers Association (CSPA). It has been produced to update the 2007 Canadian Industry Program for Energy Conservation (CIPEC) "Benchmarking Energy Intensity in the Canadian Steel Industry" (CIPEC, 2007). In addition, this report looks at technology penetration for potential further energy improvements and Greenhouse Gas (GHG) reductions and provides a high-level carbon road map for the sector to reduce GHG emissions.

Since 1990, the Canadian steel industry has voluntarily invested to reduce energy consumption and emissions, achieving a 31.5% reduction in absolute GHG emissions by 2016. This equates to an emissions intensity improvement of approximately 27.6% (CIEEDAC, 2017). As a result of these reductions, the Canadian steel sector has the lowest GHG intensity globally for the integrated steel making plants that produce steel from iron ore and the second lowest GHG intensity globally for the Electric Arc Furnace plants that produce steel from steel scrap based on an assessment of the ten largest steel producing nations (Global Efficiency Intelligence, 2019).

To continue to achieve good performance, the Canadian steel sector has an aspirational ambition to produce net zero emissions steel by 2050. The technology scan demonstrates that the Canadian sector is advanced in implementing energy efficiency measures. The sector has started to implement process efficiency improvements and there is still room for improvement in this area. These measures will continue to be important but are not sufficient to accomplish the step change in emissions reductions necessary to achieve net zero.

The steel sector's ability to decarbonize and drive emission reductions requires a range of new technologies that must be immediately supported by governments and their commitment to build out the infrastructure essential for transition. Moreover, it should be recognized that each organization's approach to decarbonization and pursuing carbon-reducing technologies will be unique and depends on several limiting factors. Limiting factors for consideration include, but are not limited to, asset configuration, technical limitations, energy/fuel availability, market variability, geographical location, etc. This will require the installation of innovative controls and technologies that are not yet commercially demonstrated, are at a research stage or require significant capital investment to replace the existing technologies that are operating in the facilities. This large gap in technology penetration will require support from government to provide clean electricity and investment in energy infrastructure to deliver this electricity at a globally competitive cost, stakeholders, and the market to drive demand for low carbon steel to bridge.

While the steel sector endeavours to meet this net zero ambition, the low carbon economy will require increased steel production; therefore, the sector must decouple production growth from carbon emissions. Low or zero carbon electricity, a hydrogen economy coupled with new breakthrough technologies such as low carbon iron ore reduction, carbon capture utilization or storage, biomass substitution, non-fossil fuel iron production or electrolysis will all be required. The scale of this market and technological challenge is significant, and the Canadian steel sector has outlined the conditions that must be in place to support this goal.

As part of the road map considerations, recommendations for the supply of low carbon electricity and research and policy support for GHG reduction breakthrough technologies from government are provided to continue the Canadian steel sector's progress in energy and GHG reductions. The industry will also have to consider the economic viability of the emerging technical and business opportunities identified in this report to ensure long term economic and environmental sustainability of the industry is maintained.

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1.0 INTRODUCTION

The Canadian Steel Producers Association (CSPA) is the national voice of Canada's $15 billion steel industry. CSPA member companies annually produce approximately 13 million tonnes of primary steel and pipe and tube products in facilities located across Canada. Domestic steel operations directly employ some 23,000 Canadians while supporting an additional 100,000 indirect jobs. Canadian steel producers are a critical component of Canada's economy, serving the needs of North American customers with high quality, competitive, and innovative products. Key market segments for member companies include: automotive; energy discovery, extraction, and transport; major infrastructure projects; commercial/residential construction; renewable energy creation; and many general manufacturing applications.

Globally, the steel sector accounts for 6-7% of Greenhouse Gas (GHG) emissions and reductions from the international steel sector are required to contribute to the goal of the 2015 Paris Climate Change Agreement to limit climate change below 2 ˚C and as close as possible to 1.5 ˚C. However, as the global economy moves to reduce GHG emissions and adapt to a changing climate, steel will be in even higher demand to build resilient infrastructure and improved transportation networks and vehicles to reduce emissions from other sectors. In addition, co-products from the steel making process are used as part of the circular economy to reduce GHG emission in other sectors or displace the need for petroleum products. For example, ironmaking slag is used in the cement industry to reduce the GHG intensity of concrete, materials recovered from the by-product cokemaking facilities reduce the need for petrochemical production using oil and gas, use of by-product off gas in cogeneration reduces the need for electricity from the grid during peak demand periods. Further innovation in high strength and novel so-called modern steels improves the energy efficiency of buildings, plants, machinery, and the transportation sector. These modern steels also yield a significant reduction in weight, energy use, and overall greenhouse gas emissions. Avoided greenhouse gas emissions from the use of high-grade applications are on average six times higher than the greenhouse gas emissions from the production of these advanced steels (World Steel Association, 2020).

The Canadian steel sector recognizes the importance of addressing carbon emissions and the transition to a sustainable, low carbon economy and that carbon management is a fundamental aspect to society's continued success. Technologies will be required to produce steel with as little energy as possible as well as decarbonizing that energy through the implementation of emerging and innovative technologies, such as the use of hydrogen and carbon capture, at a scale that is not yet technically feasible nor commercially available for many aspects of steel production processes in the near term.

Despite these challenges, the Canadian steel sector has steadily reduced its GHG emissions. Since 1990, the Canadian steel industry has voluntarily invested to reduce energy consumption and emissions, achieving a 31.5% reduction in absolute GHG emissions by 2016. This equates to an emissions intensity improvement of approximately 27.6% (CIEEDAC, 2017). It has achieved these reductions through improving its overall operational performance; adopting strong energy management practices, such as heat recovery and by-product recovery coupled with cogeneration; improving energy efficiency through its operations; and optimizing raw material selection and use.

1.1 Objectives of this Report

In 2002, the CSPA agreed to undertake an energy benchmarking study to identify opportunities for energy reduction for the CSPA and Natural Resources Canada (NRCan). The report, published in 2007 by the Canadian Industry Program for Energy Conservation (CIPEC) and titled "Benchmarking Energy Intensity in the Canadian Steel Industry" (the 2007 Energy Benchmarking Report) focussed on operations that produce steel and form it into hot rolled products. Twelve steel-producing plants took part in the study – the four integrated plants and eight of the nine electric arc furnace (EAF) plants. The study involved a detailed inter-facility comparison of the energy consumed in steel production during 2002.

Since the 2007 Energy Benchmarking Report, many important factors affecting CSPA members have changed: the implementation of national and provincial carbon pricing programs, investor requirements for climate change risk disclosure, introduction of the ISO 50001 energy management standard, and general reduction in the carbon-intensity of certain provincial electricity grids, such in Ontario.

This report has been produced to update the 2007 Energy Benchmarking Report to allow comparison between participating plants and the Canadian steel sector and with international benchmark levels and to document the work the sector has completed in increasing energy efficiency. In addition, the report also provides:

- An updated list of technologies with the potential for achieving more efficient use of energy, reducing GHG emissions and enhancing the competitive position of the Canadian steel sector;
- An updated compilation of energy-intensity and GHG benchmarks and an analysis of the penetration of energy-efficient and emissions reductions technologies for the CSPA member plants;
- An updated comparison of benchmarks and technology penetration between plants and against international plant wide benchmark levels, thereby allowing areas of potential improvement to be identified;
- A more detailed assessment of the electricity grids in both Canada and internationally for Canada's main steel trading partner countries. Updated provincial grid emissions intensity values were used in the GHG emission calculations as opposed to the fixed value based on 100% coal-based electricity generation used in the 2007 Energy Benchmarking Report;
- Inclusion of combined heat and power plants and their impact on energy intensity and GHG emissions; and
- An assessment of the Scope 3 emissions associated with the transport to the Canadian market from these steel trading partner countries.

The Canadian steel sector has identified an ambitious goal to reduce GHG emissions and several conditions for success. This report helps to outline a roadmap to achieve these goals, including:

- A carbon reduction roadmap to support the Canadian steel sector's transition to a low-carbon economy, building on the technologies identified above;
- The challenges (e.g., technological and economic) and limitations of the Canadian steel sector to transition into the low-carbon economy; and
- The support needed from stakeholders to implement these actions.

This report identifies potential opportunities for the Canadian Steel industry to pursue reductions in GHG emissions through the implementation of technological solutions, adaption of current practices and the pursuit of

necessary partnerships. However, this report does not consider the economic viability of those technologies or adaptations to business practices, nor does it fully consider the full scope of investments required within various supporting supply chains for the industry to implement many of the proposed measures. The final roadmap for the steel industry will have to contemplate these additional factors to ensure that it remains sustainable both economically and environmentally.

For the present study, all CSPA member plants except for one specialty steel plant participated.

1.2 Organization of this Report

The report is organized as follows:

- Section 2 provides background information on Canada's steel sector, the major energy and GHG sources and describes the two categories of steel plants benchmarked in this report.
- Section 3 provides an overview of the energy and GHG benchmarking and assessment of technology penetration methodologies.
- Section 4 provides the results of the energy and GHG benchmarking and assessment of technology penetration.
- Section 5 provides international GHG benchmarking and an assessment of the advantages of Canadian steel, including an assessment of Canada's electricity grid and an assessment of Scope 3 GHG emissions associated with marine transportation of steel imported to Canada from overseas.
- Section 6 provides a carbon reduction roadmap, which includes an evaluation of barriers to implementation.
- Section 7 provides conclusions of this study.

2.0 OVERVIEW OF ENERGY USE IN CANADA'S STEEL SECTOR

The individual steel plants that make up the Canadian steel sector can be divided into two general categories according to their major source of raw materials used to make steel. Plants that produce steel from iron ore using the blast furnace and basic oxygen furnace (BOF) process are referred to as integrated plants. Plants that produce steel by melting steel scrap in an electric arc furnace (EAF) process are referred to as EAF plants or "mini-mills". This report is divided into these two general categories for the purposes of benchmarking and technology evaluation. GHG reducing and energy efficient technologies that are cross cutting between process and categories of steel making have also been evaluated.

The following sections describe the two steel making processes. Appendix A contains a description of the unit process for both the EAF and Integrated plants with more details on energy use and how GHG emissions are emitted at each of the unit processes.

2.1 EAF Plants

There are 7 EAF plants located in Quebec, Ontario, Manitoba, Saskatchewan, and Alberta. These plants receive scrap steel and fluxing agents as the primary raw materials. The process flow sheet for a typical EAF plant is show below as Figure 1.

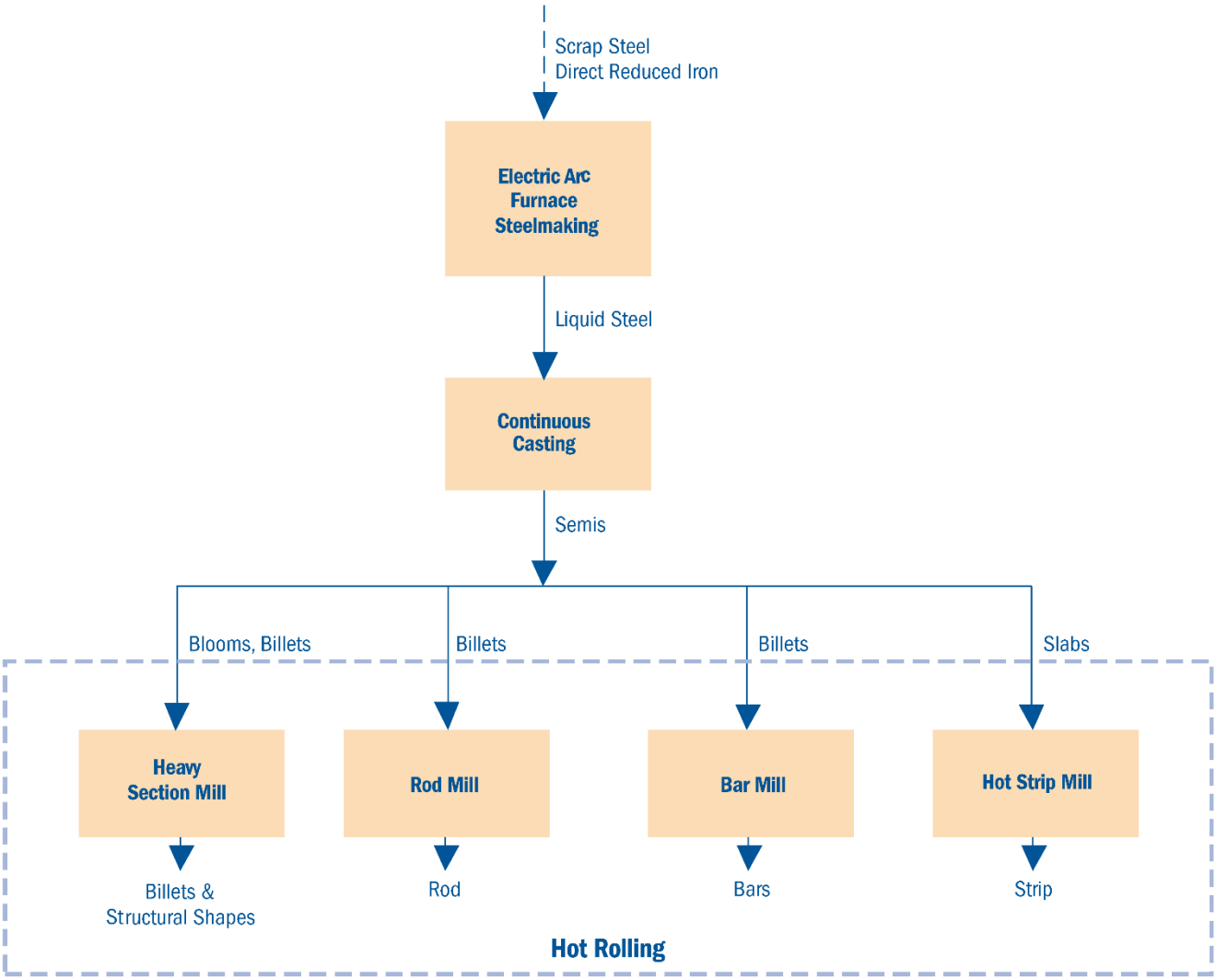

Figure 1: EAF Process Overview (CIPEC, 2007)

The primary energy source for an EAF plant is the electricity used in the furnace. Natural gas is also used to provide supplemental heat to the furnace, to the ladles used to transport the molten steel and to the hot rolling process. The EAF process is a less carbon-intensive process as iron ore is not necessary.

2.2 Integrated Plants

Since the supply of steel scrap is limited and the need for steel is increasing, Canada's steel demand cannot be supplied by EAF plants alone. Also, the steel produced from steel scrap may not meet specification requirements of some steel applications. Therefore, the steel demand must be satisfied with product made from both the EAF process and the integrated process. There are three integrated plants in Canada, all located in Ontario. One additional plant has ceased iron and steel production since 2010 but continues to produce coke and operates cold rolling processes. The operating integrated plants receive iron ore, coal, and fluxing agents as the primary raw materials. The process flow sheet for a typical Integrated plant is shown below in Figure 2.

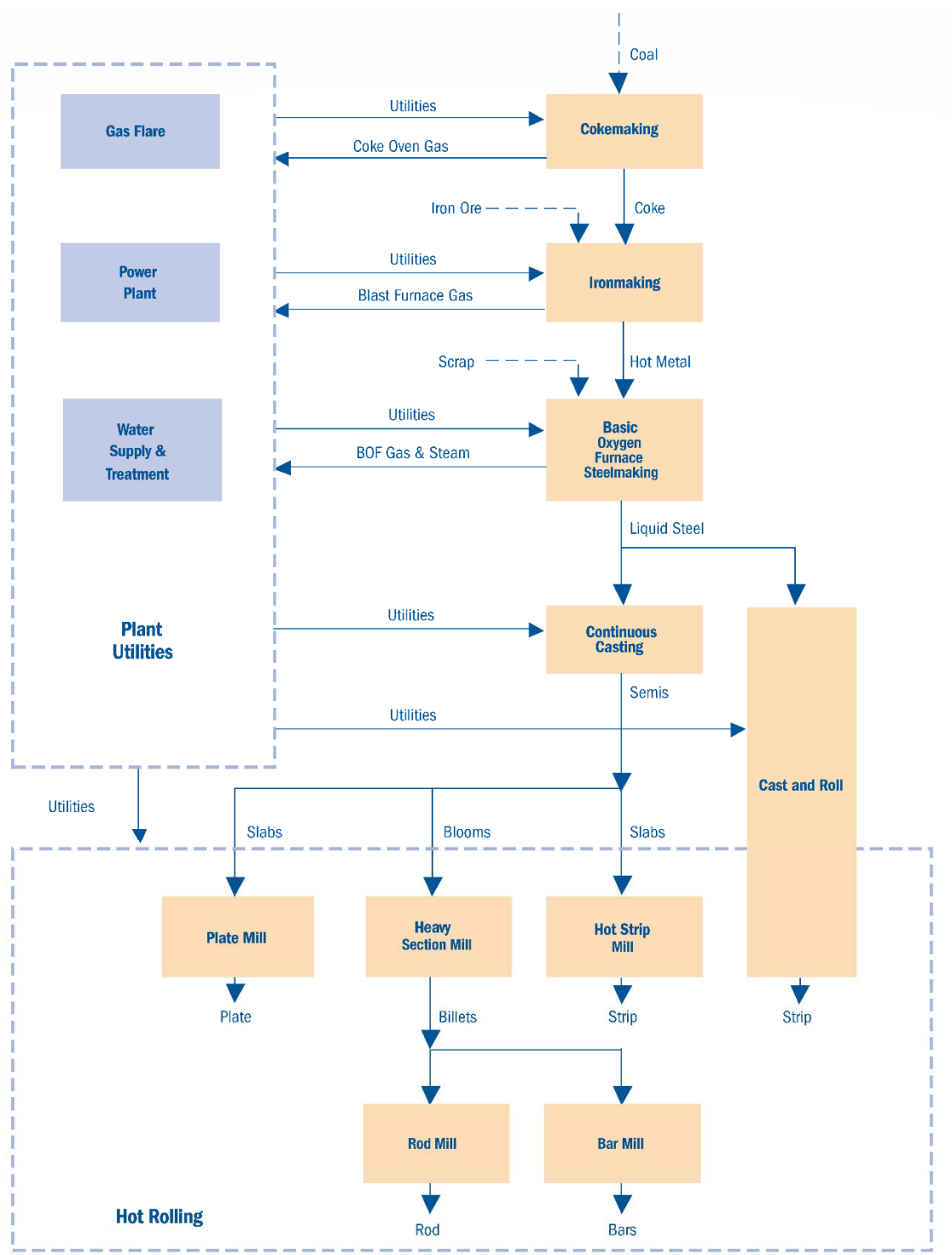

Figure 2: Integrated Steel Making Process Overview (CIPEC, 2007)

Metallurgical coal is converted into coke and used to create hot metal from the iron ore in the blast furnace. Natural gas is also used as a reductant in the blast furnace, as well as to produce steam and supplemental heat in the process. The integrated plants make use of process off-gases (e.g., blast furnace gas, coke oven gas etc.) in order to decrease the need for natural gas and to create the hot blast in the blast furnace. Some of the Integrated plants have combined heat and power facilities on site that re-use the process off-gases to produce both electricity and heat that are re-used in the processes.

For these reasons, the integrated process is highly GHG intensive. However, the carbon is used as both a reducing agent and as a source of heat necessary for the chemical reactions. Carbon becomes part of the molten iron and is removed in the Basic Oxygen Furnace (BOF). A significant amount of the energy used in the BOF is released through exothermic reactions as oxygen is blown into the molten iron bath. The integrated steel making process relies on this series of chemical reactions and was the global standard for steelmaking until recent advances in the iron ore reduction processes. All of the Canadian integrated plants currently use this process.

There is one plant in Quebec that produces iron from iron ore pellets using a direct reduction process significantly reducing GHG emissions. This and other innovative iron making process are part of the technology penetration assessment.

3.0 METHODOLOGY: ENERGY & GHG BENCHMARKING AND ASSESSMENT OF TECHNOLOGY PENETRATION

This section outlines the methodologies that were used to calculate energy and GHG intensities of the various processes of the participating plants, and to assess energy saving and GHG reduction technology penetration in the Canadian steel sector.

The calculation of energy and GHG intensity indicators requires the use of actual energy consumption and production data from a specific period. The present study is based on 2018 calendar year data.

Similar to the 2007 Energy Benchmarking Report that used 2002 data, this study breaks the various plants down into components referred to as Process Areas. The boundary of each Process Area is an imaginary line that encompasses all processes, equipment, support systems and activities that make up a given process. As per discussions between CSPA members, Process Area boundaries from the World Steel Association Energy Data Collection User's guide (September 2015) have been adopted for this study.

As agreed by CSPA members during the initial stages of this study, to protect confidentiality, this study only presents calculated energy and GHG intensities where Process Area data has been provided by 3 or more participating plants. Figure 3 presents a simplified process flow diagram for steel making, indicating the Process Areas that were used for this study, based on the World Steel Association Energy Data Collection User's Guide, and which Process Areas energy and GHG intensity results are presented in this study. Furthermore, as per CSPA guidance in the initial stages of this study, GHG emissions data for ancillary Process Areas such as flares and power plants are not explicitly presented in this study, however they are included in plant level data roll ups.

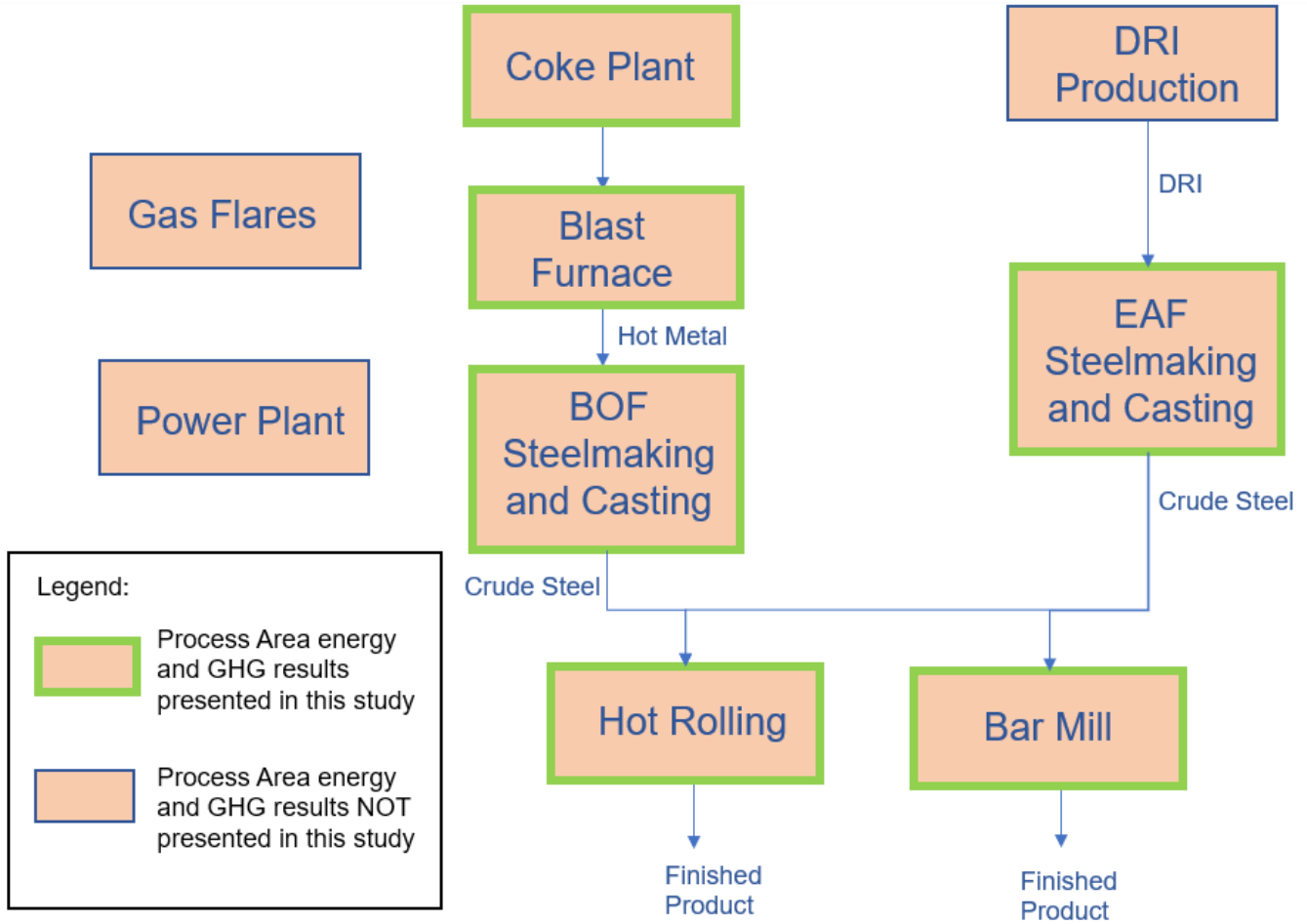

Figure 3: Process Areas for this Study

In consultation with CSPA, it was decided that finishing operations would simply be grouped according to whether the operation is considered hot rolling or a bar mill.

It should be noted that, although results are only presented for the Process Areas indicated in Figure 3, Energy and GHG analyses were completed for all applicable Process Areas at each participating plant. This was done in order to complete plant stepwise energy and GHG balances and to allow for roll up of Process Area data to the plant and sector level which is necessary to facilitate the various analyses and comparisons discussed in Sections 4 and 5 of this study. This roll up methodology is based on that which is outlined in the World Steel Association document “Energy Use in the Steel Industry”.

There are several different approaches to analyzing energy consumption and GHG emissions from steelmaking operations being used in the industry for different purposes. As such, it is often difficult to assess whether meaningful comparison of results of different studies is possible. For this study, it was decided in consultation with CSPA not to benchmark participating sites' Process Areas against the hypothetical International Iron and Steel Institute (IISI) EcoTech plant, as was done for the 2007 Energy Benchmarking Study, as the methodology required to do so does not align with World Steel Association benchmarking methodologies that CSPA requested and also yields results that do not allow for comparison to other industry data, such as publicly available international GHG benchmarking exercises referenced in this study. Rather, it was agreed to complete an analysis using an approach similar to the World Steel Association benchmarking systems for CO_2 data collection and energy, which are available exclusively to World Steel Association members, using data collected at a similar level of detail to the 2007 Energy Benchmarking Report. Following this guidance, energy and GHG intensity indicators have been developed based on data collected from participating members as described in the following sub-sections.

The energy and GHG emissions intensity indicators developed in this study allow for comparisons between equivalent Process Areas for participating plants and to "All Participating Plants" intensity indicator values. The All Participating Plants intensity indicator values are based on the total Process Area energy and GHG emissions of all participating plants divided by the total Process Area production of all participating plants. As such, the All Participating Plants intensity indicators are equivalent to a weighted average intensity of participating plants and are therefore useful to benchmark the Process Area indicators of the individual participating plants.

In addition to Process Area energy and GHG intensity indicators, energy and emissions were also rolled up to the plant level to allow for comparison of overall plant energy and GHG intensity between participating plants and to the "All Participating Plants" value. As noted in Section 2, the EAF plants and integrated plants must be compared separately in order to make meaningful comparisons.

Energy and GHG emissions data were rolled up to the plant level, including all Process Areas at participating plants except for finishing (hot rolling or bar mill). Finishing processes were excluded from plant level indicators to avoid including production output numbers that include a contribution from processing of purchased billets or slabs, which would skew energy and GHG emissions intensities since energy and GHG emissions involved with the production of these purchased billets or slabs would not be accounted for. As such the production metric used for plant-level indicators is "tonnes of crude steel". For the one plant that includes Direct Reduced Iron (DRI), the energy and GHG emissions contribution from the DRI process was excluded from plant level indicators, in order to limit the EAF intensities of the "All Participating Plants" indicators to the actual EAF steelmaking process. Plants that operate as standalone rolling mills or bar mills are excluded from the plant level indicators. Energy and emissions from the one plant that operates as cokemaking only were attributed to the integrated steelmaking plant under the same company.

3.1 Energy Use and GHG Data Collection

Surveys were distributed to the participating plants which requested calendar year 2018 energy use, GHG emissions and production data for each applicable Process Area. The surveys were in the form of a spreadsheet based on the survey developed in the 2007 Energy Benchmarking Report. The surveys also requested general facility information, including process flow diagrams and carbon flow diagrams. The surveys were completed by personnel at each participating plant and returned to the project team. The data obtained for this study is covered by a confidentiality agreement.

The data returned by participating plants was reviewed, analyzed and tabulated into summary tables for each Process Area. Missing or questionable data were identified at this stage, at which point the plants were contacted for clarification, additional and/or revised data. Dialogue continued with plant personnel so that the information used was as complete and accurate as reasonably possible. Summary tables of Process Area input and output data to be carried forward in the analysis were sent back to members for final validation before completing the analysis of energy and GHG indicators. The project team did not carry out sampling, measurements or any other independent verification of data provided by participating sites.

3.2 Energy Intensity Indicators

The main goal of the energy intensity benchmarking is to assess how much energy input is required to produce a tonne of product (coke, liquid iron, liquid steel etc.) for the Process Areas identified for this study. As a result, the energy associated with the materials that are being processed was not of concern because that energy is not consumed or spent during the process. When looking at energy inputs, only the energy sources that are consumed during the process were considered (e.g., natural gas, electricity, etc.). Like the World Steel Association methodology, this methodology used the concept of processing energy. This processing energy or energy consumed in one process (e.g., cokemaking) is the net energy input required to process the material from its initial state to its final state.

This is especially important when looking at energy inputs at the Integrated Plants, as the energy inherent in the iron ore or molten iron used as feedstock in a BF or BOF is not included in the energy analysis because this energy is not consumed during the process. For example, when looking at cokemaking, the coal inputted to create the coke is not considered an input energy source because it is not consumed, it is the material that is actually being processed. However, when we look at a blast furnace, the coke that is charged to act as a reductant is treated as an energy input because it is being consumed during the process. Therefore, energy inputs are included if they are being consumed to process a material. If the input is the material being processed itself, it was not included as an energy input.

Similarly, energy outputs include recoverable energy sources (e.g., often process gasses such as blast furnace gas), not final products nor the material that has been processed. For example, the blast furnace gas (BFG) that is produced in the blast furnaces was treated as an energy output because it is recoverable energy that is often utilized within the plant as an alternative energy source. If the output is the main material that has been processed (e.g., coke out of a coke oven, liquid iron out of a BF etc.), it was not included as an energy output. This is done to adhere to the idea of processing energy per World Steel Association's and the 2007 Energy Benchmarking Report's methodologies. If the coke that leaves a coke oven was considered an energy output, but the coal was not considered an energy input, we would obtain an incorrect (and meaningless) value. As we are only concerned with the energy a facility must input to process the coal into coke, the energy inherent to the coal entering the coke ovens and the energy inherent to coke leaving the coke ovens is irrelevant and is thus excluded. An exception is made by both World Steel Association and the 2007 Energy Benchmarking Report for the energy output of coke oven gas in the coke making process to avoid negative processing energy values. In order to allow for a better comparison between sites at the coke making process level, the coke oven gas is ignored as an energy output but it is incorporated as an energy output when the facility wide rollup is performed. This stops coke making from having negative processing energy values due to the large amount of energy of coke oven gas leaving the process and the lesser amount of energy inputted into the coke ovens to process the coal into coke.

This methodology has been applied at the process level first and then at the facility level. At the facility level while summing up the energy intensities of each individual process all energy inputs and outputs were considered. The energy inputs/outputs that are included in the energy intensity benchmarking are summarized for each process in table 1 below.

Table 1: Summary of the Energy Inputs/outputs Used in this Report's Energy Intensity Analysis

Process	Energy Inputs	Energy Outputs
Cokemaking	Natural gas, electricity, steam, industrial water, coke oven gas (COG), blast furnace gas (BFG)	COG
Blast Furnace	Natural gas, electricity, oxygen, steam, industrial water, COG, BFG, Coke, pulverized coal injection PCI, Heavy Oil	BFG
Direct Reduced Iron	Natural gas, electricity, oxygen	Not Applicable
Basic Oxygen Furnace	Natural gas, electricity, oxygen, steam, industrial water, coke	Steam, basic oxygen furnace gas
Electric Arc Furnace	Natural gas, electricity, oxygen, steam, industrial water, coke, EAF off-gas, coal	EAF off-gas
Casting & Hot Rolling	Natural gas, electricity, oxygen, steam, industrial water, COG, landfill gas	Not Applicable

Sources:

[1] CIPEC, 2007.

[2] Energy Use in The Steel Industry – Definitions Book 2015.

Appendix B contains a complete list of energy conversion factors used in this analysis.

3.3 GHG Emission Intensity Indicators

The main goal of the GHG emission intensity benchmarking exercise is to assess the amount of GHGs that are emitted to produce a tonne of product (coke, liquid iron, liquid steel etc.) for the Process Areas identified for this study. The process outlined by the GHG Protocol Initiative for the types of GHG emissions was followed including the "GHG Protocol Corporate Accounting and Reporting Standard" (The GHG Protocol Corporate Standard). Guidance from the GHG Protocol Corporate Standard is widely used for preparing corporate GHG inventories. The GHG Protocol Corporate Standard introduces the concept of direct and indirect emissions and scopes for GHG emission inventories under three broad categories, referred to as Scope 1, Scope 2 and Scope 3. Similar to the methodology outlined in the World Steel Association CO_2 data user's guide, GHG emissions have been categorized into the GHG Protocol scopes as outlined below:

- **Scope 1** – direct GHG emissions from chemical reactions determined by carbon mass balance methodology and/or emission factors for fuels.
- **Scope 2** – GHG emissions from the generation of purchased electricity.
- **Scope 3** – other indirect GHG emissions which are a consequence of a company's activities but occur from sources not owned or controlled by the company.

Data collected for each Process Area was used to complete a carbon balance for the Process Area, which allowed for the estimation of Scope 1 GHG emissions associated with chemical reactions in which carbon in materials undergoing processing was converted to, and emitted as, CO_2. Where by-product gases were reported to leave a process area to be utilized and combusted as fuel in another Process Area, GHG emissions associated with that by-product gas were estimated using emission factors and attributed to the Process Area in which the by-product fuel is combusted. Where provided, plant-specific emission factors for blast furnace gas were used. Where no plant-specific emissions factors were provided for blast furnace gas, plant-specific emission factors were developed based on the carbon balance of the blast furnace process and the quantities of energy in produced blast furnace gas, which were provided by participating plants. GHG emissions from fuels other than by-product fuels used for combustion for process heat in Process Areas were estimated using fuel energy input values and emission factors. This approach to estimating Process Area Scope 1 GHG emissions accounts for and allocates GHG emissions to the Process Area from which they were actually emitted and aligns better with World Steel Association methodology than 2007 Energy Benchmarking Report.

Following the methodology used in the 2007 Energy Benchmarking Report, a GHG emissions category referred to as "Utilities" was included as an emissions intensity component, which takes into account emissions from facilities that supply steam to a Process Area that are outside of the boundary of a Process Area, but inside the boundary of the plant. Standard emission factors taken from the World Steel Association CO_2 user's guide were used to estimate the "Utilities" GHG emissions associated with steam generated at a plant and used in a given Process Area.

Scope 2 emissions were estimated using the amount of purchased electricity provided by participating plants for each Process Area, along with provincial grid electricity emissions intensity data for 2018 taken from the Environment and Climate Change Canada (ECCC) report entitled "National Inventory Report 1990-2019: Greenhouse Gas Sources and Sinks in Canada, Part 3." Generation intensity values were used as opposed to consumption intensity values following guidance in the GHG Protocol Corporate Standard. This methodology differs from the 2007 Energy Benchmarking Report, which applied an emission factor for electricity that was equivalent to coal-fired electricity generation. The methodology used herein was deemed more appropriate for the current study as it provides a more accurate estimate of actual Scope 2 GHG emissions from participating plants, reflective of the electrical grid in which the participating plant operates, and also aligns with the methodology of "How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities" which is used for international benchmarking of Canadian Steel Production as described below in Section 5.1.

Broader Scope 3 GHG emission were not assessed in the 2007 Energy Benchmarking Report and are also considered outside of the scope of this study. As a result, GHG emissions embedded in purchased materials such as coke, billets or slabs are not considered in this assessment.

Appendix B contains a complete list of GHG emission factors that were used in this analysis. Table 2 provides a summary of the GHG emissions sources considered in this analysis for each GHG Scope and Process Area

Table 2: Emission Source Types Included for Each Process Area

GHG Emissions Type	Emission Source(s) Considered	Calculation Method	Process Area(s)
Scope 1	Fuel Combustion (includes by-product gases from other processes where applicable)	Emission Factor	All
	Process emissions	Process carbon balance	Coke Making, Blast Furnace, BOF Steel Making, EAF
Scope 2	Consumption of Purchased Electricity	Province Specific Grid Emission Factor	All
Utilities	Consumption of steam generated elsewhere at plant (where applicable)	Emission Factor	All (where applicable)

GHG emissions-intensity values for GHG emissions type (Scope 1-2, utilities) for each Process Area at each participating plant were developed by estimating each GHG emissions type in the table above for each Process Area and dividing by the production parameter that is specific to each Process Area.

As outlined above, the Process Area boundaries developed for this study were established to account for the GHG emissions that occur at each Process Area and not in other areas within the plant. This approach is different than that of the required calculation methods under the Environment and Climate Change Canada (ECCC) Greenhouse Gas Reporting Program (GHGRP) which assume that GHG emissions resulting from various processes occur at that process and ignores utilization of by-product gases in other processes at the plant. Therefore, it is important to note that the Process Area results of this study cannot be directly compared to process-specific GHG emissions reported to ECCC GHGRP for 2018. Rolling up Process Area GHG emissions estimates using the methodology of this study to plant level does, however, result in plant-wide GHG estimates that are comparable and consistent with estimates reported to the ECCC GHGRP for 2018. Furthermore, for reasons explained above, particularly concerning estimation of Scope 2 GHG emissions, GHG results of this study are not directly comparable to the 2007 Energy Benchmarking Report that does not take into consideration provincial Scope 2 electrical intensities.

3.4 Assessment of Technology Penetration Methodology

There are numerous energy saving and GHG emission reduction technologies/techniques that can be applied to the steel sector that are as varied as the individual facilities. Consistent with the International Energy Association (IEA) and World Steel Association decarbonisation approaches to 1) "*step UP"* which is to bring efficiency levels at all plants in line with industry's top performers, 2) maximize operational inputs and scrap use, and 3) implement breakthrough technology to reduce iron ore without producing CO2 (e.g.,. CCUS, hydrogen or electrolysis) (World Steel Association 2022). For the purposes of this report these reduction options have been classified under the following three categories:

- **Energy Efficiency Options**: This refers to changes at a facility that will contribute to the reduced energy consumption at the site and hence a direct reduction in on-site energy usage. Examples of these technologies include boiler retrofits or process changes to reduce the energy intensity of the production process. This includes options that reduce the consumption of energy, heat and/or steam purchased from off-site sources, which relates to both Scope 1 and 2 GHG emissions.

- **Material Substitution/Process Options**: This refers to Scope 1 reductions due to either the partial or full replacement of a carbon intensive raw material with a renewable or less carbon intensive one or the use of a lower carbon intensity fuel. These technologies include substituting recycled material in the production process. These technologies are well established and proven options for raw material substitution with some consideration of new and innovative initiatives. Examples may include materials that are used primarily for reasons other than energy (e.g., bio-coke replacing coke for carbon content). This also refers to possible changes to fuels used by a facility in their processes and stationary combustion equipment. These technologies include replacing heavy fuel oil with natural gas, adding hydrogen in the use of fuel blends, oxygen enhanced combustion and alternative fuels (e.g., biodiesel, bio-coke, biomass, waste derived fuel etc.) which are considered lower carbon fuels.

- **Innovative Controls/Technologies**: This refers to Scope 1 reduction options that are in most cases yet to be deployed on a full scale, but have been proven to be effective in pilot scale and research based testing. Example of these technologies include significant process changes such as carbon capture and storage, alternative coke or iron making process that would require significant capital investment.

Not all categories are appliable to each process area and the use of some technologies precludes the application of others (e.g., some of the technologies are mutually exclusive). Cross cutting technologies that can be applied in multiple Process Areas innovative technologies such as carbon capture utilisation and storage that are not yet commercially feasible as well as using low carbon electricity are considered separately as their own process areas.

To achieve the implementation of some of these technologies, policy support will be required such as: incentives, regulations and support for shifts in regulation and markets to promote reductions such as a Hydrogen strategy. This section only deals with the penetration of the technologies. Barriers to the technologies and the necessary support is further discussed in Section 6.

3.4.1 Literature review of Potential Energy and GHG Reduction Technologies

A literature review was performed to evaluate technologies with the potential for achieving more efficient use of energy, reduction of GHGs and strengthening the Canadian steel sector. The main sources used for the literature review are included below and cover technological reviews from North America, Europe and Asia:

- Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry by Lawrence Berkeley National Laboratory.
- Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry by Lawrence Berkeley National Laboratory.
- Ironmaking Process Alternatives Screening Study Volume I: Summary Report by USA DOE.
- The State–of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook by the Asia Pacific Partnership for Clean Development and Climate.
- Best Available Techniques (BAT) Reference Document for Iron and Steel Production (2013) by the European Commission Joint Research Centre.

A total of 125 technologies were identified and grouped into the above categories. The technologies are summarized in Table 5 in Section 4.2 and described in greater detail in Appendix C.

3.4.2 Technology Penetration Data Collection

A second questionnaire was developed to collect additional information on the energy-saving and GHG reducing technologies and practices that were already implemented for each process at each plant, what technologies were under consideration, and which technologies had not yet been considered. Technologies were ranked differently depending on if it was a technology that was equipment-specific (e.g., Midrex Process) versus if it was a cross-cutting technology that could be used in multiple processes (e.g., oxy-fuel burners). For each process area, each equipment-specific technology was ranked from 1 through to 6 as shown in the table below:

Table 3: Ranking of Technology Penetration for Equipment Specific Technologies

Ranking Number	Description
1	Not considered
2	Under consideration
3	Conducted pre-feasibility/feasibility study
4	Demo/pilot complete
5	Plan to implement / implementation in progress
6	Implemented

For the cross-cutting technologies that were applicable to multiple processes, they were ranked as follows:

Table 4: Ranking of Technology Penetration for Cross-cutting Technologies

Ranking Number	Description
1	Not implemented anywhere in the plant
2	Implemented in small percentage of possible locations
3	Implemented in most areas
4	We have a process for system implementation wherever applicable

The reporting forms were sent to and completed by personnel at each participating plant.

A list of the of energy and GHG reduction technologies for each unit process described in Section 2 and shown in Table 3 were included in the questionnaire with the responses above included in a drop-down menu for each technology. Technologies were listed with more common technologies first and progressing to more innovation technologies. Personnel were also requested to add any technologies that were not identified.

Missing or questionable data were identified by the aggregation of the data for each process. The plants were contacted and additional and/or revised data were submitted. Dialogue continued with plant personnel so that the information used was as complete and accurate as possible.

The results were displayed on a spider/radar graph for each process area with the outer rings representing a ranking of 6 (e.g., implemented) and a ranking of 1 (e.g., not yet considered) as the innermost ring. Maximum (orange), minimum (grey) and average (blue) rankings for each technology are shown on the spider graphs. Note that there was no separation in the technology penetration section between EAF and Integrated plants.

4.0 FINDINGS/RESULTS: ENERGY AND GHG BENCHMARKING AND ASSESSMENT OF TECHNOLOGY PENETRATION

A comparison of the GHG intensity between various Plants can be misleading due to the variability between processes in each of the plants. For this reason, charts comparing the energy and GHG intensities for the processes in Plants have not been shown. Each of the following sections and sub-sections highlights the factors that improve Energy and GHG Intensity in each of the processes.

Conclusions based on these findings are summarized in section 7.

4.1 Process Area Energy and GHG Intensity Indicators

In terms of energy intensity, ironmaking in blast furnaces is by far the most energy intensive step in the overall process of creating steel. It also uses large amounts of fuel, thus creating significant amounts of GHG emissions. As a result, reducing the fossil fuel usage (and therefore emissions) associated with ironmaking will have the largest impact on the energy and emission intensity of the steel making process. This can be achieved through using EAFs, using hydrogen as a fuel substitution in blast furnaces, producing DRI etc.

Casting & hot rolling have the second largest energy intensity followed by cokemaking. EAFs as well as BOF steelmaking tend to be the least energy intensive when comparing on a GJ per tonne of final product using production ratios per process. However, as discussed in Section 2 integrated plants are needed because of limited availability of scrap steel and the demand for new steel.

The following factors can significantly affect energy intensity and may be factors in the differences in energy intensity among participating facilities:

- Utilization of equipment: Energy intensity increases if equipment is not operated at or near design capacity, which reflects the market and competition.
- Product mix: The energy intensity will be higher for mills that produce a broad range of products because material losses and energy consumption occur during the period required to change over to the next product.
- Climate: Energy intensity at different Canadian mills will be greater because of the energy required to protect equipment and personnel from local winter climate and to make up for greater process heat losses caused by low ambient temperatures.
- Facilities with large production volumes will more easily be able to have lower energy intensity than facilities with smaller production volumes since there is a certain fixed amount of energy required that is divided into a larger or smaller production volume. Similarly, if there is an economic contraction and production volumes decrease, it can appear that energy intensity worsens, but that may not be a true reflection of the energy efficiency of the plant (in this case, more sophisticated techniques such as CUSUM would be required which is outside the scope of this report).
- Grade of steel being produced. Higher grades of steel typically require higher energy intensity.

In addition, implementation of energy efficiency technology will affect the energy intensity of the processes, and examples of some of the energy efficient technology implemented per process is described within each process area.

With respect to GHG emissions intensity, the factors described above which affect energy intensity are also generally factors in GHG emissions intensity, however the following are factors that can also significantly affect GHG emissions intensity:

- Energy input type: fuel and electricity energy inputs have significantly different GHG emissions profiles.
- Electricity grid GHG emissions intensity: Scope 2 emissions were estimated based on provincial grid electricity emissions intensity data for 2018, which can vary widely by province.
- By-product gas utilization: following the methodology described in section 3.3, where by-product gases were reported to leave a process area to be utilized and combusted as fuel in another Process Area, GHG emissions associated with that by-product gas were attributed to the Process Area in which the by-product fuel is combusted. As such, if the majority of a by-product gas generated in a given Process Area leaves that Process Area to be combusted in another Process Area at a participating plant, then the GHG emissions associated with combustion of that by-product will not be accounted for in the Process Area where it is generated. Different participating plants utilize by-product gases in different ways (e.g., combustion within the Process Area in which the by-product gas is generated vs flaring) which can cause variability in GHG emissions intensity at the Process Area level, but not at the plant level, since at the plant level, all by-product gas combustion is accounted for.

The following sub-sections provide the Process Area energy and GHG intensity indicators.

4.1.1 Cokemaking

The Figure below presents the Cokemaking energy intensity indicators.

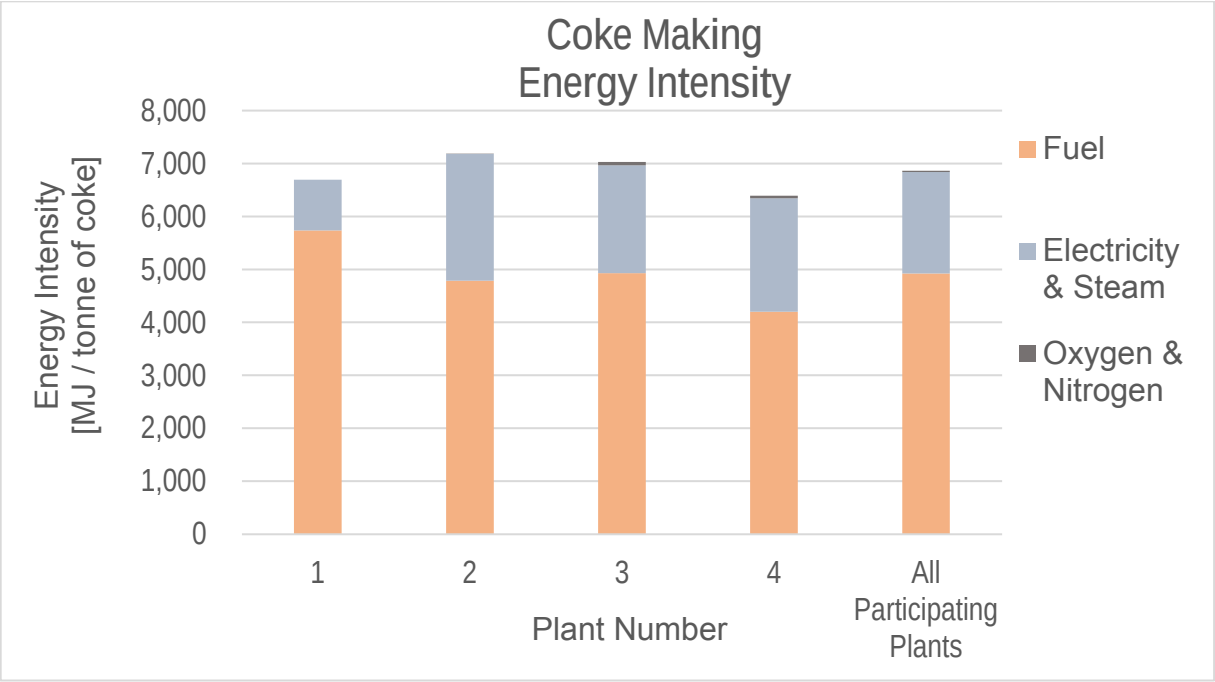

Figure 4: Cokemaking Energy Intensity Indicators

Cokemaking is very energy intensive with an average of 6,864 MJ/tonnes of coke. Note that the energy output from cokemaking (i.e. energy in the coke oven gas) has not been included as a credit as per the 2007 Energy Benchmarking Report methodology and as described in Section 3.2.

Some energy efficiency improvements that have been implemented at participating sites that likely account for some of the differences in energy intensity include coke oven gas recovery optimization and charging biomass and/or charcoal.

Scope 2 GHG emissions intensity associated with purchased electricity are negligible in comparison with Scope 1 and Utilities GHG emissions intensity for cokemaking.

4.1.2 Blast Furnace Ironmaking

The following figure presents the blast furnace iron making energy intensity indicators.

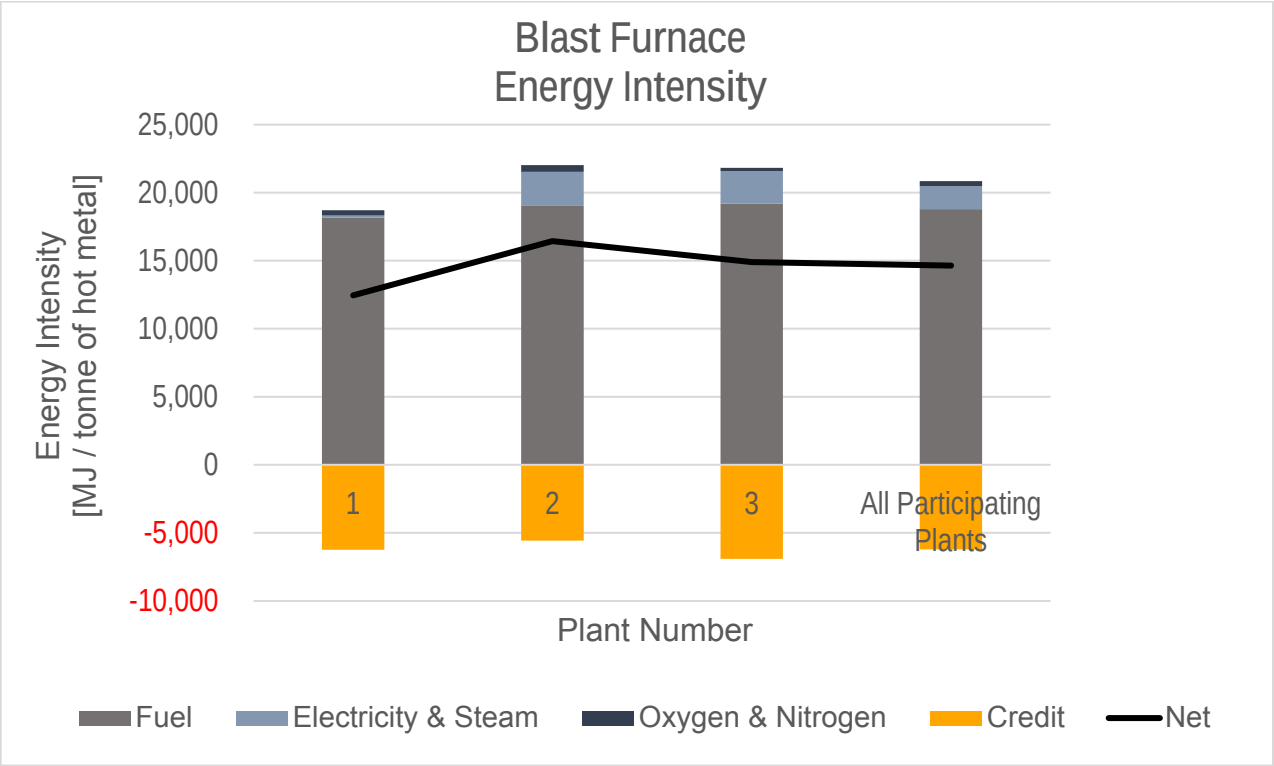

Figure 5: Blast Furnace Iron Making Energy Intensity Indicators

In ironmaking through a blast furnace, participating plants have an average net energy intensity of 14,631 MJ per tonne of hot metal. The energy intensity between participating plants are reasonably consistent. The credit included in the figure above represents the energy of the blast furnace gas that is generated within the blast furnace and can be utilized elsewhere within the plant as an alternative energy source. Energy efficiency improvements implemented at only some of the operations that will affect the energy intensity include injection of COG and/or natural gas, improved combustion in hot stoves, improved recovery of BF gases, pulverized coal injection, and dry de-dusting of BF gas.

Although energy intensity for the blast furnace Process Area of participating plants are comparable, the GHG emissions intensities vary due to varying amounts of blast furnace gas being burned in other Process Areas versus within the blast furnace Process Area. Scope 2 GHG emissions for the blast furnace Process Area are negligible in comparison with Scope 1 and Utilities intensities.

4.1.3 Basic Oxygen Furnace Steelmaking

The following figure presents the basic oxygen furnace steelmaking energy intensity indicators.

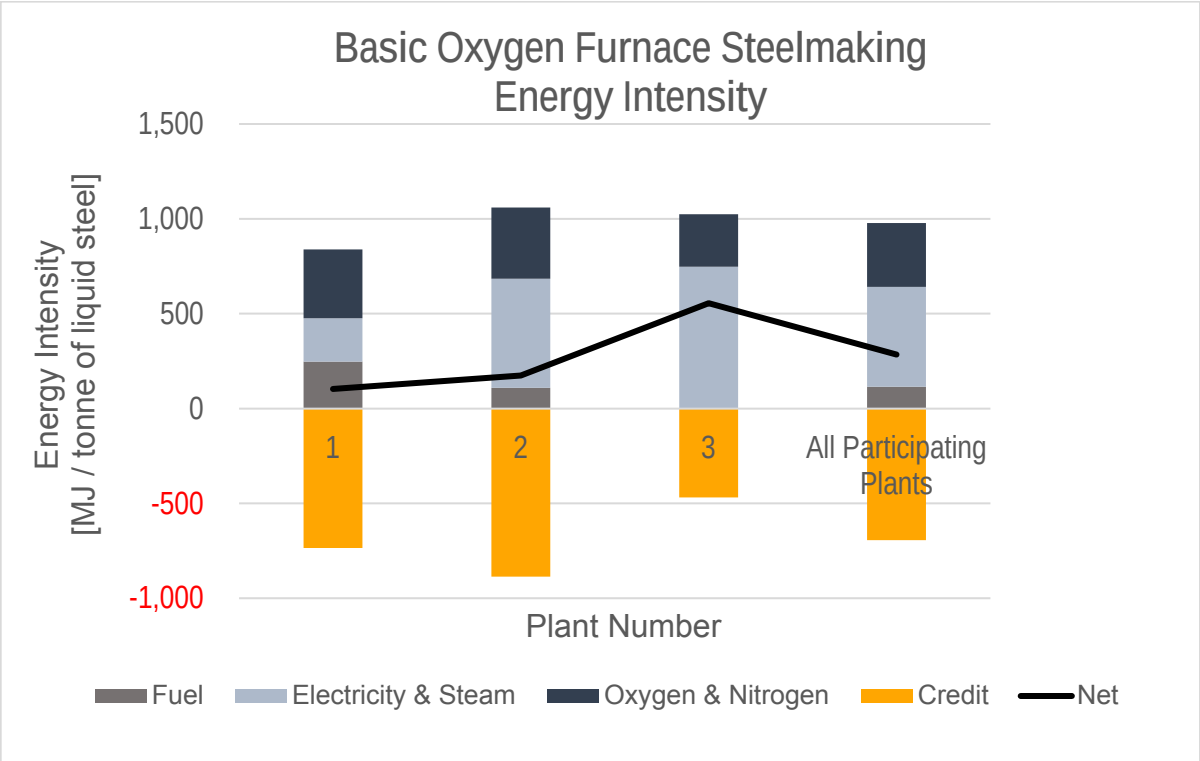

Figure 6: Basic Oxygen Furnace Steelmaking Energy Intensity Indicators

In all of the other processes, oxygen and nitrogen make up very small, usually immaterial, amounts of energy compared with electricity & steam as well as fuel. In the BOF, oxygen and nitrogen account for a substantial amount of the energy used. Participating plants have an average net energy intensity of 284 MJ per tonne of liquid steel. The credit included in the figure above represents the energy of the BOF gas that is generated within the BOF and can be utilized elsewhere within the plant as an alternative energy source.

Some of the energy efficiency improvements that are implemented at only some of the operations that affect the energy intensity include BOF heat and gas recovery, BOF bottom stirring, KOBM, and utilization of an automated steel cleanliness tool.

Similar to the blast furnace Process Area, energy intensity for the basic oxygen furnace Process Area of participating plants are comparable, but the GHG emissions intensities vary due to varying amounts of basic oxygen furnace gas being burned in other Process Areas versus within the basic oxygen furnace Process Area. Once again, Scope 2 GHG emissions for Basic Oxygen Furnace Process Area are negligible in comparison with Scope 1 and Utilities intensities.

4.1.4 Electric Arc Furnace Steelmaking

The figure below presents the EAF and continuous casting energy intensity indicators.

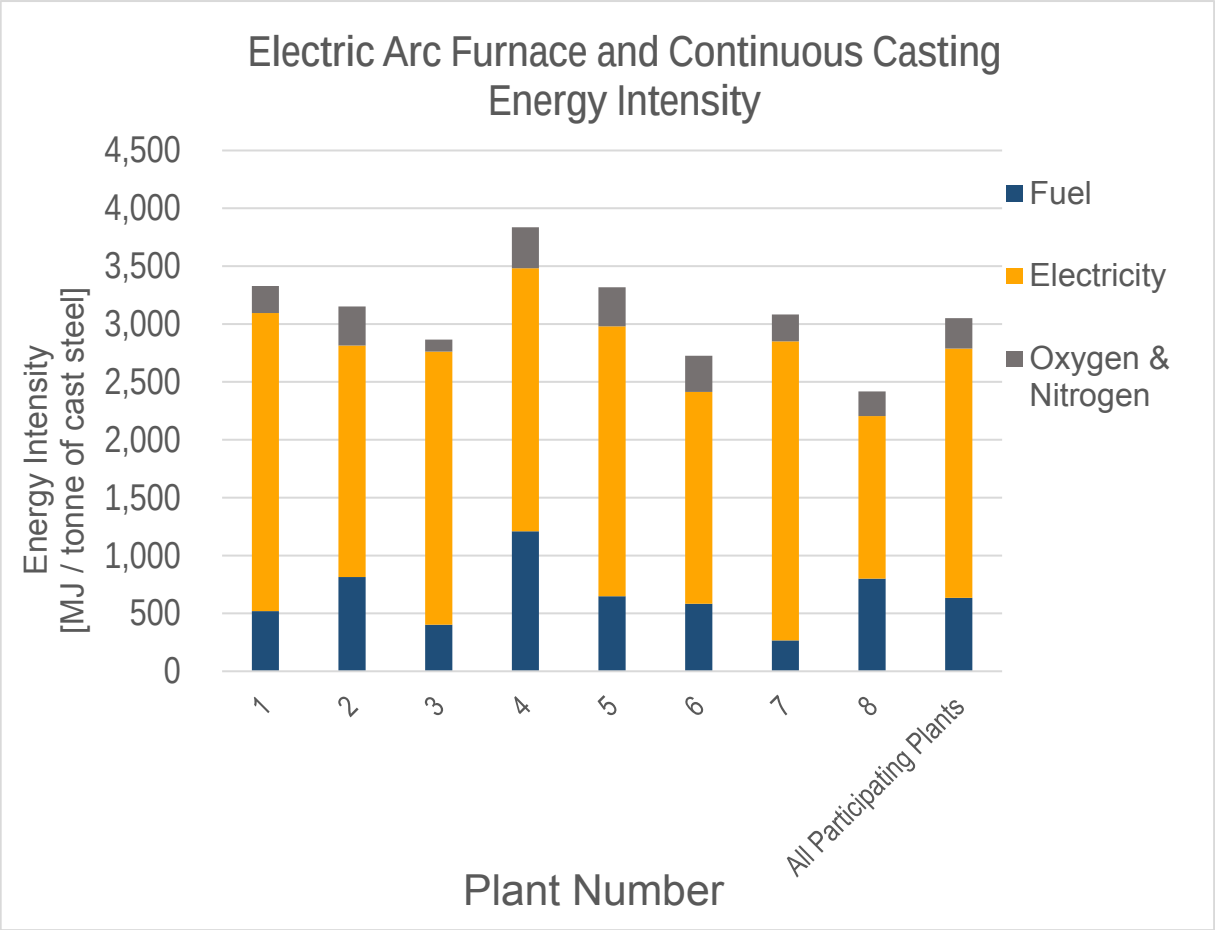

Figure 7: EAF and Continuous Casting Energy Intensity Indicators

As is expected, the large portion of energy used in the electric arc furnaces is electricity (an average of approximately 71% of all energy). Average energy intensity is 3,051 MJ per tonne of liquid steel with most plants fairly consistent.

The GHG emissions associated with EAFs varies with the source of the large amount of electricity consumed. Electricity consumed in areas with high emissions electricity grids will have high GHG intensity. As those electricity grids de-carbonize over time per planned Canadian legislation, the Scope 2 emissions of those plants will decrease as well.

Some of the differences in energy intensity are due to various different fuels charged into the EAFs (e.g. natural gas) or amounts of oxygen as well as some technological differences leading to energy efficiency improvements (e.g. eccentric bottom tapping, oxyfuel burners, foamy slag, bottom stirring, etc.).

4.1.5 Hot Rolling

The figure below presents the hot rolling energy intensity indicators in terms of MJ / tonne of hot rolled product.

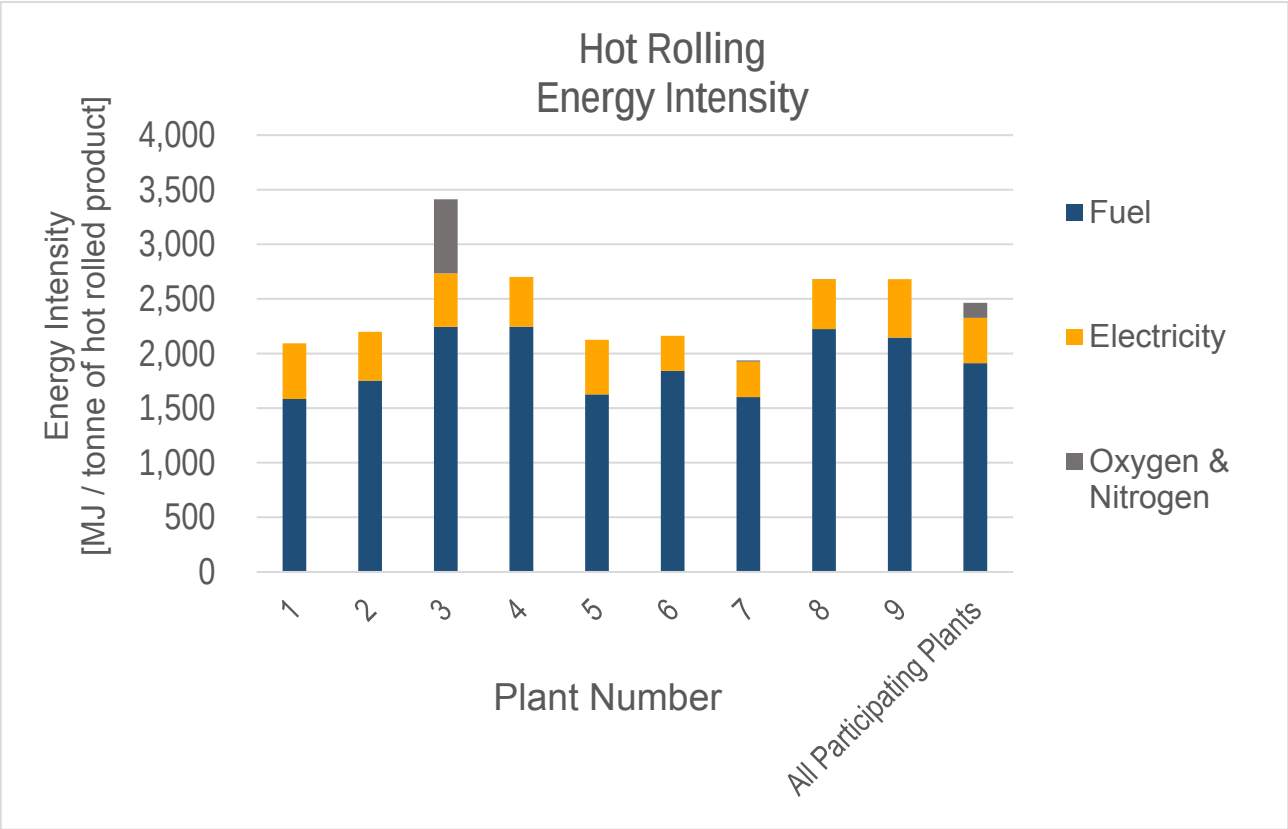

Figure 8: Hot Rolling Energy Intensity Indicators

Hot rolling is heated mainly with fuel which represents 78% of energy used in hot rolling and thus as can be seen in the GHG intensity graph, the vast majority of emissions are scope 1. The average energy intensity across the 9 plants is 2,464 MJ per tonnes of hot rolled product.

Some differences are due to energy efficiency improvements such as walking beam furnaces, direct strip processing complex (DSPC), recuperative burners for re-heat furnaces, etc.

4.1.6 Bar Mill

The figure below presents the bar mill energy intensity indicators in terms of MJ / tonne of bar.

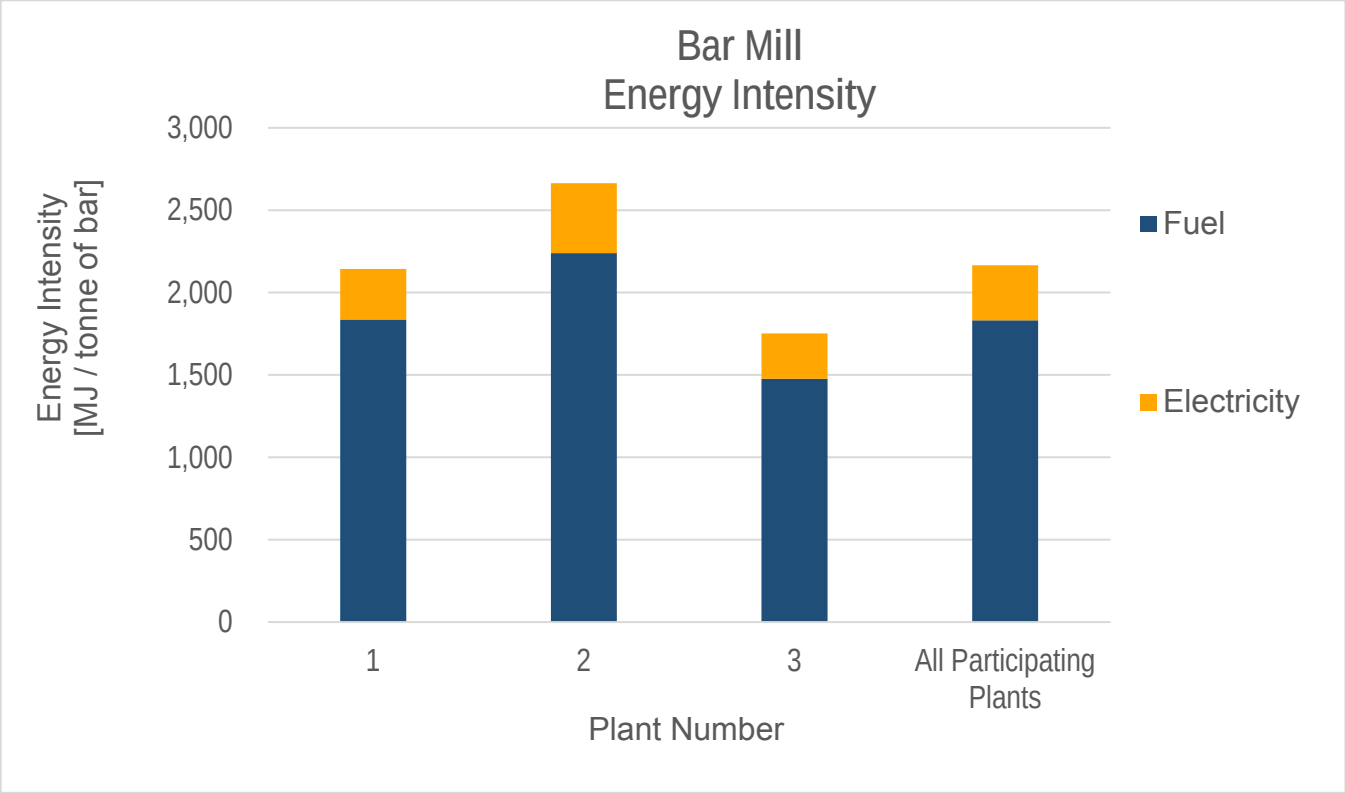

Figure 9: Bar Mill Energy Intensity Indicators

The average energy intensity of bar mills is 2,166 MJ per tonne of bar. As with hot rolling, the bar mill's energy use is mostly from fuel (an average of 85% fuel compared with total energy consumed in the bar mill process). Similar to hot rolling, the predominance of fuel energy input is evident based on the GHG emissions intensity indicators for the bar mill Process Area.

4.1.7 Plant Level Energy and GHG Intensity Indicators

The following subsections present the plant level energy and GHG intensity indicators which have been developed as described in Section 3.

The weighted average plant level energy intensity of all participating EAF plants is approximately 24% that of the corresponding weighted average net energy intensity for the Integrated plants. Similarly, weighted average GHG emissions intensity of participating EAF plants is approximately 18% of the corresponding GHG emissions intensity of the participating integrated plants. The difference between the ratios of energy and GHG intensities between EAF and integrated plants reflects the EAF steelmaking process' reliance on relatively low carbon electricity as the main energy input as opposed to fuel.

EAF

The figure below presents the EAF Plant Level Energy Intensity indicators.

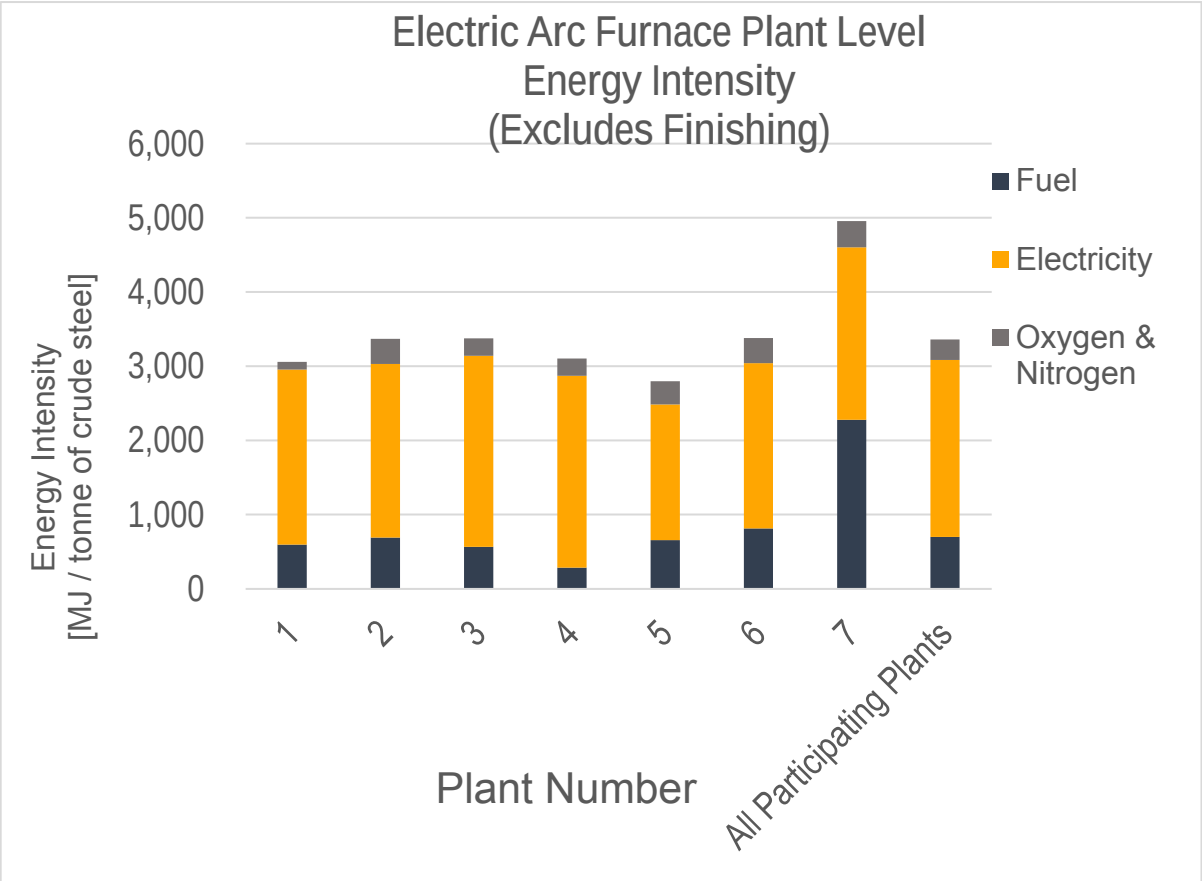

Figure 10: Electric Arc Furnace Plant Level Energy Intensity Indicators

As mentioned previously, since EAFs use scrap steel as their raw material, this process consumes substantially less energy than the Integrated plants. The majority of the energy used in EAF steelmaking is electricity, with smaller contributions from fuel and energy from oxygen and nitrogen.

Potential explanations for variation in energy intensity across participating EAF plants was explained in section 4.1 as well as by which energy efficient technologies have been implemented at each site. There is less variation in energy intensity than GHG intensity since all plants use similar amounts of energy, but the electricity grid emissions intensity where the steel plant resides will dramatically affect the scope 2 and overall GHG emissions .

Integrated

The figure below presents the Integrated Plant Level Energy Intensity indicators whereby recoverable energy refers to by-product gasses such as BFG that can be recovered and utilized elsewhere in the facility. The black line represents the net amount of energy to produce a tonne of crude steel, i.e., the difference between the energy inputs (fuel, electricity etc.) and energy outputs (COG, BFG etc.). In the case of flaring a portion of a process gas (say BFG), the total amount of BFG that is recovered from the BF is included in 'Recoverable Energy'. However, the amount of BFG that is flared is include as an energy input in the 'Fuel' bar therefore completing the energy balance as seen by the black 'net' line.

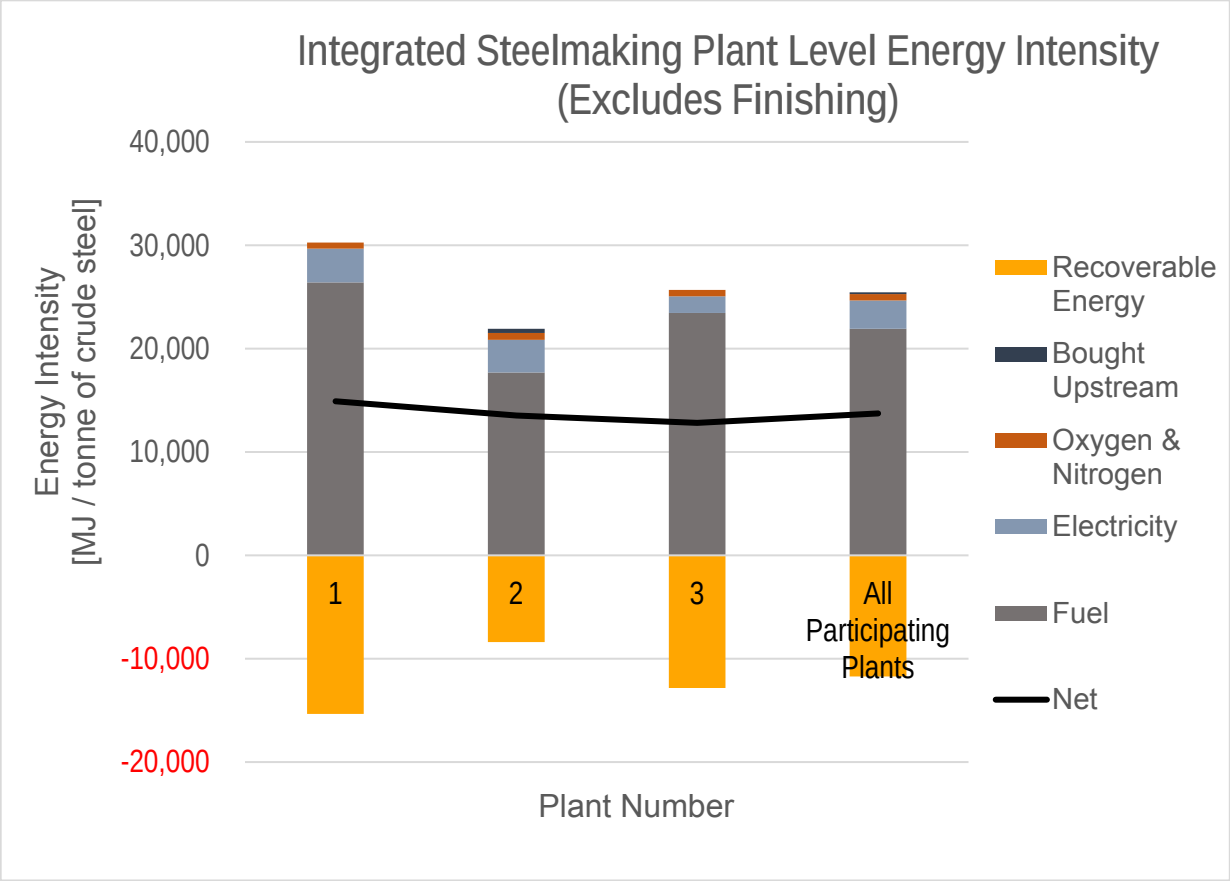

Figure 11: Integrated Steelmaking Plant Level Energy Intensity Indicators

Unlike EAFs, where the energy split between fuel and electricity is approximately equal, for the integrated plants, most of the energy used is fuel, and the integrated plants consume an order of magnitude more fuel than EAFs per tonne of finished product which explains the much higher emissions intensity for integrated vs EAFs.

Since all of the integrated plants are in Ontario there are minimal scope 2 emissions, and the majority of emissions are scope 1. Each plant can compare its GHG emissions to international country benchmarks in section 5.1, which demonstrate that in general Canadian integrated plants are the lowest carbon emitters in the world.

4.2 Assessment of Technology Penetration Results

A total of 125 technologies were identified and grouped into the categories outlined in Section 3.4.1. The technologies are summarized in the following table and described in greater detail in Appendix C.

Table 5: Summary of Potential Energy and GHG Reduction Technologies

Process	Classification	Technology/Substitution
Cokemaking	Energy Efficient Options	Coal Stamp Charging Battery, Coke Dry Quenching (CDQ), Coke Stabilization Quenching (CSQ), Coke Oven Gas (COG) Recovery Optimization, Non-Recovery Coke Ovens
	Material Substitutions/Process Options	Use of biomass in cokemaking blend
	Innovative Controls/Technologies	Single Chamber System, Novel uses for Coke Oven Gas (i.e. hydrogen production)
Blast Furnace	Energy Efficient Options	Heat Recuperation from Hot Stoves, Improved Combustion in Hot Stoves, Improved Recovery of Blast Furnace Gas, Dry Dedusting of Blast Furnace Gas, Bell Less Top (BLT) Charging System, Top-Pressure Recovery Turbines (TRT)
	Material Substitutions/Process Options	Injection of Oxy-Oil, Pulverized Coal Injection (PCI), Injection of Coke Oven Gas (COG), Injection of Natural Gas, Injection of Hydrogen, Injection of Plastic Waste, Use of high-quality ore, Renewable charcoal use
	Innovative Controls/Technologies	Injection of biogas and bio residues, Charging Carbon Composite Agglomerates (CCB), Top Gas Recycling Blast Furnace (TGRBF), Slag Heat Recovery
Direct Reduced Iron	Energy Efficient Options	Midrex Process, Midrex with CO2 Removal System, HYL III Process, Coal-Based HYL Process, Circored, Finmet, Redsmelt, SL/RN Process, FASTMET and FASTMELT, ITmk3® Process, Dust Recycling in Rotary Hearth Furnace
	Material Substitutions/Process Options	Use of hydrogen gas as partial substitute for reducing agent, Iron Carbide Process.
	Innovative Controls/Technologies	MXCOL - Midrex with Coal Gasification, Sustainable Steelmaking using Biomass and Waste Oxides, Paired Straight Hearth (PSH) Furnace, ULCORED
Smelting Reduction	Energy Efficient Options	Corex, Finex, HIsmelt
	Material Substitutions/Process Options	None identified
	Innovative Controls/Technologies	DIOS (Direct Iron Smelting Reduction), Cyclone Converter Furnace (CCF), Romelt, Tecnored, HIsarna
	Energy Efficient Options	Not applicable, no commercial applications

Process	Classification	Technology/Substitution
Future Iron Making Processes	Material Substitutions/Process Options	Not applicable, no commercial applications
	Innovative Controls/Technologies	100% H2 based DRI (e.g., Hybrit, Midrex H2), Electrolytic ironmaking, Novel Flash Ironmaking Technology (FIT)
Basic Oxygen Furnace	Energy Efficient Options	BOF Heat and Gas Recovery, BOF Bottom Stirring, KOBM BOF
	Material Substitutions/Process Options	None identified
	Innovative Controls/Technologies	Automated Steel Cleanliness Analysis Tool (ASCAT), Laser-induced breakdown spectroscopy (LIBS) for In-Situ Real-Time Measurement of Melt Constituents
Electric Arc Furnace	Energy Efficient Options	Bottom Stirring/Stirring Gas Injection, Eccentric Bottom Tapping, Tunnel Furnace Preheating – CONSTEEL Process, Shaft Furnace Scrap Preheating, Direct Current (DC) Arc Furnace, Twin-Shell DC Arc Furnace, Airtight EAF Process, Optimal Charge Calculation in EAF, Dynamic Asymmetrical Control of AC EAF, Comelt, Contiarc Furnace, Induction Furnace (IR) crucible/coreless, Model Based Steel Temperature Measurement
	Material Substitutions/Process Options	Injection of renewable bio-carbon for supplementary energy or foaming practices, Oxyfuel Burners/Lancing, Hot DRI/HBI Charging to EAF, Foamy Slag Practices
	Innovative Controls/Technologies	ECOARC, Used Tires for Insulation in EAF, New-Scrap Based Steelmaking Process using Primary Energy, Development of a process to continuously melt, refine and cast high quality steel, Hydrogen and Nitrogen Control in Ladle and Casting Operations, Waste Heat Recovery for EAF
Casting	Energy Efficient Options	Efficient Ladle Preheating, Efficient Tundish Heating, ProVision Lance-Based Camera System for Vacuum Degasser, Continuous Casting, Strip Casting (SC), Thin Slab Casting - Near Net Shape Casting, Endless Strip Production (ESP)
	Material Substitutions/Process Options	None identified
	Innovative Controls/Technologies	None identified
Hot Rolling	Energy Efficient Options	Regenerative Burners for Reheating Furnaces, Recuperative Burners for Reheating Furnaces, Flameless Burners - Dilute Oxygen Combustion, Improved Insulation of Reheating Furnace, Heat Recovery from Cooling Water, Walking Beam Furnace
	Material Substitutions/Process Options	None identified

Process	Classification	Technology/Substitution
	Innovative Controls/Technologies	Thermochemical Recuperation for High Temperature Furnaces, Innovative Reheat Furnace Management, High Temperature Membrane Module for Oxygen Enrichment of Combustion Air
Multiple Equipment/ Generic Technologies	Energy Efficient Options	Variable Speed Drives (VSD)/Variable Frequency Drives (VFD), Advanced Automation and process control systems (e.g. neural networks), Flue Gas Monitoring and Control, MultiGas Analyzer, Engineered refractories, Laser Contouring System (LCS), Rapidfire™ edge heater, Post combustion optimization, Ultra High Power (UHP) transformers, Solar thermal generation for use in plant, Geothermal heat generation for use in plant, Facility wide integrated waste heat recovery system
	Material Substitutions/Process Options	Oxy-fuel burners, Burning of biomass for thermal generation, Bio hydrogen and renewable natural gas production, hydrogen production
	Innovative Controls/Technologies	Carbon Capture and Storage (CCS), Carbon Capture and Utilization (CCU)
Power Plant	Energy Efficient Options	Combined Cycle Power Plant (CCPP) using recycled process gasses (e.g., COG), Landfill gas for electrical generation, Electrical storage (batteries, electrolyser etc.), Solar photovoltaic, Wind turbine, Geothermal electrical generation, Low-head hydro, Fuel cells for electrical generation, Small Modular Nuclear Reactors (SMRs)
	Material Substitutions/Process Options	None identified
	Innovative Controls/Technologies	None identified

The results of the Technology Penetration Study are discussed in the table below. All the 125 technologies assessed have been grouped into three categories: energy efficiency, material substitution/process options and innovation controls/technologies. In general, all facilities have considered or have implemented the process specific energy efficiency options showing the maturity of the Canadian steel sector. For example, every energy efficiency technology has been installed in at least one plant in the casting area. There is less technology penetration for the other technology categories because some of the innovative technologies are not yet commercial. Note that some of the technologies are mutually exclusive.

The results show a high technology penetration but lower emissions reduction potential for energy efficiency technology, a medium technology penetration level and a medium emissions reduction potential for material substitution/process options, and a low technology penetration level but a high emissions reduction potential for innovation controls/technologies. These results suggest that improvements in energy efficiency and material substitution/process options should continue; however, they will be insufficient to reach net zero goals. A much higher penetration of innovative controls/technologies is needed before large, step changes in emissions reductions will occur. Large investments to commercialize these innovative technologies are needed.

These high level results are summarized in the following Table 6 and shown in the following figures for each process area:

Table 6: Summary of Technology Penetration

Technology Category	Penetration	Potential Future Facility Emission Reduction	General Comments
Energy Efficiency	High	Low	The Energy Efficiency technologies are the first technologies listed on the graphs in a clockwise direction. In many graphs, the highest-ranking orange line is 6 indicating that the technology has been installed. The average blue line is 3 or more indicating that this technology is at the prefeasibility stage or above. In many cases, both lines are at 6 indicating that the majority of plants have installed this technology. And in some, the grey line indicating the lowest response is also a 6 showing that all plants have installed this technology. An exception to this is for the DRI, Smelting Reduction and Future Iron making processes. There is only one DRI plant in Canada and none that uses the other technologies as these processes replaces the need or increases the iron capacity of an Integrated Plant.
Material Substitution/ Process Options	Medium	Medium	The Material Substitution/ Process Options technologies are the second technologies listed on the graphs in a clockwise direction. For these technologies, the highest-ranking orange line is 6 for only a few technologies indicating that the technology has been installed at only a few plants. The exception to this is for the Blast Furnace and Electric Arc Furnace where these technologies have been fully adopted at many plants.
Innovative Controls/ Technologies	Low	High	These emerging to pilot technologies that can significantly decrease a facility's overall emissions have low penetration overall. An exception to this is the one DRI facility and some innovative technologies that are penetrating the Electric Arc Furnaces installed and Hot Rolling in Canada.

The spider graphs below show the technology penetration results for each Process Area. As described in s.3.4.2, The results are displayed on a spider/radar graph for each process area with the outer rings representing a ranking of 6 (e.g., implemented) and a ranking of 1 (e.g., not yet considered) as the innermost ring. Maximum (orange), minimum (grey) and average (blue) rankings for each technology are shown on the spider graphs. Note that there was no separation in the technology penetration section between EAF and Integrated plants.

Some key insights into the gaps in technology penetration include the following:

1) In casting, EAF and hot rolling, there are many technologies that are commercially available and have been implemented at a minimum of one site. It could be beneficial for other sites to examine whether these commercially available technologies are applicable to their specific site.

2) Other than combined heat and power plants using by-product off gases, no renewable energy has been implemented at steel facilities. There exists an opportunity for steel plants in higher emitting electricity grids to consider renewable energy opportunity (e.g., power purchase agreements potentially leveraging government incentives to assist in improving current economics).

3) DRI technologies are mostly mutually exclusive and would replace the existing Blast Furnaces at the integrated plants, so it is not surprising that only the Midrex process has been implemented. Although the results show that a number of other DRI technologies are under consideration the implementation of the one technology should not be considered a gap.

4) However, other future ironmaking technologies and smelting reduction that are less technologically mature or at a research stage and. are at a much earlier stage of investigation into implementation at participating steel facilities shown in the results. Given the high potential for these for GHG reductions this is a large gap in penetration and is a focus of the Low Carbon Roadmap in section 6.

5) Carbon capture utilization and storage (CCS/CCUS) has been considered by the plants but has not been implemented at any facilities. Given the high potential for these for GHG reductions this is a large gap in penetration and is a focus of the Low Carbon Roadmap in section 6.

Cokemaking

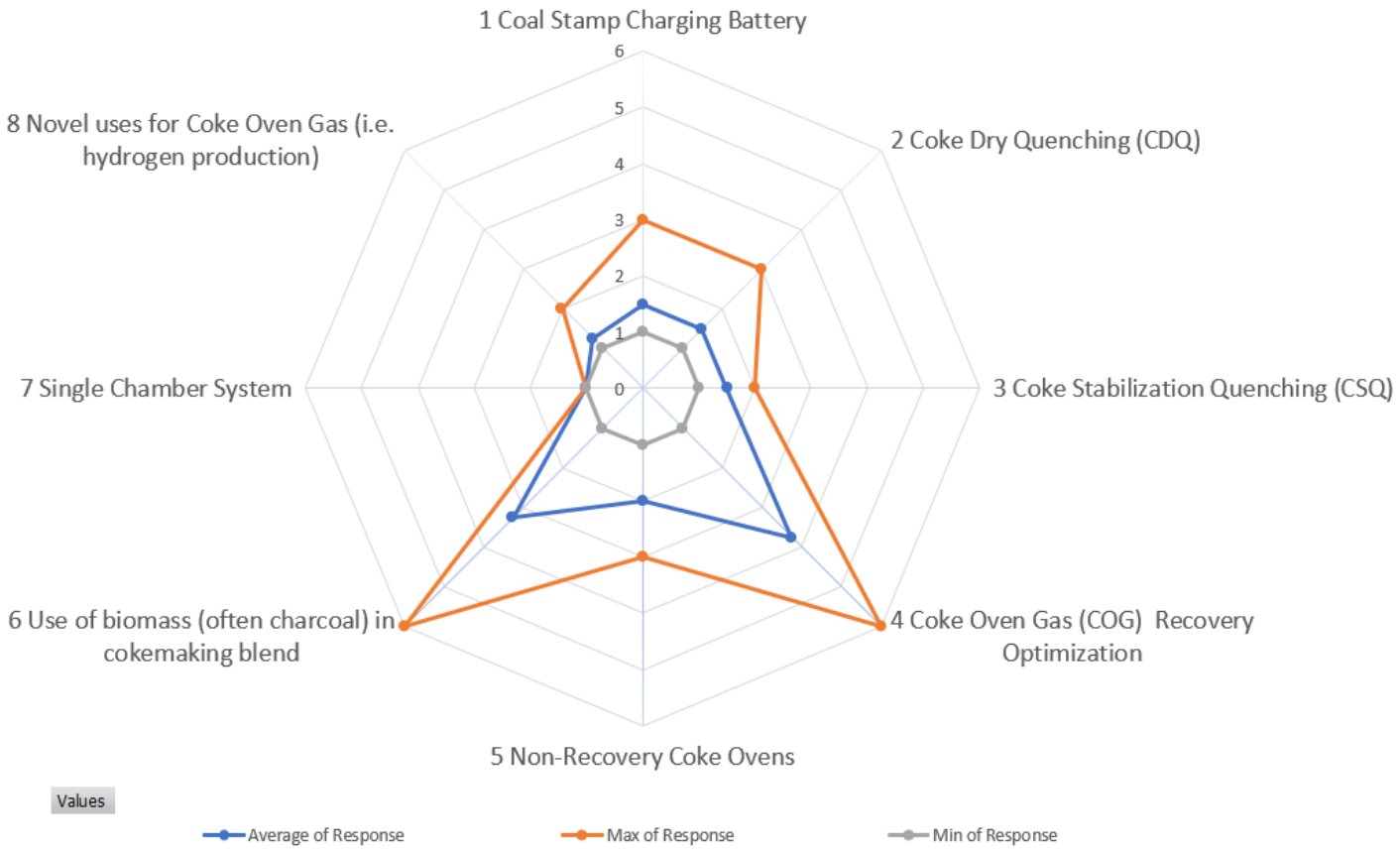

Figure 12: Cokemaking Technology Penetration Results

Blast Furnace

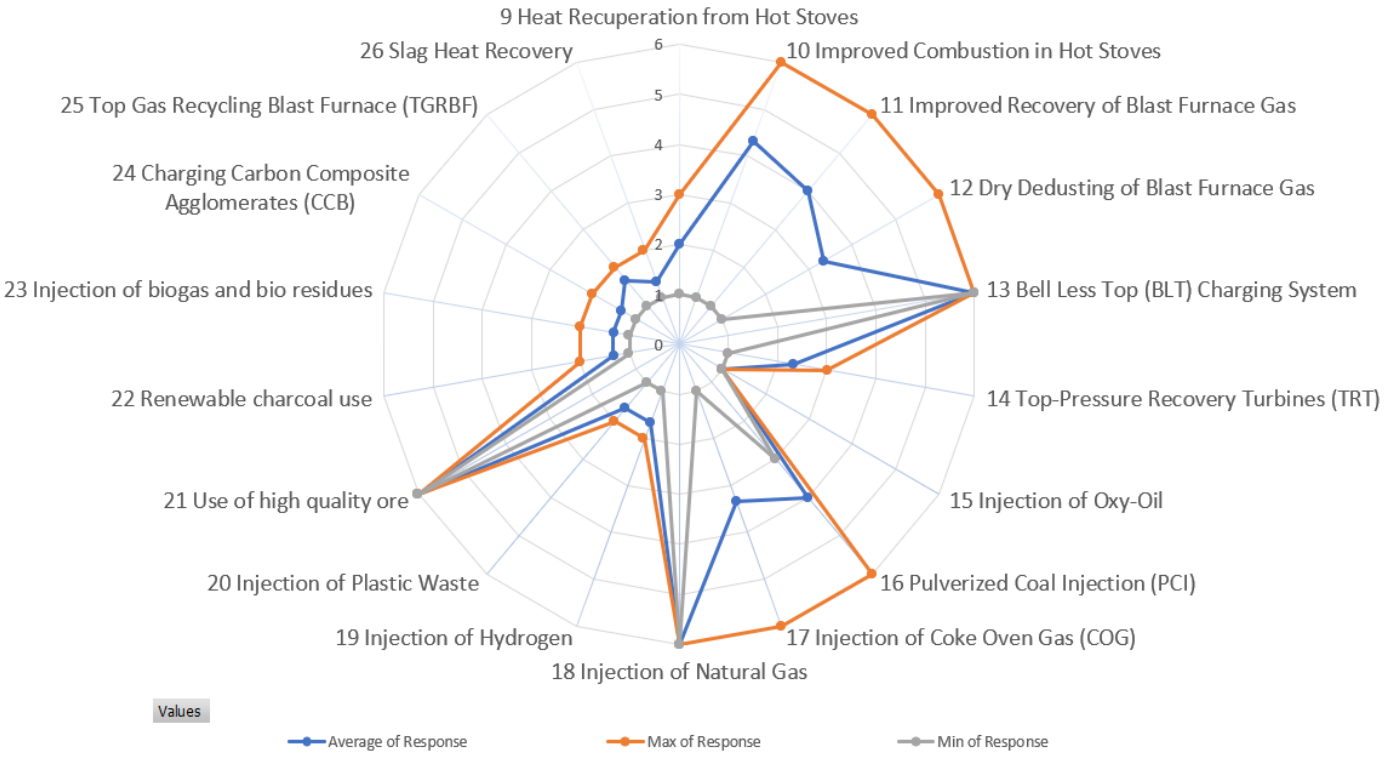

Figure 13: Blast Furnace Technology Penetration Results

Direct Reduced Iron (DRI)

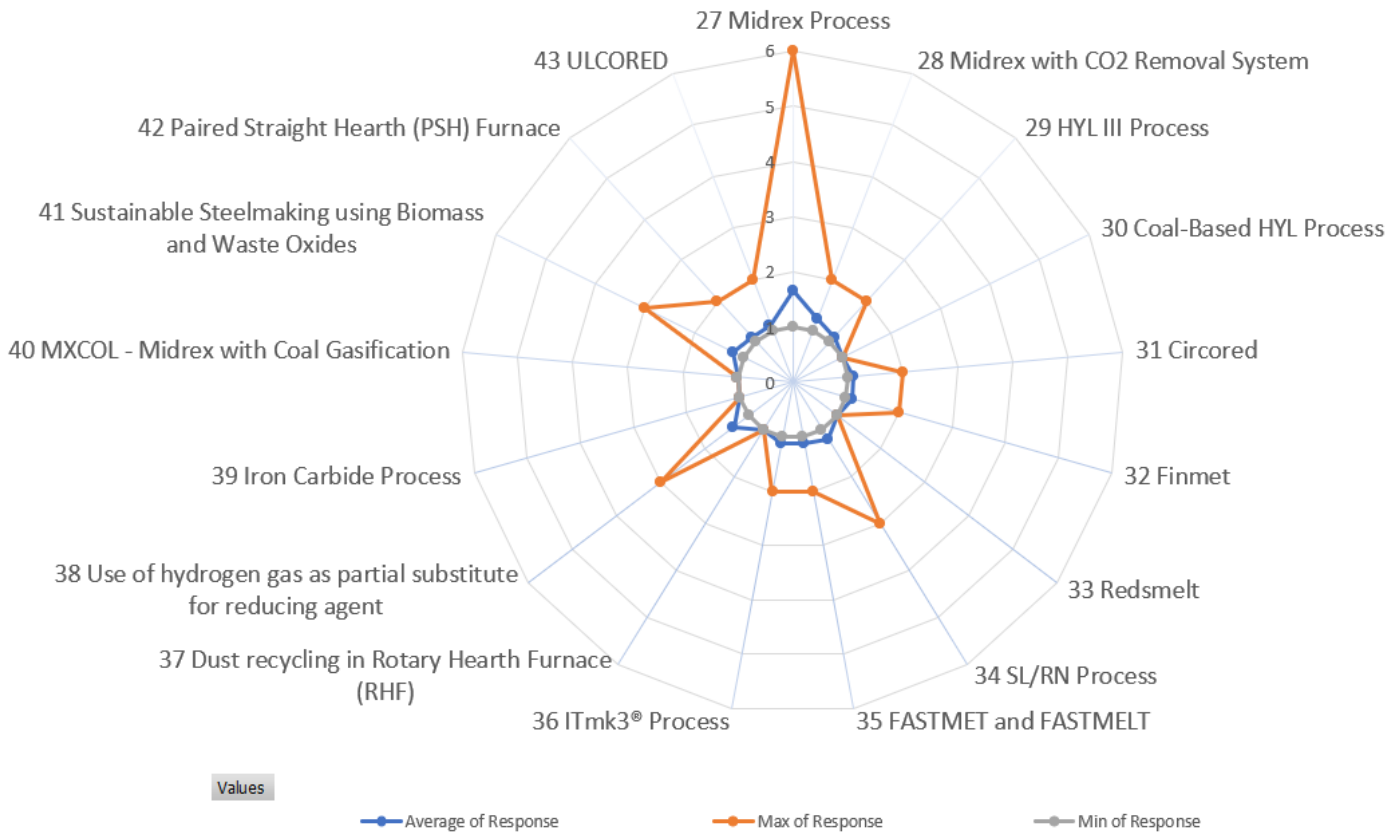

Figure 14: DRI Technology Penetration Results

Smelting Reduction (SR)

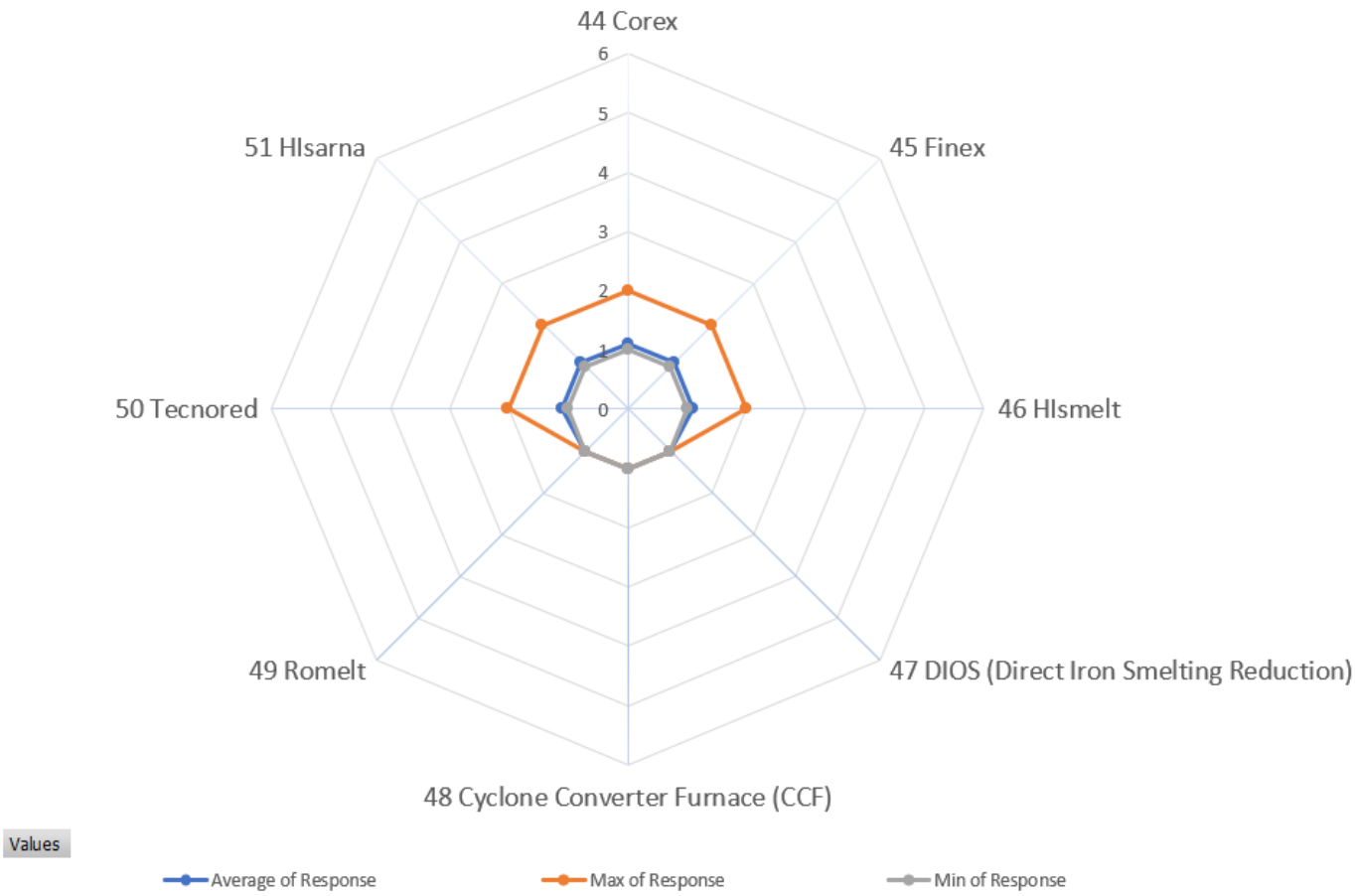

Figure 15: Smelting Technology Penetration Results

Future Ironmaking Processes

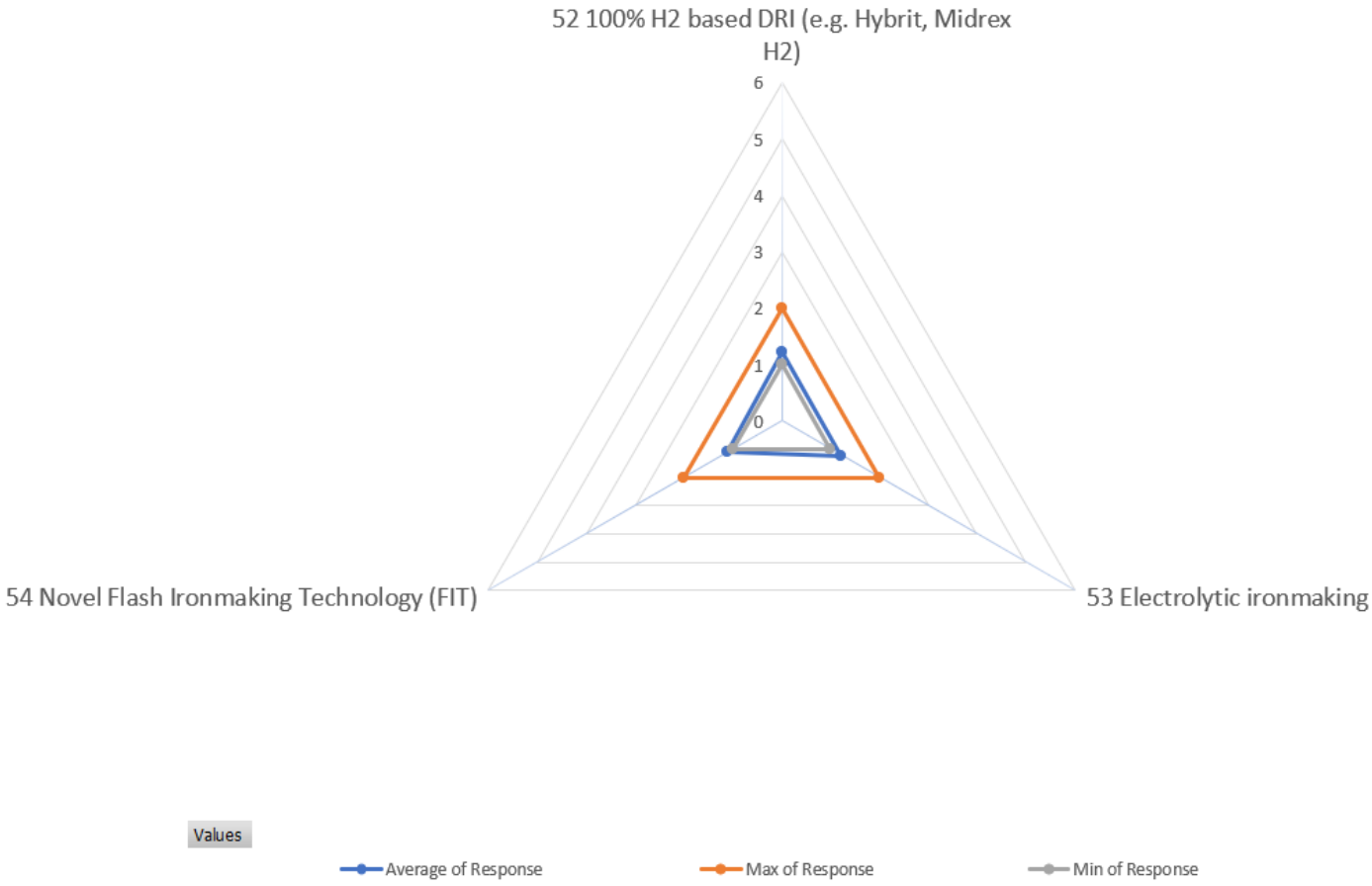

Figure 16: Future Ironmaking Technology Penetration Results

Basic Oxygen Furnace (BOF)

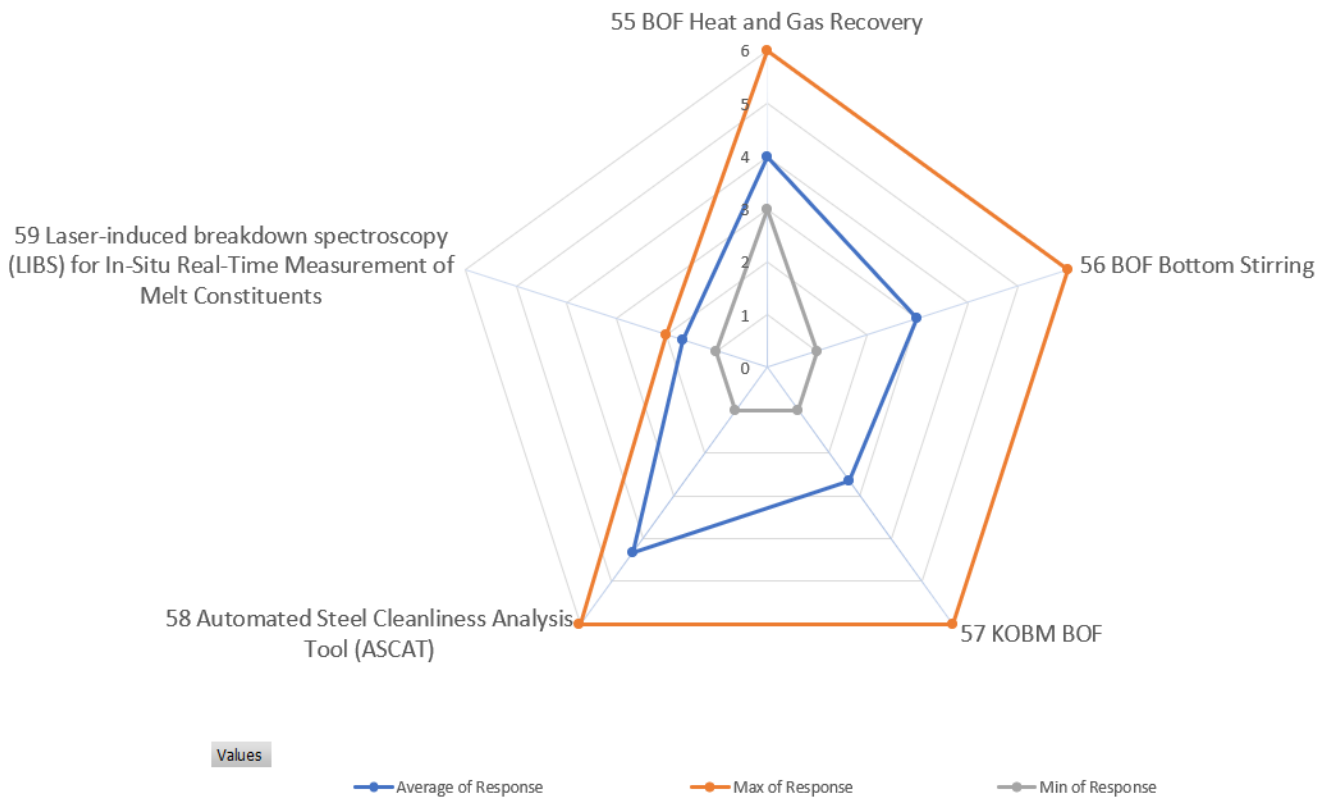

Figure 17: BOF Technology Penetration Results

Electric Arc Furnace (EAF)

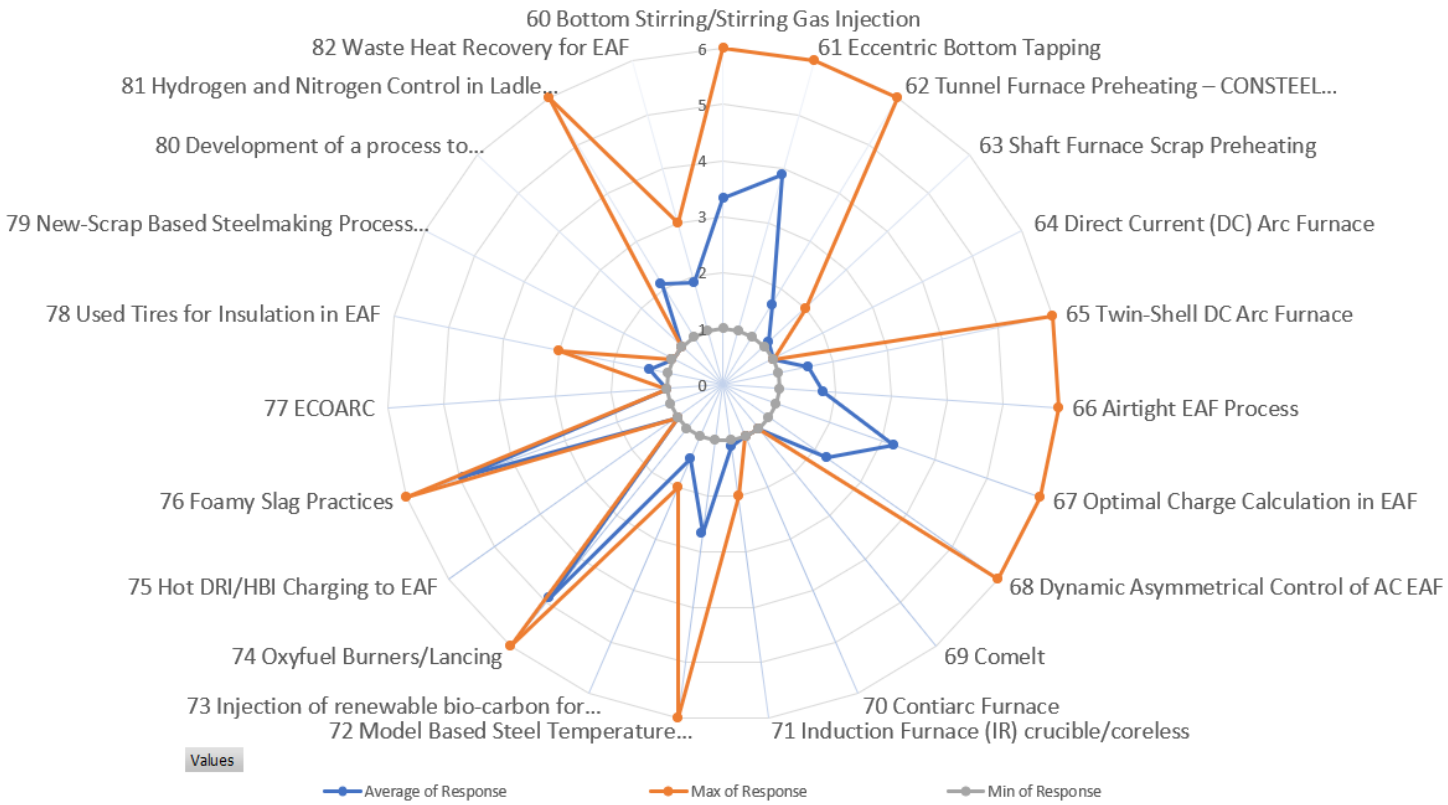

Figure 18: EAF Technology Penetration Results

Casting

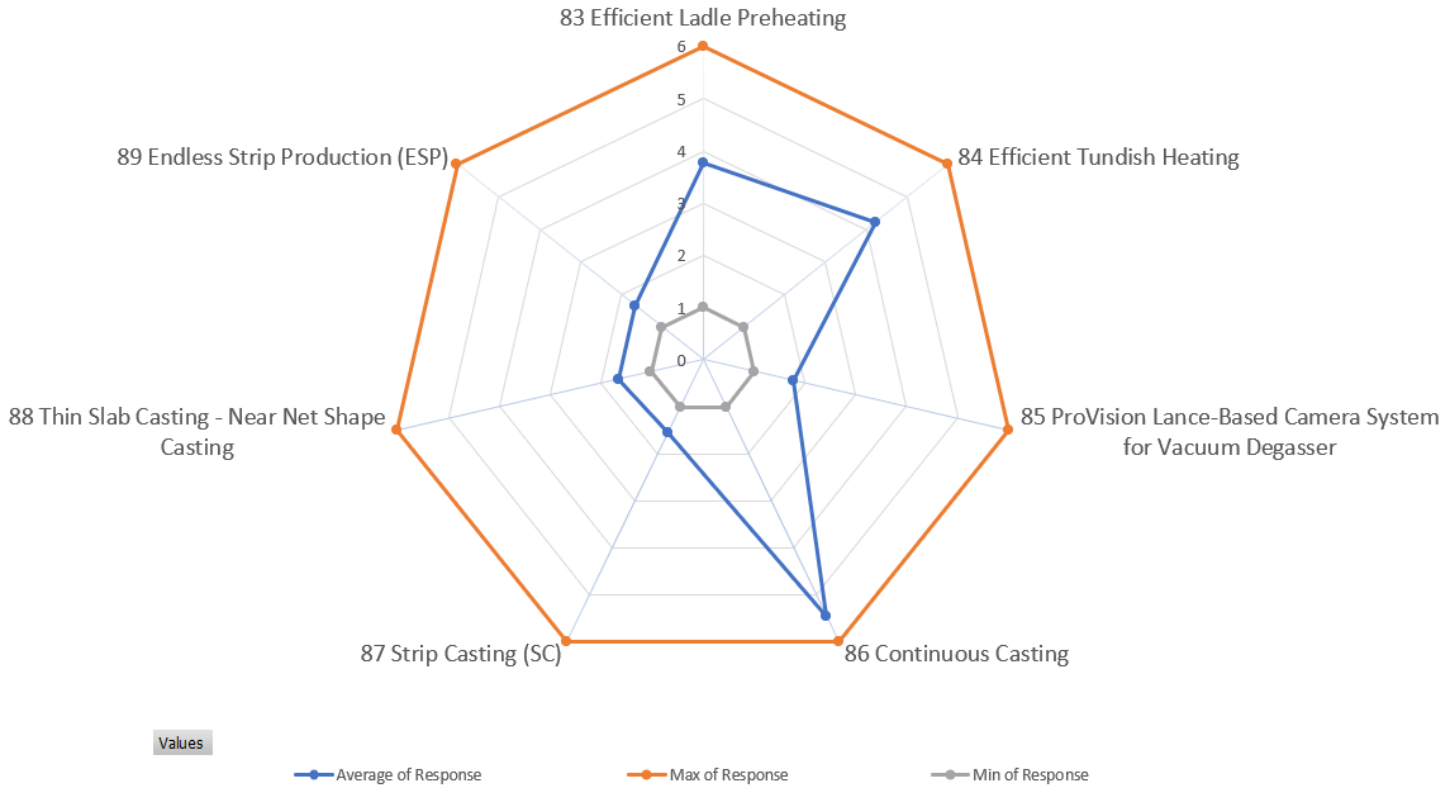

Figure 19: Casting Technology Penetration Results

Hot Rolling

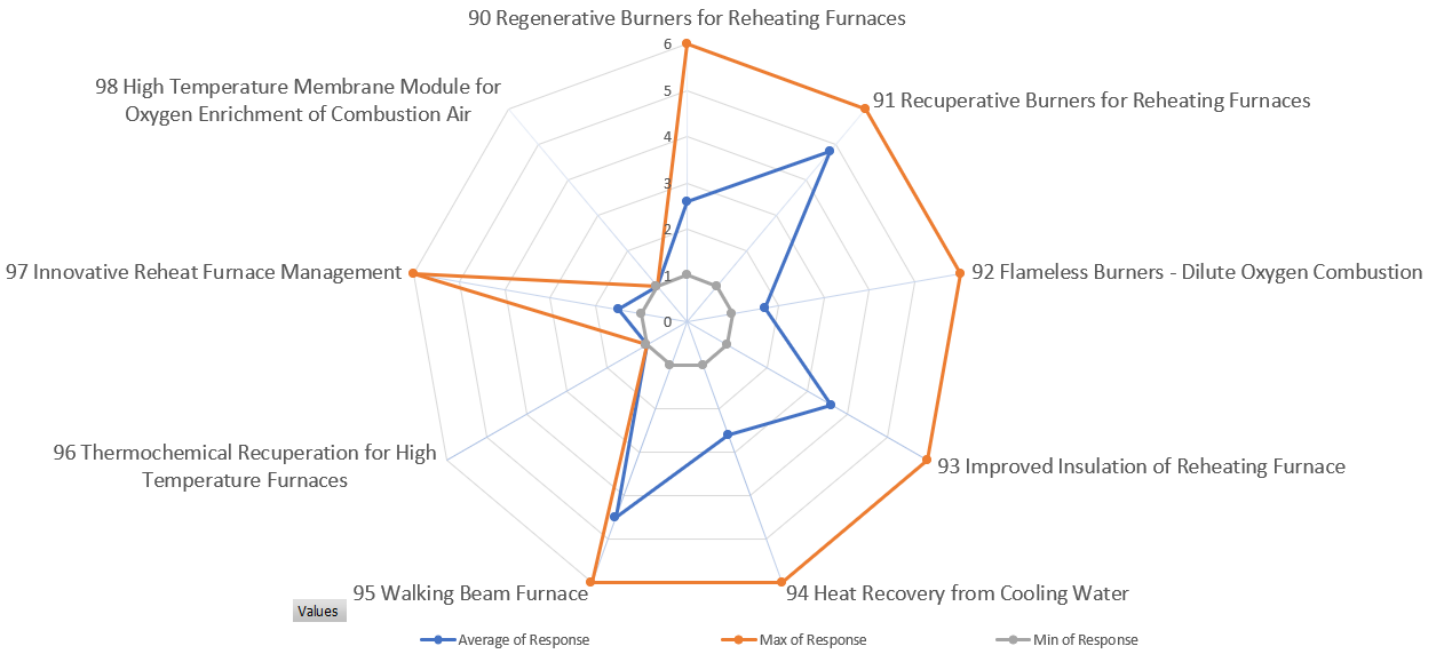

Figure 20: Hot Rolling Technology Penetration Results

Multiple Equipment/Generic Technologies

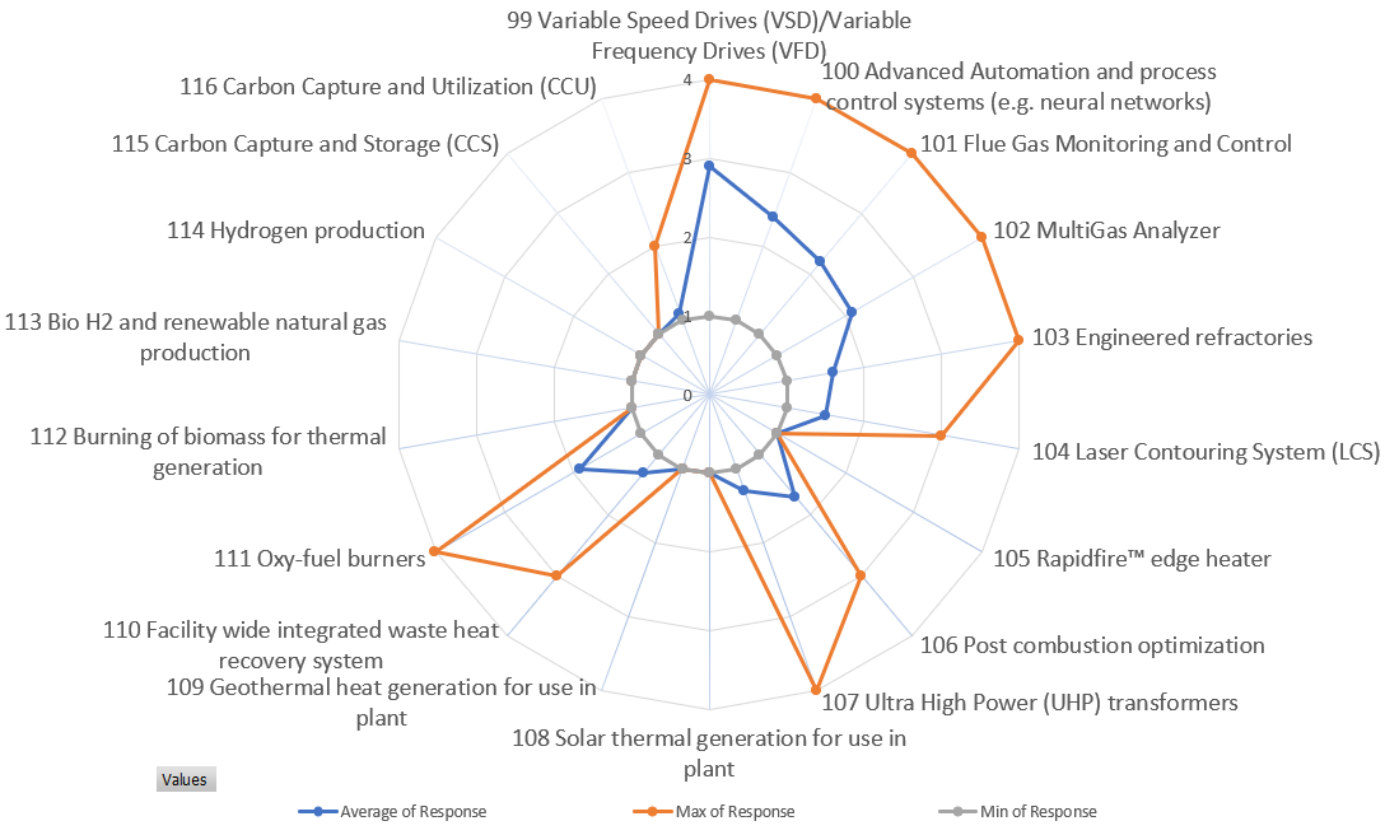

Figure 21: Multiple Equipment/Generic Technology Penetration Results

Power Plant

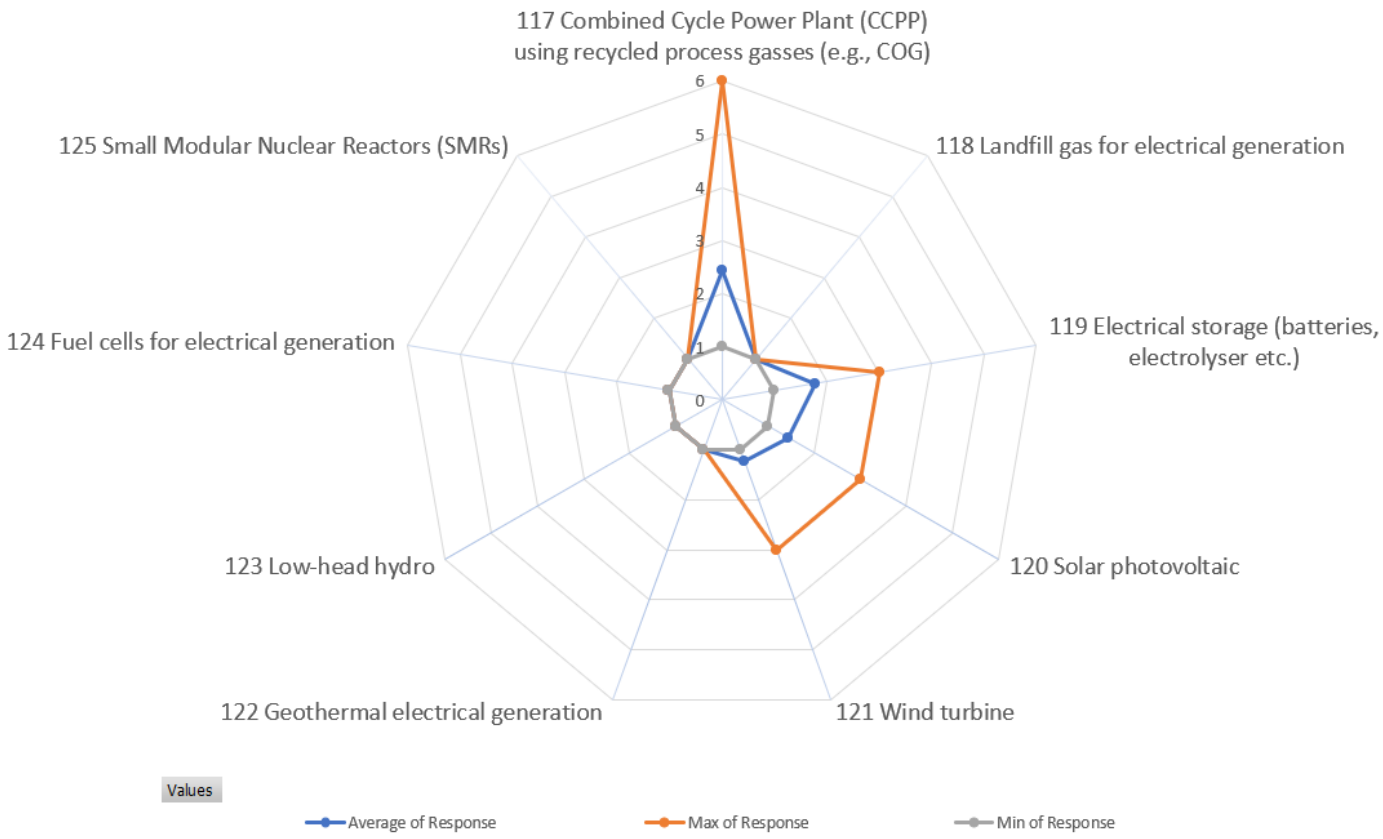

Figure 22: Power Plant Technology Penetration Results

5.0 INTERNATIONAL GHG BENCHMARKING AND ASSESSMENT OF THE ADVANTAGES OF CANADIAN PRODUCED STEEL

Steel is a global commodity made with similar technologies being used worldwide, but steel used within Canada that is produced locally by domestic steel producers has advantages in terms of embodied GHG emissions, specifically with respect to low carbon electricity and avoided long-distance overseas shipping. The top 10 countries that Canada imports steel from are shown in the figure below in blue. Of these countries, Brazil, China, Germany, India, Russia, South Korea, Turkey, and USA make up the majority of the top 10.

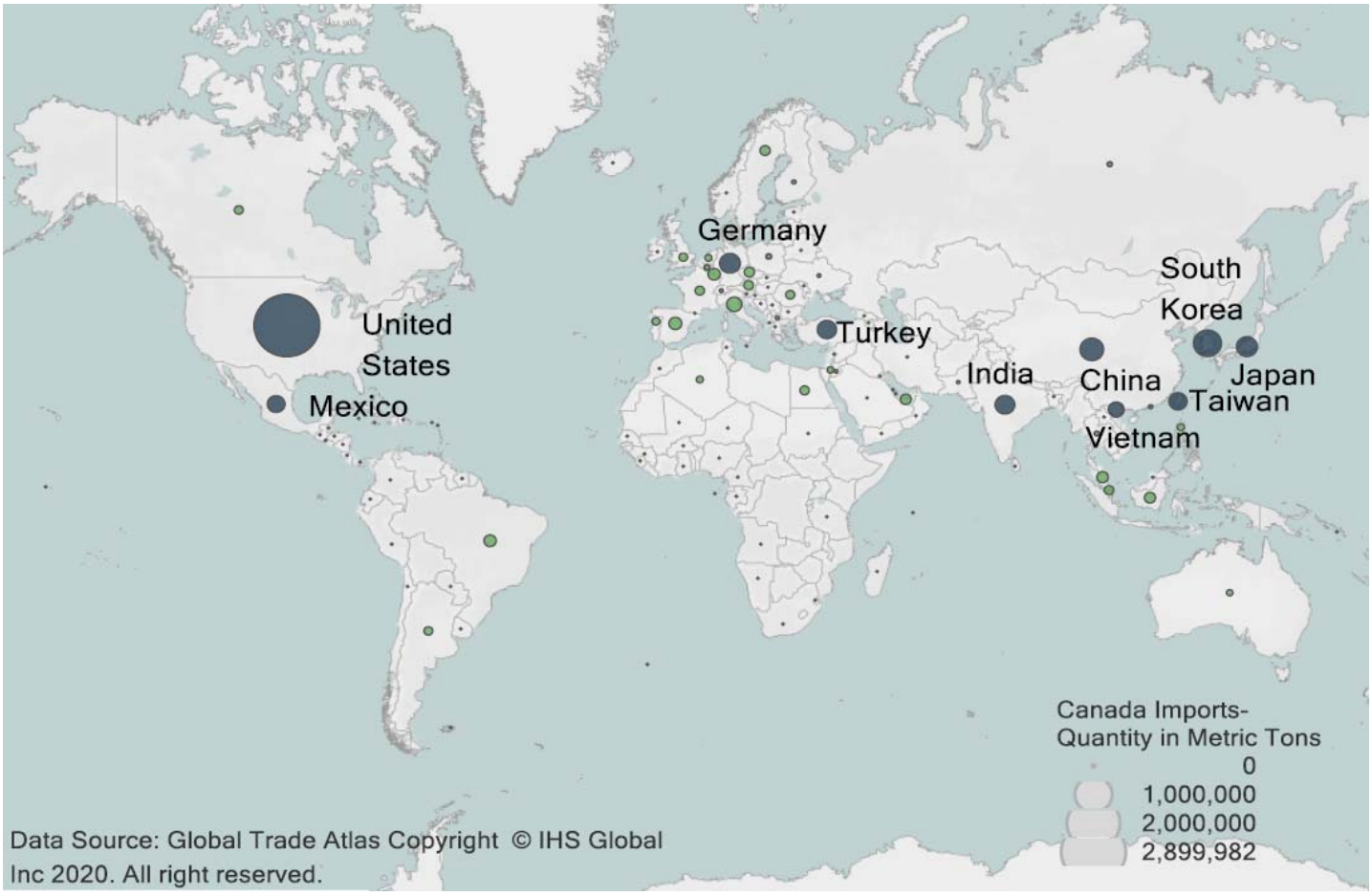

Figure 23: Canada's Imports of Steel Mill products 2019, Top 10 Countries in Blue

This section benchmarks Canadian steel compared to steel produced in other countries with respect to Scope 1 (direct GHG emissions from the manufacturing site) and Scope 2 (GHG emissions related to generation of purchased electricity) as well as Scope 3 (specifically in this case, emissions related to overseas marine transportation).

5.1 International GHG Benchmarking

A recent report prepared by Global Efficiency Intelligence titled “How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO2 Intensities” (the International Benchmarking Report) conducted a benchmarking analysis for GHG emissions intensity of the steel industry among the largest steel-producing countries using data from the year 2016. It highlights the difference in the composition of the steel industry across countries and its calculation of country-specific intensity benchmarks for EAF steel production and integrated steel production. The International Benchmarking Report is useful because the authors take different publicly reported values and convert the results to an equivalent intensity that allows country comparison.

In order to assess whether the findings of the International Benchmarking Report pertaining to Canadian steel production can be compared with intensity data calculated using information collected for this study, an analysis of the methodology outlined in the International Benchmarking Report was conducted. The analysis indicated that, using the data collected for this study, separate Canadian steel-sector wide GHG and energy intensity values for EAF and integrated steel making could be developed for comparison to the Canada-specific GHG emissions intensity data presented in the International Benchmarking Study. To develop GHG emissions intensity values that are comparable to the International Benchmarking Report values, Scope 1 and Scope 2 GHG emission sources for all primary operations up to and including the caster were summed and then divided by total crude steel production of the EAF or Integrated plants.

A comparison of Canada-wide EAF and integrated steelmaking GHG emissions intensity values developed using this methodology, and the findings of the International Benchmarking Report pertaining to Canadian steel production, is discussed below and in the following figures.

Figure 24 shows the GHG emissions intensity for EAF steelmaking from the International Benchmarking Report. Canada is ranked second best (second lowest in emissions intensity) of the countries compared. The International Benchmarking Report concludes that this is because of Canada’s low electricity grid intensity.

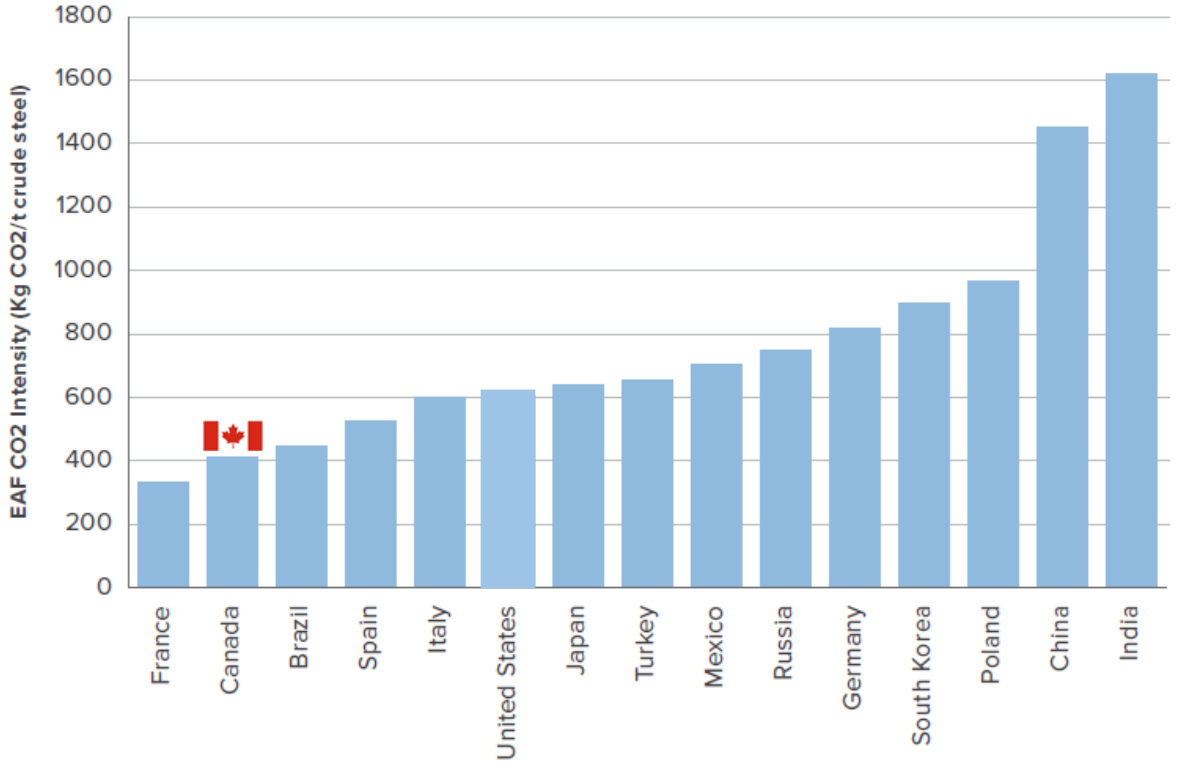

Figure 24: International Benchmarking Report Results for EAF Steelmaking (Global Efficiency Intelligence)

In this study, the Canada-wide EAF GHG emissions intensity value calculated for 2018 based on data collected from the participating plants using the methodology described in Section 3 is **417 kg CO_2e/tonne** of crude steel. Although the data in the International Benchmarking Report are from 2016, its EAF GHG emissions intensity calculated for Canada is in close agreement with the value calculated for 2018 in this study. As previously demonstrated and discussed in this study, EAF steelmaking is largely reliant on electricity as its primary energy input. Canada's ranking in the International Benchmarking Report, along with the closely agreeing GHG emission intensity value calculated in this study reflect the fact that 73% of EAF steel made in Canada in 2018 was made in provinces where the electricity grid GHG emissions intensity was 30 g CO_2e/kWh or less, furthermore 50% of EAF production occurred in provinces with grid intensities less than 1.6 gCO_2e/kWh or less. The impact of the Canadian electricity grid on overall emissions intensity of Canadian steel is further discussed in the next subsection.

Figure 25 shows the Canada-wide GHG emissions intensity calculated for integrated steelmaking in the International Benchmarking Report. Canada is ranked first in the world (the lowest emissions intensity) of the countries compared. The International Benchmarking Report concludes that this is because of Canada's high use of natural gas in the process as opposed to other heavy fuel oils.

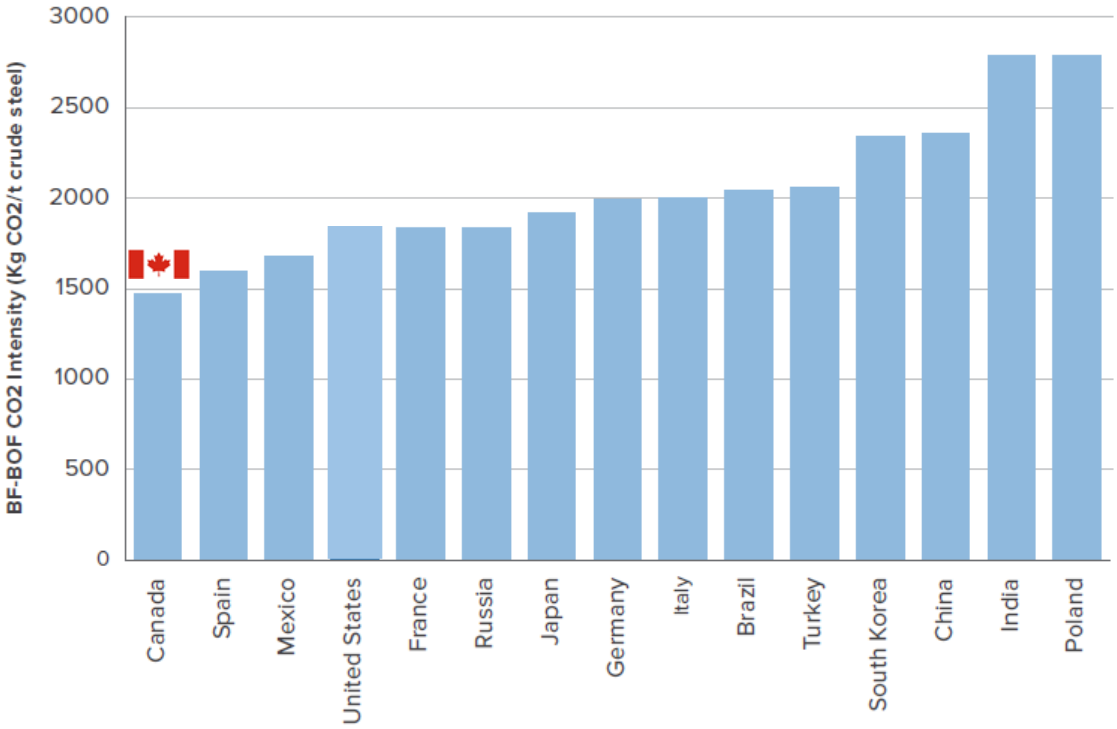

Figure 25: International Benchmarking Report Results for Integrated Steelmaking (Global Efficiency Intelligence)

The Canada-wide integrated steelmaking GHG emissions intensity value calculated for 2018 based on data collected from the participating plants using the methodology described in Section 3.0 is **1,389 kg CO_2e/tonne** of crude steel. This value is once again in close agreement with the value calculated in the International Benchmarking Report.

Based on the above, there is alignment between the GHG emissions intensity values for Canadian EAF and integrated steelmaking calculated in this study and the equivalent values calculated in the International Benchmarking Report. Those findings indicate that Canada has the second lowest GHG emissions intensity in EAF steel for the year 2016 and the lowest GHG emissions intensity in integrated steel among the largest steel producing nations.

5.2 Assessment of Canada's Electricity Grid GHG Emissions Intensity

Depending on where a steel producing facility is located, the Scope 2 GHG emissions from the electricity grid can vary significantly. To further expand on the conclusions of the International Benchmarking Report regarding the significance of Scope 2 electricity-related emissions, this section focuses on the electricity grid-related emissions from Canadian provinces and steel trading partner countries.

5.2.1 Domestic Grid Intensity

The electricity generation from the grid broken down by energy source can be seen below for Canada's provinces and territories for 2018 as shown in Figure 26.

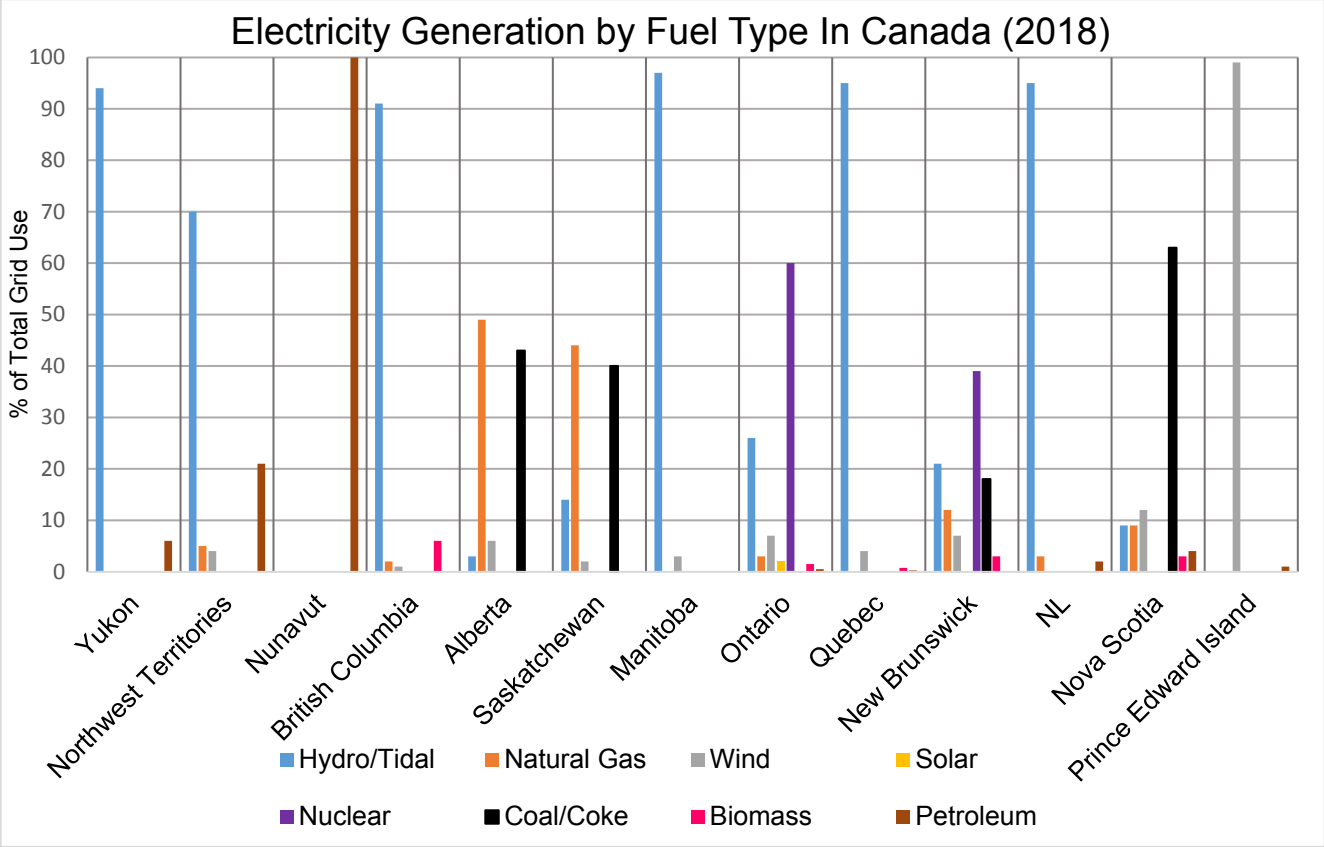

Figure 26: Electrical Generation of the Provinces of Canada by Fuel Type for 2018 (Canada Energy Regulator)

It can be noted that high emissions grids include Alberta, Saskatchewan, Nova Scotia, and Nunavut which use mainly coal, natural gas and/or petroleum-fueled electricity generation. The remainder of the provinces and territories have relatively low or very low emissions grids. Canada's steel production facilities are located in Alberta, Saskatchewan, Manitoba, Ontario and Quebec.

The following table provides a list of the current steel producers in Canada and which province(s) they have facilities located in, as well as the GHG emission intensity values of that provinces' electricity grid in terms of total electrical generation. The GHG Protocol Corporate Accounting and Reporting Standard states that electricity consumption should be used as opposed to electricity generation (in the latter, emissions due to transmission and distribution losses are added to the electricity consumed by the end user); however, the international grid emissions intensities uses the generation values. Thus, for consistency in comparing with international trading partner country grids, this report uses the generation grid emissions intensity values.

Table 7: List of CSPA Members Facility Location by Province and Corresponding GHG intensity of Electrical Grid in 2018

Province	Companies With Facilities In Province	CO2e (g) / Total Generation (kWh)
Manitoba	Gerdau	1.3
Quebec	ArcelorMittal Long Products, Noval Steel, Rio Tinto Iron & Titanium	1.3
Ontario	Algoma Steel Inc., ArcelorMittal Dofasco, Atlas Tube, Gerdau, Ivaco Rolling Mills, Nova Steel, Stelco Inc., Tenaris S.A., Valbruna ASW Inc	30
Alberta	AltaSteel, EVRAZ North America Inc., Tenaris S.A.	630
Saskatchewan	EVRAZ North America Inc.	680

Reference for GHG intensity values: Environment and Climate Change Canada, 2020.

A graphical form of this table is shown in the figure below. As many of the major emitting facilities are located within the low emitting grids of Ontario and Quebec (as well as Manitoba), many of the Canadian facilities have favorable scope 2 emissions compared to the vast majority of international competitors. In addition, Alberta and Saskatchewan have committed to eliminate coal-fired electricity by 2030 which will continue to reduce grid electricity-created GHG emissions from those provinces and reduce the steel companies' Scope 2 emissions in those jurisdictions.

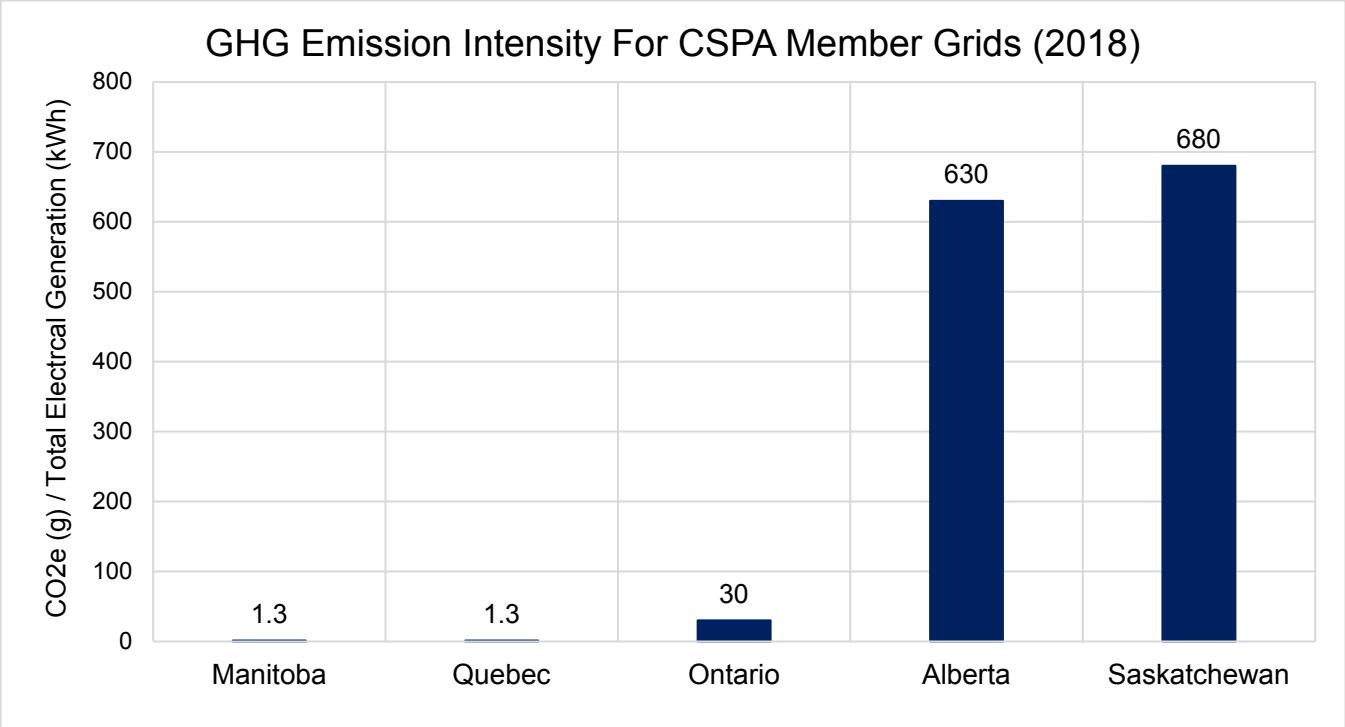

Figure 27: GHG intensity for CSPA Member Grids (Manitoba, Quebec, Ontario, Alberta and Saskatchewan) in 2018 (Environment and Climate Change Canada, 2020).

5.2.2 International Grid Intensity

For a more holistic comparison of the emission intensity of Canadian facilities to their international competitors, the scope 2 and scope 3 emissions should be taken into account. The emission intensity of the 8 countries listed previously and the emission intensity of Canada are shown below for 2018. The majority of these values came from the 2019 climate transparency report with the German emission intensity reported by the Association of Issuing Bodies (AIB), the USA emission intensity reported by the Environmental Protection Agency (EPA) and the Canadian emission intensity reported by UN Framework Convention on Climate Change [3]. The graph shows that India has the largest electricity grid emissions intensity by a significant margin. China, South Korea, Turkey, USA, Germany and Russia, in that order, have relatively similar emissions intensities ranging from 325 gCO_2e/kWh to 555 gCO_2e/kWh. Finally, Brazil and Canada have the lowest grid emissions intensity by far at 74 gCO_2e/kWh and 130 gCO_2e/kWh respectively, largely due to their use of hydropower and/or nuclear power.

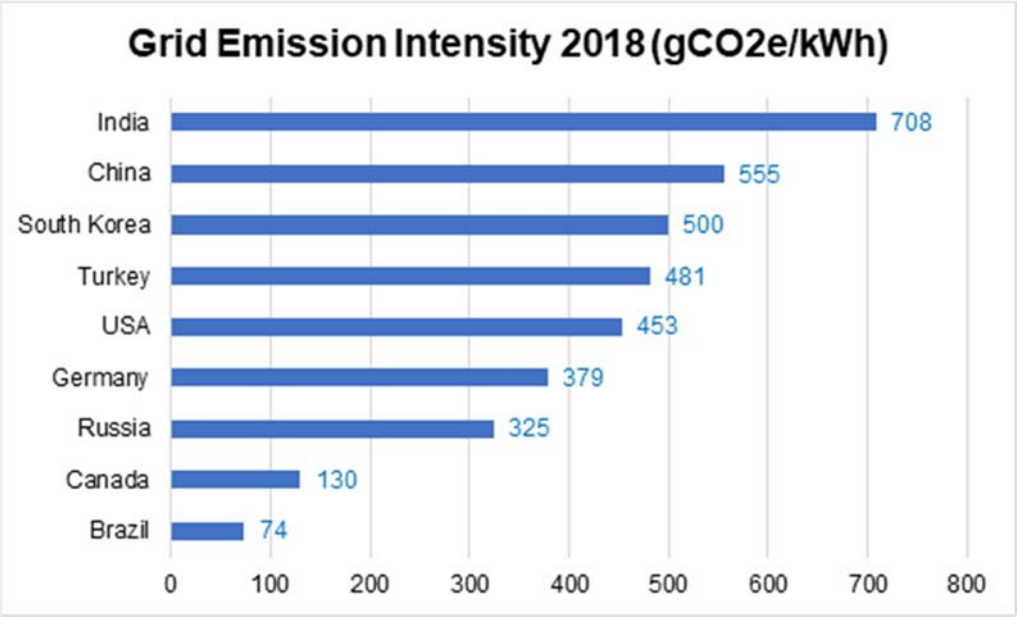

Figure 28: Electricity Grid Emission Intensity/factors of CSPA Selected Trading Partner Countries

5.2.3 How Canada compares to Main Trading Partners

When comparing these countries to the provinces that host Canadian steel producing facilities, we can see that the Ontario, Quebec and Manitoba electricity grids have far lower emission intensities than any of the listed countries (with Brazil being the closest) as shown in the figure below. Saskatchewan and Alberta are currently higher than all other trading partners except India; however, with the commitment to eliminating coal-fired electricity by 2030, those provinces' electricity grid emissions intensities should drop substantially.

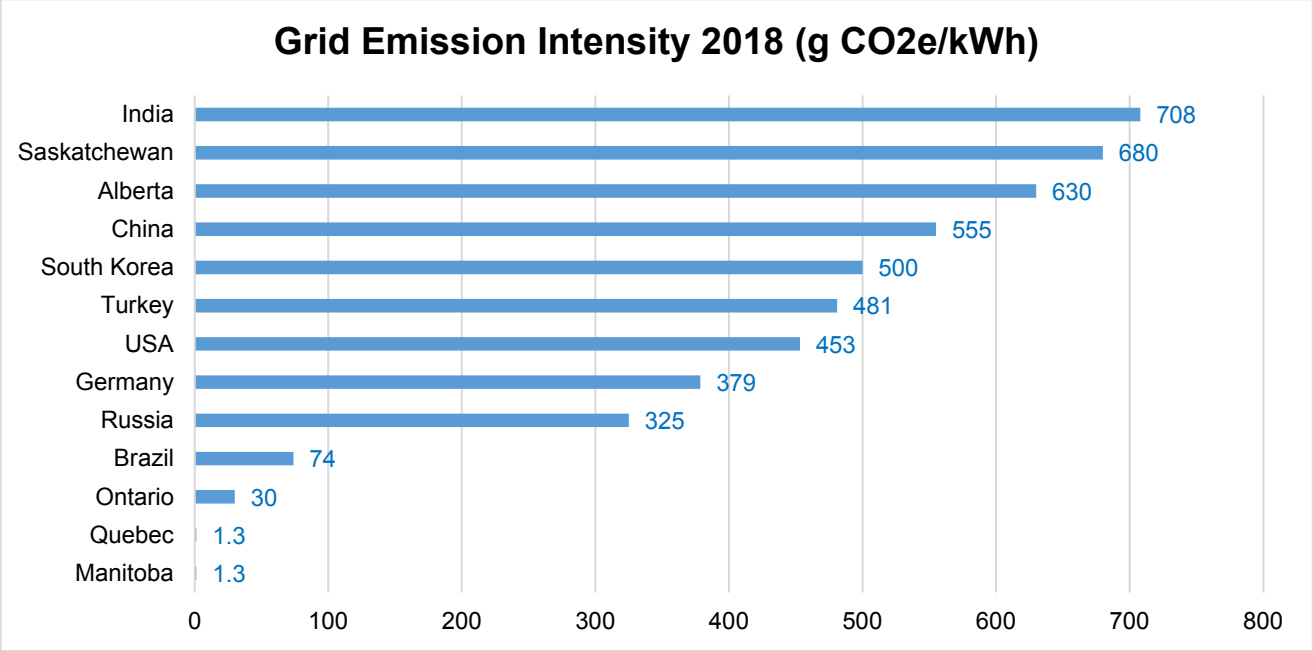

Figure 29: Comparison of Grid Emission Intensity of CSPA Identified Trading Partner Countries with Canadian Steel Producing Provinces

The majority of the larger steel producing facilities in Canada (including all integrated steel facilities) are located in Ontario or Quebec. As a result, the scope 2 emissions for the majority of Canadian facilities should be much lower than their international competitors. With many environmental and carbon pricing strategies being implemented in the upcoming decade including potentially carbon border adjustments, this large advantage in scope 2 emissions will have a significant monetary value for Canadian steel being used in Canada or exported compared to importing steel from other countries. This supports the conclusions of the International Benchmarking Report.

5.3 Assessment of Scope 3 GHG Emissions Associated with Marine Transportation of Steel Imported to Canada from Overseas

This section assesses the GHG emissions associated with marine transportation of imported steel to Canada from Brazil, China, Germany, India, Russia, South Korea, and Turkey. GHG emissions were quantified based on the marine shipping distance, GHG Protocol emission factors (GHG Protocol) for marine shipping, and the tonnes of steel imported for each country in the year 2018.

The transportation route of internationally imported steel varies depending on the country of origin and the end destination within Canada. This analysis quantifies the emissions associated with marine transportation only, due to the limitations of estimating land transportation parameters. Excluded are the various routes to origin ports in international countries, various routes from destination ports in Canada, and various end destinations in Canada, among others. Therefore, once imported steel reaches a Canadian marine port, it is assumed that land transportation within Canada is comparable with the land transportation of domestic steel.

The inability to quantify the transportation emissions from steel produced in the USA is a large gap in this analysis. It is assumed that steel imported to Canada from the USA is transported via land transportation options, which is not quantified herein. In recognizing that the majority of imported steel is from the USA, land transportation emissions are likely to be high due to the volume of steel being transported. In addition, land transportation generally has a higher per kilometre emissions factor than marine transportation (Chamber of Marine Commerce). Future efforts focusing on a methodology to quantify the emissions from land transportation of imported steel would improve the robustness of the comparison across Canada's major steel trading partner countries.

Table 8 summarizes the trading partners selected for this assessment of Scope 3 GHG emissions associated with marine transportation of steel imported to Canada from overseas and the quantity of steel imported from each partner in 2018. The 2018 year was selected for analysis to be consistent with other parts of this report.

Table 8: Imported Steel from Trading Partners Identified for this Analysis in 2018

Trading Partner	Imported Steel [tonnes][1]	% of Total Imported Steel
China	540,089	9.3%
Turkey	497,193	8.6%
South Korea	485,435	8.4%
Germany	193,397	3.3%
India	104,135	1.8%
Brazil	50,316	0.9%
Russia	20,625	0.4%

The trading partners listed in Table 8 accounted for a total of 33% of all of Canada's imported steel in 2018. The USA accounted for 46% of total imported steel in 2018.

The port of origin for each trading partner was assumed to be the country's largest port. Both the Port of Vancouver and the Port of Montreal were considered as potential destinations in Canada. The shorter distance between the port of origin and either Vancouver or Montreal was assumed to be the more common shipping route and was used in the calculation of marine transportation emissions intensity for imported steel. Marine distances were estimated based on overseas shipping routes and a 15% additional distance allowance added to total distance between ports for route variations or detours.

GHG emissions intensity values for marine shipping were developed for each trading partner based on the shipping distance and marine shipping emission factors obtained from GHG Protocol Emission Factors from Cross-Sector Tools. There is a fairly wide range in emission factors available from the GHG Protocol for shipping on large bulk carriers, and therefore the results of this analysis are presented as ranges.

Table 9: Summary of Shipping Route, Shipping Distance and Range of Marine Shipping GHG Intensity for Imported Steel

Trading Partner	Assumed Marine Shipping Route	Shipping Distance [km]	Marine Shipping GHG Emissions Intensity for Trading Partner [kg CO2e / tonne of imported steel][1]	
			Lower Range	Top of Range
China	Shanghai - Vancouver	10,883	48	90
Turkey	Istanbul - Montreal	10,607	47	88
South Korea	Busan - Vancouver	9,846	44	81
Germany	Hamburg - Montreal	7,267	32	60
India	Mumbai - Montreal	17,335	77	143
Brazil	Santos - Montreal	11,776	52	97
Russia	Novorossiysk - Montreal	11,578	52	96

Notes:
[1] based on indicated shipping distance

As indicated above in Table 9, marine transportation of steel from Canada's largest overseas steel importing partners can add between 32-143 kg CO_2e/tonne in embedded GHG emissions. These embedded GHG emissions are directly correlated with distance. Countries with the furthest marine shipping distance have the highest shipping emissions intensity. Taking a weighted average of the above ranges based on quantities imported from each trading partner results in an average of approximately 47-87 kg CO_2e/tonne imported steel in embedded GHG emissions from these partners. These are Scope 3 GHG emissions that are purely additional to Scope 1 and Scope 2 steel production emissions, which have already been demonstrated to be significantly higher than domestic steel production (see sections 5.1 and 5.2).

To put this amount of embedded GHG emissions in imported steel from transportation alone into context, it should be noted that the Canada-wide EAF steel production GHG emissions intensity value calculated for 2018 based on data collected from the participating plants using the methodology described in Section 6.1 is 417 kgCO_2e/tonne of crude steel. As such, 47-87 kg CO2e / tonne of imported steel, simply representing GHG emissions from marine transportation from imported steel, would be equivalent to 11-21% of the total emissions intensity for EAF steel produced in Canada.

This analysis demonstrates that, in addition to significantly lower Scope 1 and Scope 2 GHG intensity, Canadian steel used in Canada has an added GHG benefit resulting from the avoidance of a significant amount of Scope 3 GHG emissions associated with marine shipping over long distances.

6.0 CARBON REDUCTION ROADMAP

Since 1990, the Canadian steel industry has voluntarily invested to reduce energy consumption and emissions, achieving a 31.5% reduction in absolute GHG emissions by 2016. This equates to an emissions intensity improvement of approximately 27.6% (CIEEDAC, 2017). However, despite these reductions, the Canadian steel sector is one of the largest industrial sector emitters and contributes approximately 2 % of Canada's GHG emissions. This national contribution is compared to the global contribution of the sector which is currently responsible for about 8% of global final energy demand and 7% of energy sector CO_2 emissions (including process emissions) (IEA, 2020). To further reduce the sector's contribution to Canadas's GHG emissions, the Canadian Steel Producers Association announced an aspirational goal to achieve net-zero emissions by 2050 (CSPA). The steel sector is a hard-to-abate, emissions intensive, trade exposed (EITE) sector. In order to achieve net zero emission by 2050, currently existing GHG reduction technologies, energy efficiency and process optimization will be needed, but not sufficient to meet this aspirational goal on their own. Step changes in emissions reductions are needed to meet the 2050 goal through novel GHG reducing technologies.

CSPA's approach to achieving the net zero by 2050 aspirational goal is based on achieving the following five conditions:

1) Creating unique partnerships and research collaborations. The CSPA and the Canadian Carbonization Research Association (CCRA) have developed an R&D action plan following a stepwise transition approach. This research and development is focused on near future R&D and implementation of technologies to reduce GHG emissions of ironmaking and steelmaking using existing production facilities and long term R&D that include: potential reduction of fixed-process emissions and the pursuit of net-zero carbon emission steelmaking technology.

2) Developing and adopting breakthrough clean technologies and innovative products. Section 4.2 of this report outlines the technology penetration in the Canadian steel sector.

3) Driving operational excellence through state-of-the-art manufacturing. As shown in Section 4.2, the adoption of process control technology to improve process reliability, production yields, and overall production efficiencies to reduce losses has resulted in lower amounts of energy used to produce each tonne of steel.

4) Leveling the playing field and supporting the carbon advantages of domestic use of Canadian steel. As shown in Section 5, Canada's steel sector GHG intensity is the lowest of the integrated plants and the second lowest of the EAF plants from the 10 largest steel producing nations studied (Hasanbeigi, A. and Springer, C. 2019) and marine shipping can add significantly to the net GHG intensity of imported steel. Both a domestic and global market with premium pricing for low carbon footprint steel needs to be developed.

5) Ensuring global leadership in sustainability, energy management and environmental best practices. As shown in Section 5.2, the Canadian steel sector benefits from lower electricity GHG intensity than their trading partners; however, as shown in Section 4.1, some plants have significantly greater Scope 2 GHG emissions based on their provincial grids.

The following sections describe some of the barriers to the implementation of these technologies, some solutions to leveling the playing field and provide a high-level roadmap considerations and options to demonstrate how the technologies and support from government and other stakeholders can help the Canadian steel sector to achieve this net-zero goal.

6.1 Evaluation of Barriers to Implementation of GHG Emissions Reducing Technologies, Strategies and Required Support

Currently, carbon pricing covers 21.5% of global emissions (World Bank, 2021), which is expected to grow in coming year. This will assist in levelling the playing field internationally. In the interim, however, the lack of carbon pricing in many jurisdictions continues to be a barrier to low carbon footprint steel. Furthermore, the Organisation for Economic Co-operation and Development (OECD) has recognized that there is significant excess capacity in the steel industry at a global scale in part due the generous grants given to steel producers in foreign countries (OECD,2015). The potential for a large influx of steel products into the Canadian market is a major concern, which prevents Canadian steel producers from competing on a level playing field with their global counterparts. Therefore, the G20 created a Global Forum on Steel Excess Capacity in 2016 and members have been engaging industry and key stakeholders in their exchanges that include decarbonization strategies. This is supported by the IEA Iron and Steel Technology Roadmap (IEA, 2020). The global nature of the steel sector must be considered when developing a Canadian low carbon strategy for steel.

Key themes to consider in the support to overcome barriers to the implementation are as follows.

Long Life Assets

Iron and Steel manufacturing assets are very long lived. The last integrated plant constructed in Canada is the Stelco Lake Erie Works facility, built in the 1980s. The other integrated and EAF plants were constructed decades earlier. With the exception of the DRI process in Quebec, also constructed in the 1980's, this lack of investment in new plants decreases the ability for technology penetration as part of capital planning. This is one of the key barriers.

An example is the absence of energy-recovery technology for blast furnace top gas for integrated steelmaking facilities in Canada. The integrated plants were built when the prevailing technology was to flare the blast furnace gas and recover the required amount of heat for its energy in blast furnace stoves, and steam generation hoods. Canadian blast furnaces are designed for the potential energy to be recovered is less than newer blast furnaces designed and operated with high top-gas pressure. One possible reason is that the technology was not available or practical when the facility was built and is now difficult or impossible to retrofit.

Another example is the unfired charge preheat zone length of a steel reheating furnace. To add an unfired charge preheating zone or to lengthen an existing one requires adding to the overall length of the furnace. That is often extremely difficult because the mills are laid out so that the furnace fits between the furnace charging equipment and discharging equipment. To accommodate a change in furnace length, the mill layout would need to be altered and equipment relocated, which would be costly and may not be possible given building footprint constraints.

A second consideration is that many of the Innovative Technologies identified in Section 4.2 preclude the use of their existing technology or require the plant to choose one new manufacturing process over another. If a facility has recently invested in a major upgrade of their process to improve environmental or operational parameters there is limited or no incentive for the facility to replace the existing equipment prior to the end of life.

Support for capital expenditure is required to accelerate the investment needed to replace existing capital equipment with newer lower emission equipment.

Lack of a Market Premium on Low Carbon Footprint Steel

A lack of premium pricing for low carbon footprint steel is creating a disadvantage for first movers as low carbon and traditionally-made steel will compete in the same market for some time. In a highly competitive sector, market signals to provide this product are not present (Material Economics, 2021). The International Energy Agency "estimates the additional cost of [low carbon footprint steel] production to be between 10% and 50% compared to today, a cost increase significantly exceeding production margins. Thus, it is critical to be able to charge premium pricing for low carbon footprint steel. "Today, the higher cost of low-CO_2 production, the so-called green premium, is the primary reason holding back the development and deployment of low-CO_2 steel technology. A few ways to create the right market conditions include providing certainty of demand; matching low carbon footprint steel supply & demand volumes, geographies and steel grade; having buyers prepared to pay a 15-40% green steel premium; and, precise and defined, direct offtake agreements which "are likely to be the most impactful way to catalyse the necessary investment in breakthrough technologies (Material Economics, 2021)." Future purchase commitments and indirect demand signals such as from multiple companies to decarbonize their supply chains will likely be insufficient to unlock investment unless sufficient volumes of aggregated demand are committed.

In addition, initiatives such as the federal government's "Greening Government Strategy" and the Low Carbon Assets through Life Cycle Assessment (LCA) will assist in developing a domestic low carbon footprint steel market. In addition, steel companies' scope 1 & 2 emissions are the scope 3 emissions of its clients such as automotive, mining, construction as well as renewable electricity manufacturers wind turbines. These companies are becoming more interested in understanding, reporting and reducing their scope 3 emissions (specifically, for example, the embodied carbon in the steel they purchase), so steel companies who can provide this information and show meaningful reductions will have an advantage in the market.

International Competition from Higher Emissions Steel

Given the global overcapacity for steel production, domestic lower carbon footprint steel producers are at a disadvantage from jurisdictions with no carbon pricing. In order to level the playing field, it is recommended that the government, in addition to a carbon pricing program that acknowledges the international benchmarking in this Report, also consider trade measures such as carbon border adjustments to avoid potential carbon leakage.

Barriers to Material Substitution

Some of the material substitution technologies involve the use of materials that are currently considered waste and are being landfilled or the potential renewable fuels are not available or much more costly compared to natural gas. In certain jurisdictions, the environmental permitting process can be a barrier to the use of these materials. Lower cost renewable fuels would improve penetration.

Government should remove these barriers and develop the supply chains as much as practical to promote these technologies that can be implemented in the near term. Additional support for collection and sorting of end-of-life steel products can enable the circular economy and enhance the recycling content and supply of scrap steel available for making new steel.

Potential for Cooperation to address needed Research and Technological Agenda

The innovative technologies and controls necessary to further reduce emissions are not yet commercially available. Government and other stakeholders should work together to promote and further develop these

technologies and controls. The current R&D efforts of the CSPA must continue and allow for the implementation of these GHG reductions.

One example of this cooperation is the development of CCUS/CCS installations in the sector. As noted above, steel plants are longed lived, so development of new capacity in areas with local sequestration potential is not likely and therefore infrastructure must be created to allow for utilization or transportation of the captured carbon to sequestration areas.

Threat of Substitution effects from Other Products

New steel products can reduce overall GHG emissions from their use. This is driving innovation in the Canadian steel sector. A market that looks at the life cycle emissions of all building materials and does not focus solely on Scope 1 and Scope 2 emissions from production should be cultivated. Government must promote lower carbon domestic steel in order to create a market for these products and applications in the future. Otherwise, the global emissions of GHGs may increase if a lower cost steel with higher GHG intensity is produced or other commodities take its place.

The government procurement process should:

i) Account for the environmental impacts in the award of public contracts.

ii) Include shadow carbon price (> Carbon Price), functional carbon or technical requirements.

iii) Create lead markets for climate-friendly product design, material choice and usage patterns.

iv) Allow governments to respond to local initiatives and national and global emission reduction targets.

v) Consider providing financial support for incremental cost.

Low Carbon Electricity

Canada already enjoys a lower electricity GHG intensity in select provinces than our trading partners - this is the key reason that EAF steel produced in Canada has the lowest global GHG intensity. Low carbon grid power must be made available in all steelmaking provinces. Many of the innovative controls such as CCUS will increase the electricity demands.

In addition, significant increased supply and reduction in cost of electricity is required to allow on site hydrogen production for use as a reductant to replace the need for coal or for electrolytic iron reduction processes. One example is the use of Small Modular Reactors (SMR) to meet industrial energy requirements without the need for significant electricity infrastructure upgrades.

Efficient Carbon Pricing

Canada has a national carbon pricing program that is not currently present in some of its key trading partners. This places increased pricing pressure on Canadian plants in emissions intensive trade-exposed industries like steel. This carbon price can act as a signal to invest in energy and GHG reduction technologies. However, with little ability to pass these costs onto customers given the global oversupply of steel and lack of premium pricing for low carbon footprint steel, the carbon pricing can decrease investment in Canada. If production moves to other global locations, then global GHG emissions will increase as Canadian made steel has a lower GHG intensity than these other jurisdictions and the IEA forecasts that steel demand will continue to increase as part of the global low carbon transition.

The ongoing design of provincial and federal carbon systems must consider this and return any revenues to the sector to promote technology investment, and research and development. Furthermore, these programs should ensure that maximum compliance mechanisms, such as offsets, are encouraged to generate voluntary emissions reductions from activities that go beyond common practice and promote innovation. One design example is that there is not currently a clear approach to incent facilities to capture CO2 and utilize it for another application, as there is uncertainty if the CO2 will continue to be counted towards the facility's GHG emissions profile. This should be resolved to further promote CCS/CCUS technologies and hubs.

Scale of the Technological Challenge

As shown in the benchmarking, Canada's steel sector has invested in energy efficiency technologies and have some of the lowest GHG intensities in the world. However, as each energy efficiency improvement is implemented, the next cumulative improvement can be more difficult to implement since each subsequent technology typically has a greater capital cost and longer payback time. The historic energy improvements were driven by fuel and electricity costs and the co-benefit of GHG reduction was secondary or not considered in a facilities approval process. Facilities reported that they have implemented the majority of low cost/high return projects and there are limited "low hanging fruit' options remaining.

However continual energy efficiency must be part of overall continuous improvement and operational excellence in each steel facility's decarbonization transition. As shown in World Steel's 3 step process (World Steel, 2022), the first step is to "StepUp" by improving the efficiency of all plants in line with the industry's top performing plants. The IEA says that energy efficiency is the most important plank in efforts to decarbonise the global energy system and achieve the world's climate objectives and is also critical within steel plants. However, as shown in the benchmarking and technology penetration sections, Canada's steel sector is already amongst the lowest GHG emitters globally with many energy efficient opportunities already implemented. Therefore, energy efficiency will not be sufficient to achieve the 2050 decarbonization goals and step changes using Innovative Controls/ Technologies not yet commercialized is needed, but energy efficiency will continue to play an important role.

The IEA concludes that energy improvements and material efficiency cannot achieve the global targets alone. The IEA estimates that to achieve the global decarbonization goals, the steel sector must build DRI plants to replace existing Blast Furnace / BOF capacity, install CCUS on existing Blast Furnaces, implement a hydrogen economy and develop and implement other steelmaking processes such as electrolytic processing that are in the pilot phase. Government and other partnerships are needed for long term transformation here in Canada.

6.2 Carbon Reduction Considerations and Options

In order to pursue the Canadian Steel Sector's net zero by 2050 aspiration, there are multiple pathways that individual facilities can implement, however there are some common themes that each pathway must incorporate. The first three rows of Table 10 provides signposts for these pathways grouped by implementation timing for each option or technology category. The implementation of new technology and the adaptation of business practices to reduce GHG emissions must also consider the economic sustainability of the industry and the individual businesses and individual businesses can pursue economic and environmentally sustainable opportunities that support the broader industry goal. There are no "one size fits all" solutions for the sector.

The last three rows of Table 10 provide signposts for the supporting actions that must be in place to overcome the barriers listed in section 6.1 above. These are grouped into the themes of low carbon electricity, research and policy grouped by implementation timing for each supporting action category. With out this support then the ability of facilities to achieve the reductions will be prevented or compromised.

Table 10: Carbon Reduction Considerations and Options

	Past	Current – 2030	2030 – 2050	Beyond 2050
Energy Efficiency Options	Primary focus has resulted in low GHG intensity for the Canadian sector	Continued implementation on long life assets (e.g. maximize waste heat recovery, increase amount of recycled scrap, efficient combustion)	Continue to implement new, energy efficiency technologies (e.g. slag heat recovery, low carbon smelting reduction)	Refocus to improve efficiency of innovative technologies that have replaced existing technologies
Material or Fuel Substitution/Process Options	Replacement of heavy fuel oil	Full use of process off-gasses for onsite cogeneration (minimize flaring) Widespread use of low carbon fuels and improve raw material optimization Increased use of EAFs & DRI Electrification of fossil fuel heating	Continued Electrification of heating or the widespread use of hydrogen in existing process that still have remaining capital life	New technology advancement
Innovative Controls/Technologies	Strategic adoption based on availability and local market demands	Increasing adoption but significant barriers exist	High adoption as new steel making technologies replace existing processes such as low carbon ironmaking (e.g. electrolytic, hydrogen based, CCUS)	New technology advancement and ongoing capital replacement
Supporting Action - Low Carbon Electricity	Reduction in electricity GHG intensity in select provinces	Low carbon grid power in all steel making provinces. Reductions in cost of energy storage.	Increased supply and reduction in cost of renewable electricity and energy storage to allow for innovative Technologies such as Hydrogen	Ongoing investment in future green technologies
Supporting Action - Research	Near future R&D and implementation: Implementation of technologies to reduce GHG emissions of ironmaking and steelmaking using existing production facilities		Long term R&D: Breakthrough technologies to significantly reduce CO2 footprint. Pursuit of net-zero carbon emission steelmaking technology	
Supporting Action - Policy	Carbon pricing, Clean Fuel Standard	Removal of barriers to low carbon fuel Mitigating competitive EITE disadvantages Creation of market with premium pricing for low	Removal of all barriers to low carbon energy Some examples include SMR	Ongoing investment in future green technologies and multi sector integration

	Past	Current – 2030	2030 – 2050	Beyond 2050
		carbon footprint steel and border adjustments Archive research priorities Funding necessary to promote Innovative Technology investment such as CCS/SSUS	Widespread availability of hydrogen as a reductant Demonstrated CCS/CCUS installations in the sector	

7.0 CONCLUSIONS

This Report updates the 2007 CIPEC "Benchmarking Energy Intensity in the Canadian Steel Industry" to allow comparison between the individual Canadian plants and against international benchmark levels. In addition, this report looks at technology penetration that will allow further energy improvements and GHG reductions and provides a high-level carbon reduction road map to reduce GHG emissions. This roadmap outlines many options available to the industry but is not absolute as businesses must also consider site specific technology constraints and economic and market sustainability while pursuing this GHG emission reduction agenda. The key findings of the report are as follows.

7.1 Energy and GHG Intensity Benchmarking

Energy and GHG Benchmarking was conducted for the sector. Based on the confidentiality process outlined in Section 3, the following process level Benchmarks were produced:

- Cokemaking
- Blast Furnace Ironmaking
- Basic Oxygen Furnace Steelmaking
- Electric Arc Furnace Steelmaking
- Hot Rolling
- Bar Mill
- Plant Level – EAF plants
- Plant Level – integrated plants

A comparison of the GHG intensity between various Plants can be misleading due to the variability between processes in each of the plants. For this reason, charts comparing the energy and GHG intensities for the processes in Plants have not been included in this study.

The benchmarks were generally consistent for each process area, showing that the energy and GHG intensities are similar across the sector. There are plant to plant variations due to variations in process efficiency and production as expected. The plant-wide roll-up showed less variability than the individual process areas. The exception to this is the GHG intensity for Scope 2 emissions related to electricity and the use of the by product off -gasses in the integrated plants. The GHG intensity of the purchased electricity varies by province, and this is evident in the benchmarking. Integrated plants that make better use of process off-gases have improved energy efficiency and reduced GHG emission intensity by reducing the amount of other fuels needed in the process.

7.2 Technology Penetration

The Technology Penetration Study looked at 125 technologies that can increase energy efficiency and reduce GHG's. These technologies were grouped into three categories that is consistent with the IEA and World Steel association decarbonisation strategies as follows:

- energy efficiency
- material substitution/process options
- innovation controls/technologies.

In general, all plants have considered or have implemented the process specific energy efficiency options, showing the maturity of the Canadian steel sector. There is increasingly less technology penetration for the material substitution/process options and innovative controls/technologies categories because of barriers to implementing lower carbon materials and some of the innovative technologies are not yet commercially available or are still in early implementation. A significant gap is caused by the fact that some of the technologies are mutually exclusive or would replace the current technologies operating at the facility.

Given the high technology penetration but lower emissions reduction potential for energy efficiency technology, and the medium technology penetration level and a medium emissions reduction potential for material substitution/process options, they alone will be insufficient to reach net zero goals. There is a low technology penetration level but a high emissions reduction potential for the innovation controls/technologies. A much higher penetration of innovative controls/technologies is needed before large, step changes in emissions reductions will occur. This will require large investments to commercialize these innovative technologies and controls like carbon capture with utilization or storage.

7.3 International Steel Production GHG Benchmarking and Assessment of Advantages of Canadian Produced Steel

Consistent with the scan showing high energy efficiency technology penetration, there is close agreement between the GHG emissions intensity values for Canadian EAF and integrated steelmaking calculated in this Report and the equivalent values calculated in the International Benchmarking Report “How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO2 Intensities”. These findings indicate that Canada has the second lowest GHG emissions intensity in EAF steel and the lowest GHG emissions intensity in integrated steel in the year 2016 among the ten largest steel producing nations.

In addition to the results from the International Benchmarking Report, Canada’s domestic companies have advantages regarding lower Scope 3 GHG emission from transportation and the availability of grid electricity from renewable low GHG sources. Two areas were analysed:

- The shift towards clean electricity in many of the provincial electrical grids where the plants operate. This plays an important role in lowering Scope 2 GHG emissions of Canadian facilities in relation to their international competitors who are located in areas that often rely primarily on coal fired electricity generation. This is particularly important for EAF plants as electricity is the largest energy input.
- The Scope 3 marine transport GHG emissions associated with moving steel from Canada’s trading partners to Canadian Ports. Calculations show that this is equivalent to 11-21% of Scope 1 and 2 emissions from EAF steel production calculated in the benchmarking assessment above. The range is dependent on the distance from the trading partner to the port with greater distances resulting in a higher percentage.

These Scope 3 emissions in addition to the lower scope 2 GHG intensity must be considered to help the sector maintain its competitive advantage and support conversations with the government addressing border adjustment discussions.

7.4 Barriers to Implementing the Low Carbon Options

To continue to be global leaders, the Canadian sector has an aspirational ambition to produce net zero emissions steel. The scale of the market and technological challenge is significant and will require support from government, stakeholders to meet this challenge. At the same time as meeting this net zero ambition, the low carbon economy will require increased steel production. One objective for the sector is to decouple production growth from carbon emissions. Low or zero carbon electricity, a hydrogen economy coupled with new breakthrough technologies for low carbon iron ore reduction, carbon capture with utilization or storage, non-fossil fuel iron production or electrolysis are amongst the innovative technologies that will be required. The key barriers that will need to be overcome include:

- **Long Life Assets:** The process at the plants have very long operating lifetimes. Support for capital investment is required to accelerate the investment needed to replace existing capital equipment with newer lower emission equipment and control technologies.
- **Lack of a Market Premium on Low Carbon Footprint Stee**l: There is no market premium on low carbon footprint steel. This further erodes the support for capital investment in new technologies that could add a 15 to 40% premium versus current steel production costs. Standards for the measurement and reporting of embodied carbon or a life cycle assessment should be included in GHG reporting programs and corporate disclosure. In addition, support for low carbon footprint steel is necessary to provide an incentive for capital improvements.
- **Threat of Substitution effects from Other Products**: The threat of substitution from other building products that could be used in the construction and manufacturing in place of steel. Steel has higher Scope 1 and 2 emissions compared to other building materials; however, steel is 100% recyclable and can reduce the GHG emission associated with its use. As noted in the above bullet point if a full life cycle assessment is not conduced, then there will be no incentive to invest in low carbon footprint steel and global GHG emissions may increase. Government procurement processes should require this assessment and support the market for low carbon footprint steel.
- **Lack of Clarity in Carbon Pricing Revenue Recycling Design**: Canada has a national carbon pricing program that is not present in some of the key trading partners and the efficiency of this program must be increased. The carbon pricing program places an increased pricing pressure on Canadian plants. This carbon price can act as a signal to invest in energy and GHG reduction technologies but can also decrease investment in Canada. If production moves to other global locations, then global GHG emissions will increase as Canadian made steel has a lower GHG intensity than these other jurisdictions and the IEA forecasts that steel demand will continue to increase as part of the global low carbon transition. The ongoing design of the federal and provincial carbon pricing systems must consider the international benchmarking in this report and return any revenues to the sector to promote technology investment and research and development.
- **International Competition from Higher Emissions Steel**: The global oversupply of steel making capacity creates an international competition from sources of higher emission steel that create uneven competition with jurisdictions with no carbon pricing. In addition to a carbon pricing program that acknowledges the international benchmarking in this Report, it must also consider additional policy instruments such as carbon border adjustments. The steel sector is an Emission Intense Trade Exposed sector with a high potential for carbon leakage.

- **Barriers to Material Substitution:** Some of the material substitution technologies involve the use of materials that are currently considered waste and are being landfilled or the potential renewable fuels are not available or much more costly compared to natural gas. The environmental permitting process should be updated to remove the barrier to the use of these materials and increase the availability of lower cost renewable fuels would improve penetration. In addition, support for collection and sorting of end-of-life steel products can enable the circular economy and boost EAF plant steel production.
- **Need for Increased Support for International R&D collaboration** The innovative technologies and controls necessary to further reduce emissions are not yet commercially available and increased cooperation between stakeholders is needed to address CSPA's research and technological agenda. Support is needed to create hubs that will allow for utilization or storage of carbon captured from the process.
- **Access to Low Carbon Electricity**. Canada already enjoys a lower electricity GHG intensity in select provinces than our trading partners. This is the key reason that EAF steel produced in Canada has the lowest global GHG intensity. Many of the innovative controls such as CCUS and the need for hydrogen as a reductant or electrolytic iron production will increase electricity demand. Abundant low-carbon and low-cost grid power must be made available in all steel making provinces.
- **Scale of the Technological Challenge**: Implementing existing energy efficiency and process optimization technologies as well as material substitution will be necessary but insufficient to achieve the sector's net zero carbon goals. Necessary step changes in GHG emissions reductions will occur through not yet commercially available breakthrough technologies.
- **Maintaining Economic Viability**: The implementation of new technology and the adaptation of business practices to reduce GHG emissions must also consider the economic sustainability of the industry and the individual businesses. Alternative pathways to achieving net zero emissions exist and flexibility must be afforded to ensure individual businesses can pursue economic and environmentally sustainable opportunities that support the broader industry goal.

For the reasons above, the individual steel companies cannot overcome these challenges by themselves. Government and other partnerships are needed for the long-term transformation in Canada that will allow the production of not just low carbon but net zero carbon footprint steel.

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APPENDIX A

Steel Production Process Descriptions

APPENDIX B

Energy Conversion Factors and GHG Emission Factors Used in this Assessment

APPENDIX C

Potential Energy and GHG Reduction Technology Descriptions

The following are detailed descriptions of process units identified in Sections 2.1 and 2.2 of the Report. A list of references is included following the text.

COKE MAKING

Coke is a carbon product formed by thermal distillation of metallurgical coal at high temperatures in the absence of air. Coke is produced in batteries of coke ovens. Coke is used to provide a reducing atmosphere in a BF and is also a source of fuel. One of the key characteristic of coke is its porosity which enables the gas exchange throughout the BF from the bottom to the top. Approximately one-third of the cleaned coke oven gas (COG) is used to fuel the coke ovens. The remainder is either flared or used in other steel plant combustion units. The primary CO2 emissions point at coke batteries is from the combustion of the COG and discharge through a combustion stack from the ovens. Utilizing the COG can reduce the need for natural gas in the coke ovens or other combustion units. (U.S. EPA 2010).

IRONMAKING

The subsections below describe three ironmaking processes, the conventional process used currently in a Blast Furnace (BF), direct reduction that is installed at one facility in Canada , and smelting reduction processes that is a innovative technology.

BLAST FURNACE

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal . Hot metal is a solution of molten iron at approximately 1,480ºC, which contains 4 percent carbon and some Silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically “tapped” from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF-BOF steelmaking process, generating large quantities of CO2 (AISI 2010).

DIRECT REDUCTION

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state and an alternative to the BF. This technology encompasses a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. Natural gas is used as a reducing agent to enable this process. The metallization rate of the end product, called Direct Reduced Iron (DRI) or 'sponge iron', ranges from 85 percent to 95 percent (often even higher). The one DRI plant in Canada uses the MIDREX technology. The MIDREX process typically consists of four stages: 1) reduction, 2) reforming, 3) heat recovery, and 4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO. The iron is then formed into briquettes, and heat from the process is recovered. The amount of CO2 produced can be reduced by increasing the amount of hydrogen used as a reductant. (IEA 2010).

SMELTING REDUCTION

Smelting reduction iron (SRI) is an innovative technology and an alternative to the BF, as it also produces liquid iron. Smelting reduction was developed to overcome the need for coke. Instead smelting reduction is aimed to use coal and iron fines. Several processes are under development; some have been commercially proven (COREX, FINEX, ITmk3), others are under demonstration (e.g. Hismelt). Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage - similar to DRI - is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidized to generate additional heat to smelt the iron. Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting. CO2 is still produced by the process but is reduced compared to the BF process. (IEA 2010).

STEELMAKING

The subsections below describe the steelmaking process with BOF or EAF.

1.1 Basic Oxygen Furnace (BOF)

The BOF converts liquid hot metal from the BF into steel. The main operation is the addition of oxygen to remove carbon from the hot metal. The liquid steel is sent to a Ladle Metallurgy Station (LMS) to create the steel alloys required. A BOF is endothermic producing energy and scrap steel can also be loaded into the BOF. A modification of the BOF process known as the Klockner Oxygen Blown Maxhutte (KOBM) is used at one of the plants in Ontario. CO2 is produced from the flaring of excess by product gas.

1.2 Electric Arc Furnace (EAF)

EAFs are mainly used to produce steel by recycling scrap steel. DRI and pig iron can also be fed to the EAF as a scrap substitute and in the case were an EAF is co-located at an integrated plant molten iron. EAFs are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in EAF-steelmaking is much lower, as the energy-intense reduction of iron ore has already been carried out in the iron making stage above. The liquid steel from an EAF is generally sent to a LMS to improve the recycled steel quality. A small amount of CO2 is produced from the carbon electrode and impurities in the scrap steel but the primary energy source for the process is electricity. (APP 2010).

CASTING, ROLLING, AND FINISHING

The molten steel produced by both BOFs and EAFs follows similar routes after leaving the furnace: it is transferred from the LMS to the continuous caster, which forms the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, and other special sections). Steel from the continuous caster is mainly processed in rolling mills to produce the final shapes that are sold by the steel mill. These shapes include coiled strips, rails, sheets, many structural shapes, rods and bars. The products from the hot rolling mill may be further processed in various ways, such as annealing, hot forming, cold rolling, heat treating (tempering), pickling, galvanizing, coating, or painting. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature. Rolling mills consume electricity to power the large motors necessary to roll the steel and natural gas or process gas is consumed in furnaces to anneal and reheat the steel before rolling. (U.S. EPA 2010).

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Table B1: Energy Conversion Factors

Energy Type	Conversion Factor	Unit	Reference
Electricity	3.6	GJ/MWh	constant
Oxygen	4.9	GJ/km^{3}N	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Nitrogen	1.96	GJ/km^{3}N	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Coal	32.2	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4 (coking coal)
Coke	30.1	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Petroleum coke	35	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Coke Oven Gas	19	GJ/kNm3	World Steel CO2 Data User's Guide V.10
Blast Furnace Gas	3.3	GJ/kNm3	World Steel CO2 Data User's Guide V.10
LP Steam	3100	MJ/t	CIPEC 2007 Energy Benchmarking Report
MP Steam	3200	MJ/t	CIPEC 2007 Energy Benchmarking Report
HP Steam	3300	MJ/t	CIPEC 2007 Energy Benchmarking Report
Industrial Water	100	Wh/m3	CIPEC 2007 Energy Benchmarking Report
Compressed Air	120	Wh/m3	CIPEC 2007 Energy Benchmarking Report
Heavy Oil	35.8	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Tar	37.00	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4
Benzol	40.57	GJ/t	World Steel Energy Use in the Steel Industry - Definitions Guide 2015 Table 1.4

Table B2: GHG Emission Factors

Energy Type	GHG Emission Factor	Unit	Reference
Natural Gas	0.056	tCO_2/GJ	World Steel CO2 Data User's Guide V.10
Electricity (Ontario)	30	gCO_2e/kWh	NIR 2021 Table A13-7
Electricity (QC)	1.3	gCO_2e/kWh	NIR 2021 Table A13-6
Electricity (Man)	1.3	gCO_2e/kWh	NIR 2021 Table A13-8
Electricity (Sask)	680	gCO_2e/kWh	NIR 2021 Table A13-9
Electricity (Alberta)	630	gCO_2e/kWh	NIR 2021 Table A13-10
Coke Oven Gas	0.044	t CO_2e/GJ	World Steel Data Collection User Guide, version 10
Blast Furnace Gas	Site specific value provided or developed (see s.3.3 of report)		
LP Steam	224.2	kg CO_2e/t	CIPEC 2007 Energy Benchmarking Report
MP Steam	240	kg CO_2e/t	CIPEC 2007 Energy Benchmarking Report
HP Steam	267	kg CO_2e/t	CIPEC 2007 Energy Benchmarking Report
BOF gas	0.185	t CO2e/GJ	CIPEC 2007 Energy Benchmarking Report

The following are detailed descriptions for each technology identified in Section 3.3 of the Report. A list of references is included following the text.

COKEMAKING

Energy Efficiency Options

1 Coal Stamp Charging Battery

Before the coal is placed into the oven, it is stamped into stable briquettes that are very similar in size to the coke oven chamber [3]. This increases the bulk density of the coke by 30-35% and results in a 10-12% increase in the productivity of the ovens. Coal of lower quality can be utilized as an input.

2 Coke Dry Quenching (CDQ)

A practice whereby the coke is cooled using an inert gas rather than spraying it with water [3]. This process reduces CO2 emissions as well as allowing for the recovery of thermal energy in the quenching gas. This thermal energy is often used for the production of steam and electricity, for preheating of the coke ovens or for district heating. CDQ also reduces the coke consumption in the blast furnace by increasing coke quality.

3 Coke Stabilization Quenching (CSQ)

A wet quenching technique used in Germany whereby the hot coke comes into contact with water from both the top and bottom [3]. The high quenching rate and low reaction time results in a higher quality coke, and potential in energy savings.

4 Coke Oven Gas (COG) Recovery

Around 25-30% of the mass of coal that is charged into coke ovens is driven off as gas that is then dried and separated into tar, light oil, Sulphur fractions and COG [3]. COG has a low heating value of around 18 MJ/Nm3 and is often used to heat coke batteries, heat other furnaces or for power generation.

5 Non-Recovery Coke Ovens

Unlike recovery coke ovens, coal tar and volatile by-products are combusted inside the oven to provide the heat required for the coke making process [3]. Heat can be recovered from hot exhaust gasses that can then be used to produce electricity and steam. As the majority of the by-products are combusted in the oven, there isn't a need for flue gas and wastewater treatment facilities. However, this process results in a smaller output of coke than traditional ovens. Due to the relatively high investment costs, it is only economical where the price for electricity is high, and/or there is demand for high quality steam.

Material Substitution/Process Options

6 Use of biomass in cokemaking blend

The creation of 'bio-coke' can be achieved by including biomass in the cokemaking feedstock blend [74]. The effects of incorporating charcoal in coal blends for cokemaking are as follows: 1) A significant decrease in oven wall pressure during coking 2) Coarse charcoal will result in an increase in the amount of small sized coke 3) Fine charcoal can be used to produce coke with the same cold strength as traditional coke

Innovative Controls/Technologies

7 Single Chamber System

A single chamber system are large dimension ovens that use preheated coal fed from above and have much thinner oven walls allowing for improved heating and combustion [3,45]. This leads to improvements in the thermal efficiency of the system and a reduction in GHG emissions due to less pushes being required. The Single chamber system can also use a wider range of coal blends in its charge [45].

8 Novel uses for Coke Oven Gas (i.e. hydrogen production)

Recent research has been centered around producing pure hydrogen from COG through sorption-enhanced steam reforming [4].

BLAST FURNACE (BF)

Energy Efficiency Options

9 Heat Recuperation from Hot Stoves

Around 33% of the energy required to make iron is attributed to the hot blast stoves and accounts for 10-20% of the total energy demand in an integrated steel mill [3]. Flue gases that are hot, can be used to preheat the combustion fuel and / or the air entering the stoves. This increase in sensible heat will also improve the combustion efficiency, resulting in considerable fuel savings [32].

10 Improved Combustion in Stoves

Efficient burners as well as monitoring and automatically adjusting the fuel/oxygen ratio in real time inside the stoves can be used to improve the combustion condition [3].

11 Improved Recovery of Blast Furnace Gas

The blast furnace gas produced accounts for 30% of the gross energy consumption in the BF [3]. This energy can be captured by recovering, cleaning and storing the BF gas for reuse, one example being in electrical generation [45]. Often BF gas is enriched with COG or natural gas prior to use due to its relatively low energy content.

12 Dry Dedusting of Blast Furnace Gas

Electrostatic precipitator or a bag filter are used to clean the blast furnace gas [3]. Dry dedusting eliminates generation of polluted water/slurry and improves gas cleanliness. Dry dedusting required 50% smaller footprint than wet dedusting. More power can be created from dry dedusted BF gas if using a Top (gas) Recovery Turbine TRT compared with wet dedusted BF gas.

13 Bell Less Top (BLT) Charging System

Input materials (coke/sinter) are screened before charging to ensure proper distribution [3], which improves the cokerate, This technology provides leverage to pinpoint where to place the raw materials into the furnace; thereby, improving shaft permeability and gas efficiency that will decrease the coke rate and increase productivity [58].

14 Top-Pressure Recovery Turbines (TRT)

On some modern BF the gasses leaving the furnace at the top can be pressurized at approximately 3 bar and 200 degrees Celsius due to the high-pressure blasts taking place in the blast furnace [3]. This pressurized gas can be used to generate electricity in an expansion turbine through the addition of a TRT [58]. In order for proper turbine operation, the dust particles must be removed and therefore TRT are categorized as wet or dry systems.

Material Substitution/Process Options

15 Injection of Oxy-Oil

Special oxy-oil burners are installed at all tuyeres and allows for double the injection rate of oil [3]. Oil and oxygen are separately fed, with the oil preheated to 220 degrees Celsius. Significant energy and emissions reductions are expected due to the large decrease in coke consumption [64].

16 Pulverized Coal Injection (PCI)

A process involving blowing large volumes of fine coal granules into the blast furnace [3]. This reduces the need for coke as the PCI provides the carbon content and therefore reduces energy, emissions and maintenance costs associated with cokemaking [61]. However, as coke provides gas permeability and physical support, it cannot be eliminated completely. It should be noted that, for furnaces that are already injecting natural gas, natural gas injection can be preferable from the point of view of energy efficiency and green house gas emission.

17 Injection of Coke Oven Gas (COG)

COG can be used as a reactant in the BF to reduce the consumption of coke or other reactants [3]. This cuts down the CO2 and SO2 emissions. However, analysis has shown that the use of PCI is more energy efficient.

18 Injection of Natural Gas

Similar to PCI, the use of natural gas in the BF allows for a reduction in coke usage while also providing benefits as hydrogen is used as a reducing agent rather than carbon monoxide [3].

19 Injection of Hydrogen

Like other reducing agent substitutions, the injection of hydrogen aims to reduce the coke usage but also has numerous other benefits. These benefits include the elimination of the CO2 formation, reduction in heat demand, and improved productivity [3,45]. Hydrogen improves the reaction kinetics when injected into a BF while the reduction by hydrogen is less endothermic than reducing with carbon [75]. This leads to a better thermal balance within the blast furnace and, thanks to its small density, results in a decrease in pressure losses in the furnace stack.

20 Injection of Plastic Waste

Plastic waste can also be injected into the BF to reduce the usage of coke with similar benefits seen when natural gas is injected [3]. Only certain compositions of plastics can be used to reduce the need for additional flue gas treatment (i.e., low levels of Cl and PVC) [32]. Depending on the blast furnace configuration, plastic injection may increase or decrease its carbon footprint.

21 Use of high quality ore

The use of high-quality ore as a feedstock source material reduces the need for reducing agents and therefore decreases energy consumption, CO2 emissions while also increasing productivity [3]. However, the availability of high-quality ore is limited and therefore if widespread adoption occurred, the price of high-quality ore would be driven up [64].

22 Renewable charcoal use

Charcoal can be used as a substitute for coke, however its low mechanically stability means it cannot fully replace coke [3]. If the charcoal is sourced sustainability, it can significantly reduce the CO2 emissions of the BF. There are also significant decreases in capital and operating costs due to the decrease in amount of coke required [32].

Innovative Controls/Technologies

23 Injection of biogas and bio residues

Residues such as used oils, fats and emulsions of used oil and water generated throughout the steelmaking process can be injected into the blast furnace at the tuyeres level as a partial substitute for coke/coal [3]. The resulting reduction in the coke consumption rate results in a decrease in energy usage and CO2 emissions [64].

24 Charging Carbon Composite Agglomerates (CCB)

CCB are a mixture of iron ore fines and fine carbonaceous materials (ex. fine coke, charcoal etc.) with some binding agents often added [3]. The reaction speeds of the reduction of the iron and carbon gasification are both increased and occur at lower temperatures [32].

25 Top Gas Recycling Blast Furnace (TGRBF)

In TGRBF, pure oxygen is used instead of air to eliminate the N2 content in the off-gas and reduce the amount of CO2 in the off-gas that is captured and stored [3, 31]. The remaining gasses, mostly CO and H2 are then used as reactants in the BF. There are numerous types of TGRBF with the removal of CO2, with/without preheating and position of injection being the primary differences.

26 Slag Heat Recovery

In modern blast furnaces, there is around 0.25-0.3 tons of liquid slag produced at a temperature of 1450 degrees Celsius for every ton of pig iron [3]. There has been a lot of recent research in slag heat recovery systems, but no commercially developed systems yet.

DIRECT REDUCED IRON (DRI)

Energy Efficiency Options

27 Midrex Process

The Midrex process is a gas-based shaft furnace that has three main operations: iron ore reduction, gas preheating and natural gas reforming [15]. The exhaust gas that leaves the top of the shaft furnace is cleaned and cooled by a wet scrubber and recirculated for reuse. The top gas that contains CO2 and H2O is pressurized by a compressor, mixed with natural gas, preheated and fed into a reformer furnace to be reused as a reducing agent. The sensible heat of the flue gas that leaves the reformer is used to preheat the feed gas mixture and the burner combustion air. This allows the Midrex process to operate in a simple closed loop which minimizes energy consumption and reduces the number of moving parts within the plant.

28 Midrex with CO2 Removal System

An additional amine-type system is added to the Midrex process to remove CO2 from the top gas [3]. This system lower CO2 emissions, lowers natural gas use and increases production of DRI as additional reformer bays are not required.

29 HYL III Process

The HYL III is a gas-based DRI process like Midrex; however, HYL III uses its reducing gases within a moving bed shaft furnace reactor [3]. In comparison to other DRI process, it runs at a slightly higher temperature and pressure. The process consists of two main sections, first a reducing gas generation and then the reduction sections. Typically, the first section is a conventional natural gas steam reformer while the reduction section includes the moving bed shaft furnace, a gas heater and a scrubbing unit for dedusting/cooling and recycling of top gas. The HYL III process allows for the use of lump ore or pellets as its feedstock and produces DRI (i.e. not hot DRI) [64].

30 Coal-Based HYL Process

This process is similar to the HYL process (i.e., gas based DRI process in a moving bed shaft furnace reactor), however, in this case, a coal gasifier instead of natural gas steam reformer is used to produce the reducing gas from practically any carbon bearing material [3]. Like the gas-based HYL III process, the top gas is cooled, cleaned, the CO2 is removed and then the remaining gas is recycled into a reducing gas circuit [32].

31 Circored

The Circored process involves a two-stage fluidized bed that operates at lower temperatures and uses natural gas that is reformed to produce the reducing gas [3]. This process also uses iron ore fines as the feed and produces hot briquetted iron (HBI). The heat requirement of the DRI processes is provided by burning natural gas while the off gas is recirculated into the fluidized beds. A reduction in energy use and emissions are expected due to the process not requiring sintering.

32 Finmet

The Finmet process utilizes 4 fluidized bed reactors with a H2 rich gas produced by steam reforming as the reducing agent [3]. The Finmet process uses iron ore fines as the feed and produces hot briquetted iron (HBI) [20]. Primetals (the creators of the Finmet system) assert that if renewable H2 is used with the Finmet system, it can have a zero CO2 footprint [21].

33 Redsmelt

The Redsmelt processes involves reducing green pellets consisting of iron ore, reductant fines and binders in a rotary hearth furnace to produce hot metalized DRI [3]. This hot metalized DRI is then fed into a submerged arc furnace to produce hot metal and slag. This process operates at high temperatures and atmospheric pressure with the final hot metal product often sent to EAFs. Benefits of this process include the use of ore fines as a feedstock, the wide variety of solid reductants that can be used and the relatively quick reduction time (12-18 minutes) [36].

34 SL/RN Process

Stelco-Lurgi/Republic Steel-National Lead (SL/RN) process is a widely used DRI process that uses a rotary kiln and coal as the reducing agent [3]. The process operates at high temperature/pressure and uses lump ore, pellets or ilminate ore as input materials. The main benefit of this process is the ability to use low quality coal; however, there is a significant amount of residual gas produced that needs to be captured and used in other processes/power generation in order to be energy efficient. This can be done through the use of heat recovery systems for the production of electricity or for the utilization of the thermal energy itself [72].

35 FASTMET and FASTMELT

A rotary hearth furnace (RHF) based DRI process that uses pulverized non-coking coal as the reductant while using iron ore pellets, iron ore fines and metallurgical waste from the steel plant as the feed source [16]. The FASTMELT version includes an Electric Iron Melting Furnace (EIMF) to produce liquid iron or hot metal. Of the current commercial plants using this technology, many use metallurgical waste as the primary feed source.

36 ITmk3® Process

The ITmk3 is a mark 3 iron making technology (mark 1 = BF-BOF and mark 2 = gas based DRI) that is much faster than other technologies (10 minutes vs 8 hours for BF vs 6 hours for gas based DRI) [17]. The four-step process includes (1) agglomeration of iron-ore and coal, (2) reduction and melting of the agglomerates in a RHF, (iii) separation of metallic iron from the slag, and (iv) treatment of exhaust gases and recovering of the heat. Non-coking coal and iron ore fines are used (i.e., lower quality material/energy inputs), yet the process produces high quality granular iron (iron nuggets) at a lower temperature than a BF (1350 C). There are lower capital and operational costs than a traditional BF [32]. As no coke oven is required, significant energy and emission savings occur [32].

37 Dust Recycling in Rotary Hearth Furnace

Excess dust and sludge are agglomerated with iron oxide and carbon into pellets and fed back into a RHF DRI process to produce DRI pellets [3]. During the DRI process, the zinc present due to the inclusion of sludge is removed through reduction and gasification. The resulting DRI pellets are strong enough to be used in a BF. This process solves the issue of being able to reuse sludge which has a high iron/carbon content, but the inclusion of zinc has made it difficult to recycle [19].

Material Substitution/Process Options

38 Use of hydrogen gas as partial substitute for reducing agent

Hydrogen can be mixed into the reducing gas to provide numerous benefits including a reduction in CO2 emissions, increased reduction potential and an increase in the volume flow within the furnace [76].

39 Iron Carbide Process

Iron Carbine is a compound that consists of 93% iron and 7% carbon allowing for it to be the only feed for BOFs/EAFs thus eliminating the need for coke/coal [3]. However, the iron carbide can also be used in a two-stage fluidized bed process that uses methane/hydrogen as the primary reducing agents and operates at lower temperature/pressures than other DRI processes [3,73]. The product of the iron carbide process is Fe3C powder which contains 6% carbon content.

Innovative Controls/Technologies

40 MXCOL - Midrex with Coal Gasification

MXCOL (pronounced M-X-Coal) is a Midrex system that uses syngas derived from coal instead of natural gas as the reducing gas [18]. The syngas can also come from a variety of other sources including commercial gasifiers, export gas from coal-based COREX process, other parts of the steelmaking facility etc.

41 Sustainable Steelmaking using Biomass and Waste Oxides

This process utilizes a rotary hearth furnace (RHF) that uses waste ore pellets (composite pellets) whereby the coal is replaced with wood charcoal [3,22]. The output of the RHF is fed into a smelter to produce hot metal with the high energy off-gas from the smelter fed back into the RHF. This process drastically reduces emissions compared to a typical BF while also lowering capital and operational costs [22].

42 Paired Straight Hearth (PSH) Furnace

The PSH furnace is a new process for making metalized pellets while using non-metallurgical coal-based reduction [3]. Iron oxides such as iron ore or by-product oxides from other steelmaking processes are combined with coal and binders to produce “green balls”. As the green balls or pellets are heated on the hearth, CO gas is evolved and combusted above the pellets in order to drive the process [22]. The off gasses from the furnace are fully combusted and increase the temperature of the furnace to 1,600 degrees Celsius with reoxidation of the pellets prevented due to the CO-rich gas rising through the pellet bed.

43 ULCORED

ULCORED is one of the research areas within the ULCOS project (EU low CO2 steelmaking initiative) with a focus on improving direct reduction technologies based on natural gas using a shaft furnace [3, 23]. The main change is replacing the traditional reforming stage with the partial oxidation of natural gas in order to reduce capital expenses. Another key feature is the use of pure O2 rather than air which results in an off-gas that is nearly 100% CO2 [23]. This off-gas is recycled back into the DRI process after the CO2 is captured and the final product is solid DRI.

SMELTING REDUCTION (SR)

Energy Efficiency Options

44 Corex

The Corex processes uses lump iron ore or pellets, non-coking coal and oxygen as the main inputs to produce hot metal [3]. Like other smelting reduction processes, it is two staged: the first is a reduction shaft furnace where the ore feed is reduced to DRI via a reducing gas; the second is a melter-gasifier whereby the reduced iron is charged with coal, and oxygen blasts are performed to gasify the coal into carbon monoxide [33]. The carbon monoxide acts as a reducing gas in the melter-gasifier to increase the level of metallization and is an exothermic reaction producing the heat necessary to melt the DRI to hot metal.

45 Finex

The Finex process is a more complicated form of the Corex process that utilizes a fluidized bed to reduce iron ore fines to DRI instead of using lump ore as a feed [3].

46 HIsmelt

The HIsmelt process uses a vertical smelt reduction vessel (SRV) to produce liquid iron/hot metal [3]. At the bottom of the vessel, there is a molten bath of metal containing around 4% dissolved carbon [34]. Coal and preheated iron ore are injected at high velocities directly into the bath with the coal providing the 4% carbon content that needs to be replenished due to the iron oxide reduction reaction that takes place in the molten bath. Iron ore fines are injected deep in the bath and immediately undergo a reduction reaction with the dissolved carbon to produce iron and carbon monoxide. This rapid release of gasses from the molten bath produces a fountain of metal and slag into the top section of the furnace. Hot air blasts occur in the top section of the furnace combusting the reaction gas and producing the thermal energy needed to maintain a thermal balance [34]. This thermal energy is transferred to the bottom of the vessel due to the falling fountain of heated molten metal/slag [35]. As a result, the top of the furnace is viewed as the oxidizing region with the bottom of the furnace being the reducing region.

Innovative Controls/Technologies

47 DIOS (Direct Iron Smelting Reduction)

The DIOS process uses two fluidized bed reactions in series to preheat the iron ore fines and then pre reduce them to 15-25% metallization utilizing cleaned offgas from the smelter [3, 36]. The partially reduced iron is charged into the smelter reduction furnace along with non-coking coal and fluxes. Oxygen is injected into the smelter from the top whereby it reacts with the coal to form carbon monoxide which further reduces the iron oxides. The DIOS process produces liquid iron/hot metal.

48 Cyclone Converter Furnace (CCF)

In a CCF, ore fines and coal are injected into the top of the furnace, the melting cyclone, which is located on top of a vertical type converter [38]. Gravity brings the pre-reduced molten ore downward to the smelter where it enters the molten iron bath. Coal and oxygen are injected into the molten bath to further reduce the molten ore to its final product, liquid iron. The carbon monoxide rich gas produced in the smelter is combusted in the melting cyclone to provide the thermal energy for melting as well as being used as a reducing agent.

49 Romelt

The Romelt process is a bath smelting technology that does not utilize any pre reduction to produce liquid iron [36]. One of the main advantages is that any iron containing material can be used in the feed such as iron ore fines, BF dust, BOF dust etc. Non-coking coal, iron material and fluxes are charged into the furnace from above without any mixing and fall due to gravity into the slag bath to dissolve. A row of blast tuyeres on each side of the furnace injects oxygen rich air directly into the slag bath to gasify the coal but also to agitate the bath to instigate mixing. A set of tuyeres above the bath inject pure oxygen for post-combustion of the CO and H2 rich gas that evolves from the bath [39]. This provides most of the thermal energy needed for the reactions taking place in the slag bath. Two tap holes are used to periodically remove slag and hot metal into separate vessels.

50 Tecnored

The Tecnored process uses self-reducing pellets in a low-pressure moving bed reduction furnace to produce liquid pig iron [3,36]. The Tecnored process is flexible in the feed materials it can use, for example iron ore fines, iron bearing residues etc. can be used for the iron feed and pet coke, coal, charcoal etc. can be used for the carbon bearing material [40]. The iron and carbon bearing materials are mixed with fluxes and cement (binding agent), agglomerated and cured on a dryer. The pellets are fed into the top of the Tecnored furnace while additional solid fuel is fed into the bottom furnace. Hot air blasts (not pure oxygen) provide the oxygen necessary to combust the solid fuel that provides a lot of the energy necessary for the process. Side feeders extract a small amount of the furnace gas to preheat and dry the pellets. A cold air blast is injected near the top of the furnace to promote post combustion of CO in the upper section of the furnace.

51 HIsarna

The HIsarna processes is an initiative of ULCOS (ultra low carbon dioxide steelmaking) consortium of European steelmakers [3]. It is a combination of 2 processes with the upper portion of the vessel being developed by Tata Steel as Isarna and the lower portion of the vessel being developed by Rio Tinto as Hismelt [37]. Iron ore is injected into the top of the reactor where it is immediately liquified and pre reduced in a high temperature cyclone converter furnace (CCF). The high temperature necessary to melt the ore in the CCF is generated as pure oxygen is injected into the vessel and reacts with the reducing gas (derived from the smelter offgas). The liquid partially reduced ore drips downwards into the bottom of the vessel whereby it reacts in a bath with powered coal that is injected into the reactor to produce liquid metal. Like other SR processes, a significant amount of carbon monoxide is produced in the smelter and is used in the CCF. The remaining waste flue gas has very little calorific value and is therefore treated as exhaust out of a stack or mitigated with CSS techniques.

FUTURE IRONMAKING PROCESSES

Innovative Controls/Technologies

52 100% H2 based DRI (e.g. Hybrit, Midrex H2)

These processes aim to use 100% hydrogen to produce DRI with a focus on using renewably sourced hydrogen to try to create a net zero CO2 emission ironmaking process [77,78]. The absence of the exothermic carbon monoxide reduction means that additional thermal energy needs to be supplied to the furnace. It should be noted that some hydrocarbons need to be added to the steelmaking processes at some point because using pure H2 DRI results in a DRI with a 0% carbon content [77]. This is not desirable as most EAF operators want DRI with a 1-3% carbon content.

53 Electrolytic ironmaking

Electrolytic ironmaking involves the electrolytic decomposition of iron oxides. Iron forms at the cathode and oxygen is produced at the anode [79,80]. Similar processes have been done in the aluminum industry for decades [81]. When this process is coupled with carbon-free electricity, climate change impact is severely mitigated [79]. Significant capital cost reductions are likely as coke plants/BFs/BOFs are not necessary as the resulting iron is charged into an EAF [32]. Another benefit of these processes is the fact that the product is chemically pure iron [81]. The most promising forms of electrolytic ironmaking include low temperature electrowinning (ULCOWIN) and high temperature molten oxide electrolysis (ULCOLYSIS) [32].

54 Novel Flash Ironmaking Technology (FIT)

The novel flash ironmaking technology is based on the proven flash technology used in the copper industry [82]. This process is still in R&D and includes the direct gaseous reduction of fine iron oxide concentrates in a suspension reduction process [3]. Gaseous hydrogen or natural gas would be used as the reducing agents because the penetration rate of hydrogen into iron ore is 5 times higher than carbon monoxide leading to faster reducing times in traditional BFs [32]. The goal of the process is to drastically reduce or eliminate CO2 generation during the ironmaking step of steelmaking [3]. Significant reductions in the emissions and energy requirements are observed if pure hydrogen is used as the reducing agent [82]. However large energy and emission savings are still observed when natural gas is used as the reducing agent instead.

BASIC OXYGEN FURNACE (BOF)

Energy Efficiency Options

55 BOF Heat and Gas Recovery

The gas leaving a BOF has a temperature of 1200 degrees Celsius, contains 70-80% carbon monoxide and has a heating value of 0.84 GJ/t-steel [3]. As a result, recovery of the sensible and latent heat of the top gas is the single most important opportunity to improve energy efficiencies of BOFs. Heat recovery is split up into 2 methods; combustion and non-combustions. For the combustion method, large volumes of air are blow into the exhaust hood to combust the carbon monoxide in the off gas which is then utilized in a heat recovery boiler to produce high pressure steam. For the non-combustion method, the sensible heat of the off gas is recovered in a waste heat boiler to generate high pressure steam. The gas is then cleaned, stored and used as a fuel by mixing it with COG, BF gas etc.

56 BOF Bottom Stirring

In the BOF bottom stirring or combined blowing process, an inert gas is introduced at the bottom of the vessel into the molten bath [3]. This causes mixing within the bath and promotes a desirable carbon-oxygen equilibrium in the bath and slag. It also increases yield due to less slag formation, reduces oxygen and flux consumption and increases the vessel's lifespan. Some more complex systems include the injection of oxygen, fluxes and other gasses at the bottom of the vessel as well.

57 KOBM BOF

The Klockner Oxygen Blown Maxhutte or KOBM BOF is a combined blowing furnace whereby in addition to lance delivered oxygen, there is oxygen blown into the vessel at the bottom as well [55]. Typically, 70% of the oxygen is delivered through the lance while the other 30% is delivered through the bottom of the vessel through tuyeres (nozzles). This dual oxygen injection reduces yield losses while also improving steel chemistry, thus saving both time and money [57]. Often powered lime is inserted through the bottom of the vessel to aid in the slag formation, particularly to reduce the levels of sulfur and phosphorous by combining with their acidic oxides [56].

Innovative Controls/Technologies

58 Automated Steel Cleanliness Analysis Tool (ASCAT)

Research is being performed to integrate an ASCAT into two steel mills in order to allow steel makers to evaluate the quality of the steel they are producing during the production stage itself i.e. in real-time [3]. One of the main functions of the ASCAT technology is to analyze inclusions (defects) in the material [43]. The properties of these inclusions can be controlled based on the chemistry of the metal and slag. By controlling inclusions, there will be a reduction in the amount of steel that is rejected and therefore has to be remelted. This will increase productivity, decrease energy usage and allow for the production of higher quality steels.

59 Laser-induced breakdown spectroscopy (LIBS) for In-Situ Real-Time Measurement of Melt Constituents

A laser-induced breakdown spectroscopy (LIBS) technique is used to perform in-situ measurements of the composition of the melt to reduce the number of defects [3]. This will lead to a higher quality steel; however, the process is currently too expensive for widespread commercial adoption.

ELECTRIC ARC FURNACE (EAF)

Energy Efficiency Options

60 Bottom Stirring/Stirring Gas Injection

In EAFs that do not include oxygen injection, an inert gas can be injected at the bottom of the furnace to agitate the melt which promotes heat transfer [3]. This process increases liquid steel yields by 0.5% while also reducing electricity usage.

61 Eccentric Bottom Tapping

Eccentric Bottom Tapping EAFs are a type of EAF whereby the tap hole is located at the bottom of the furnace rather than the traditional side mounted spout technique [48]. The furnace is tilted at an angle of 25 degrees during the melting process. It is believed that the water-cooling rate of the furnace material is increased therefore decreasing the refractory material and electrode consumption rate [48]. This is a slag-free tapping technique that reduces tap-to-tap times, thus making it more likely to produce cleaner steel [3].

62 Tunnel Furnace Preheating – CONSTEEL Process

The CONSTEEL process is a conveyor belt scrap preheating process that allows for continuous charging and has seen widespread commercial adoption worldwide [45]. The scrap moves along the conveyer through a tunnel whereby air is injected to combust a counter flow of exhaust gas from the EAF in order to preheat the scrap [46]. This increases productivity and decreases in energy consumption.

63 Shaft Furnace Scrap Preheating

A more modern approach of the scrap preheating processes whereby multiple shaft furnaces are used to preheat the scrap [3]. Reduction in tap-to-tap times of 10-15 minutes are observed when finger shaft furnaces are used.

64 Direct Current (DC) Arc Furnace

A DC system can be incorporated in an EAF if the furnaces are large enough [3]. In these DC systems, there is one electrode that acts as the cathode with the bottom of the furnace serving as the anode. A decrease in power consumption is observed compared to traditional 3-phase AC EAF with higher melting efficiency and extended hearth life also observed.

65 Twin-Shell DC Arc Furnace

Twin-shell DC arc furnaces include 2 EAFs that use a common arc and power supply [3]. While the charge is melting in the 2nd vessel, the off gases are being utilized to preheat the charge in the 1st vessel. Increases in productivity due to reduced tap-to-tap times are observed with a reduction in energy consumption due to less thermal losses.

66 Airtight EAF Process

During the normal operation of an EAF, there is considerable air infiltration that causes significant thermal losses due to the invading air being at ambient temperatures [3]. Improvements in energy consumption rates are observed for airtight EAFs.

67 Optimal Charge Calculation in EAF

A statistical method has been developed to determine the metallic yield, specific energy consumption and chemical composition of each individual scrap type from a EAF steel sample [3]. This allows for the calculation of the total energy requirement of the melt, providing both energy and cost savings.

68 Dynamic Asymmetrical Control of AC EAF

This system optimizes the melting rate within an EAF while also limiting the heating loads on the wall cooling elements in an asymmetrical fashion [3]. As the temperature of the wall cooling elements is monitored, the arc radiation can be reduced in areas where the wall temperature is too high until the temperature returns to normal operating conditions.

69 Comelt

A Comelt furnace is a DC EAF furnace that usually includes 4 slanted electrodes that produce 4 inclined DC arcs to melt the feedstock [3]. Reduction in tap-to-tap times is observed as well as reductions in energy consumption, electrode consumption and a reduction in off gas volume by up to 70%. Other advantages of Comelt furnaces are complete off gas collecting at all times and a reduction in noise levels.

70 Contiarc Furnace

The Contiarc furnace has continuously-fed feedstock into a ring between the central shaft furnace and the outer furnace vessel [3]. As the feedstock material moves downwards, it is preheated by the rising process gasses in a counter-current flow pattern. Reductions in energy/electricity losses are observed with a considerable decrease in the waste gas and dust volumes as well.

71 Induction Furnace (IR) crucible/coreless

The induction furnace pertaining to steelmaking is a type of electric melting vessel whereby melting occurs by the heat generated in the iron by eddy currents produced by a high frequency alternating magnetic field (i.e., induction heating) [83]. The main type of IR furnace used in the steelmaking industry is the crucible/coreless type of IR and includes a nonconductive core that holds the iron charge that is to be melted. Some of the benefits of the coreless IF compared to an EAF include less dust/slag production, much less melt losses, lower requirement of the electrical grid, ease of adding alloying elements, relatively low investment costs and no electrode consumption costs [84]. Drawbacks of the IF compared to an EAF include the sensitivity of the refractory lining, more stringent requirements on the quality of the scrap, and they are not as good at removing impurities in the metals.

72 Model Based Steel Temperature Measurement

For mini-mills, the liquid steel temperature required for casting is controlled via the EAF or ladle furnace [3]. As a result, continuous monitoring of the liquid steel temperature has been performed and enables an optimization of the electrical energy required to produce a melt with a certain temperature.

Material Substitution/Process Options

73 Injection of renewable bio-carbon for supplementary energy or foaming practices

Renewable or carbon neutral bio-carbon can be used in an EAF to aid in foaming practices and as a chemical energy source to replace coal/coke that is used traditionally for these processes [85]. This will result in both emission and energy reductions while a reduction in the operating costs may also occur (depending on bio carbon/coal/coke prices). The Canadian Carbonization Research Association (CCRA) has set short term research goals to replace 100% of the injected carbon in a EAF with renewable bio-carbons [86].

74 Oxyfuel Burners/Lancing

Oxygen and hydrocarbon fuels can be used in an EAF through oxyfuel burners or lances as a partial substitute to electricity [3]. This process reduces energy consumption and can cause a more uniform temperature distribution within the EAF if the heat produced by the burners are directed at cold spots in the furnace. Other benefits of oxygen injection include the reduction of elements like phosphorus, silicon and carbon in the steel bath. In modern operation, the burners are turned on at the start of the operation to aid in the melting process and then they are used as oxygen lances when the liquid bath forms to help remove impurities from the melt.

75 Hot DRI/HBI Charging to EAF

Energy savings, increased productivity and improved slag foaming can be achieved by charging the EAF with Hot DRI rather than cold DRI [3]. This process has been adopted largely within recent years and is only applicable for facilities that produce hot DRI on site.

76 Foamy Slag Practices

The formation of a foamy slag on top of the liquid steel bath reduces the radiative thermal losses from the melt/bath [3, 45]. Foamy slags can be instigated through the injection of granular coal and oxygen into the melt. Increased productivity is observed by reducing tap-to-tap times and there are also reductions in electricity usage.

Innovative Controls/Technologies

77 ECOARC

In the ECOARC furnace, the preheating shaft furnace is connected directly to the melting chamber allowing for the continuous charging of scrap and high thermal efficiencies [32]. Significant energy consumption reductions are expected with the total exhaust gas volume being approximately half that of traditional EAFs due to its semi-airtight design [3,32]. The ECOARC furnace also produces significantly less dioxins and dust emissions.

78 Used Tires for Insulation in EAF

In order to insulate molten steel to minimize energy losses, coke or anthracite are used in an EAF [3]. Researchers at the University of New South Wales have used polymers (such as rubber from used tires) to replace some of this insulating coke resulting in energy and emission savings.

79 New-Scrap Based Steelmaking Process using Primary Energy

Electricity is the main type of energy used in an EAF. Fossil-fuel based (thermal) electricity production has a lot of efficiency losses along the way as electrical energy is converted to thermal and vice versa [32]. For example, the primary energy source (e.g. natural gas or coal) is first converted to heat in a power plant where it is then converted to electrical energy in the next step. This electrical energy is transported to the EAF (undergoing transmission losses) whereby it is converted back to thermal energy to produce the heat necessary for melting. This results in losses of almost two-thirds of the original primary energy due to conversion losses from source to EAF. As a result, research has been performed to make use of on-site primary energy in the form of heat. This is done through the use of two vessels, a counter-current reactor that uses coal to heat/melt the scrap and a superheating EAF that has the power requirements of a ladle furnace. Significant energy and emissions reductions are expected.

80 Development of a process to continuously melt, refine and cast high quality steel

This continuous steelmaking process utilizes three contiguous vessels to replace the batch ladle operations that connect the EAF to the continuous casting process [3]. These vessels are specifically designed to facilitate fast, near equilibrium reactions and allows for a high level of control and flexibility. This results in energy savings and likely increases in production quality and productivity.

81 Hydrogen and Nitrogen Control in Ladle and Casting Operations

Dissolved gasses in steel such as nitrogen and hydrogen affect its properties significantly [49]. Research has been performed to quantify the sources of nitrogen and hydrogen in ladle furnace and casting operations using mathematical models [3].

82 Waste Heat Recovery for EAF

This technology aims to recover the waste heat from EAF exhaust gasses by utilizing their energy to produce saturated steam or hot water [3]. The steam can be used in power generation, air separation etc. It is reported that up to 1/3rd of energy input is lost in most EAFs via exhaust gas waste heat [47].

CASTING

Energy Efficiency Options

83 Efficient Ladle Preheating

The ladle used in casting needs to be preheated to reduce thermal losses and is usually heated with gas burners [3]. Improvements have been made to further reduce thermal losses such as the installation of hoods, temperature controls and the use of recuperative burners and oxyfuel burners.

84 Efficient Tundish Heating

Like the ladle, the tundish must be preheated to reduce thermal losses, to avoid bubbles in the first slab at the start of the casting process and to avoid degradation due to thermal shock [3]. Improvements include use of recuperative burners as well as heating the tundish with electrical induction in the absence of combustion [52].

85 ProVision Lance-Based Camera System for Vacuum Degasser

The ProVision system is a lance-based fiber-coupled optical pyrometer that measures the melt temperature in the vacuum degasser [3]. To produce certain grades of steel, the melt temperature and chemistry are of utmost importance. This system measures the temperature of the melt automatically before and after oxygen blowing to allow for the production of ultra-low carbon steels.

86 Continuous Casting

Before the molten steel can be shaped or rolled, it needs to solidify and be formed into semi-finished products called billets, blooms or slabs [51]. The molten steel is transferred to the tundish allowing for a continuous process as the ladle can then be refilled with molten steel from the steelmaking process. The molten steel is then transferred from the tundish to a water-cooled copper mold of the casting machine which acts as the primary cooling process. At this point, only the outer shell of the steel has solidified. The steel is then drawn downwards from the bottom of the mold through a curved arrangement of support rolls and water sprays until it emerges horizontally as a solid steel strand from the end of the machine. It is then cut automatically into the required lengths [51].

87 Strip Casting (SC)

During the casting process, the steel is cast between two water cooled rollers in order to directly produce a strip with 3 mm thickness [3]. This results in high production speeds and very rapid cooling of the liquid steel which lead to considerable decreases in capital cost and energy consumption. The first commercial SC technologies include Castrip, Eurostrip, and Nippon/Mitsubishi [45]. Reduced material losses can lead to indirect energy savings while the operations and maintenance costs are expected to drop by 20-25%.

88 Thin Slab Casting - Near Net Shape Casting

Near shape casting involves casting the steel to dimensions that are close to the required dimensions of the final product [3]. This process integrates the casting and rolling processes into one step and as a result reduces the need for reheating. The two main types of near net shape casting are Thin Slab Casting (TSC) and Strip Casting (SC), which are both continuous processes. For TSC, the slabs are cast to thickness around 30-60 mm instead of traditional 120-300 mm thickness resulting in significant energy savings [45].

89 Endless Strip Production (ESP)

Endless Strip Production is the newest technology in the Thin Slab Casting and Rolling (TSCR) class of technologies and is seen as an improvement on the In-line Strip Production (ISP) process [53]. Directly after the continuous caster, the steel passes through a roughing mill, it is then heated in an inductive heater where it then enters the finishing mill and finally is cooled and coiled. Significant energy savings and productivity improvements are reported as well as a reduction in other consumable usages (molds, rollers etc.) [3].

HOT ROLLING MILL

Energy Efficiency Options

90 Regenerative Burners for Reheating Furnaces

Regenerative burners are part of a heat recovery system that utilizes the waste heat of furnace exhaust gas to preheat the combustion air [3]. They can be thought of as rechargeable storage batteries for heat, whereby during operation exhaust gasses flow through the burners and heat a storage medium [45]. After the storage medium becomes fully heated (or charged), the exhaust gas flow is turned off and cold combustion air absorbs the heat from the storage medium before it enters the burners. Unfortunately, regenerative or recuperative burners/furnaces often increase NOx emissions.

91 Recuperative Burners for Reheating Furnaces

Recuperative burners, like regenerative burners, utilizes the heat from exhaust gas to preheat the combustion air [3]. A recuperative burner is placed on the stack of the furnace and use tubes or plates to transfer heat from the exhaust gas to the incoming combustion air while keeping the streams separate [45]. Recuperative burners reduce energy consumption significantly while also reducing emissions.

92 Flameless Burners - Dilute Oxygen Combustion

There are two main types of flameless burners; flameless airfuel and flameless oxyfuel [3]. Flameless airfuel burners use air as an oxidizing agent while oxyfuel use pure oxygen. These burners utilize internal flue gas recirculation to carry out combustion in a diluted oxygen condition. This results in a flame that is invisible and provides numerous benefits including reduction in NOx emissions, improved thermal efficiency, and reduced fuel consumption compared to normal oxyfuel burners [45].

93 Improved Insulation of Reheating Furnace

Ceramic low-thermal mass insulating materials can be used in a reheating furnace to replace existing materials and results in lower thermal losses through the walls of the furnace [3, 45]. Energy savings are reported with further improvements seen if additional coatings (such as CO4 coatings) are applied to the materials.

94 Heat Recovery from Cooling Water

After the steel is ejected from the hot mill, it is cooled by spraying it with water at 80 degrees Celsius [3, 45]. Waste heat can be recovered from this cooling water with technologies such as an absorption heat pump to produce low pressure steam.

95 Walking Beam Furnace

A walking beam furnace is the state-of-the-art technology for use as a reheating furnace [3,45]. The stock is placed on stationary ridges and a rotating beam 'walks' the product through the furnace until it reaches the exit whereby the beam returns to the furnace entrance [3]. Significant reductions in fuel and electricity consumption were observed when used with a combustion control system.

Innovative Controls/Technologies

96 Thermochemical Recuperation for High Temperature Furnaces

Another method for recovering energy in the waste heat of the flue gas is through thermochemical recuperation [32]. This technique recovers the sensible heat of the flue gas and uses it to transform the hydrocarbon fuel (being used to heat the furnace) into a reformed fuel with a higher heating content. This reformed fuel is used to heat the furnace leading to reductions in fuel consumption rate, CO2 emissions and NOx emissions.

97 Innovative Reheat Furnace Management

To avoid surface defects in steel due to oxidation in hot-dip galvanizing lines, the reheat furnaces must be operated in oxygen free atmosphere [32]. This is often done by operating the reheat furnaces with a fuel gas surplus resulting in extra emissions and energy usage. BFI have developed a system to try to tackle these problems through the use of continuous burn-out measuring system, under-stoichiometric burner with forced burn-out and rollers made from more suitable materials. Reduction in energy and emissions are observed as well as high quality final products.

98 High Temperature Membrane Module for Oxygen Enrichment of Combustion Air

By enriching combustion air with additional oxygen, the flame temperature inside reheat furnaces can be increased [3]. A new method to produce O2 at a low cost using ceramic membranes allows for previously unusable process gasses and biogases to be enriched with oxygen and used in reheat furnaces. This results in less natural gas consumption, less CO2 emissions and reduces operating costs.

MULTIPLE EQUIPMENT/GENERIC TECHNOLOGIES

Energy Efficiency Options

99 Variable Speed Drives (VSD)/Variable Frequency Drives (VFD)

A VSD drive is a device that allows for the control of the speed and output torque of mechanical equipment [66]. This results in productivity improvements as well as energy (and associated emission) reductions in equipment such as centrifugal compressors, fans and pumps. Particular places that VSD or VFD (for AC equipment) can be incorporated in iron & steelmaking include COG compressor, ventilation fans, dust collection fans, combustion fans etc. [3].

100 Advanced Automation and process control systems (e.g. neural networks)

Automation and process control systems are industrial systems whereby processes are monitored and controlled automatically with a variety of sensors and actuators across the facility [67]. The goal is to automatically optimize parameters such as productivity, energy usage, emission released etc. These control systems can be incorporated in a number of places within an iron and steelmaking facility including automating COG supply, blast furnace process control, BOF process control, EAF process control and casting/rolling automated control systems [3].

101 Flue Gas Monitoring and Control

The composition and flowrate of the flue gas can be monitored to improve off-gas post-combustion operations by optimizing the fuel/air mixture [3, 45]. By monitoring the intake airflow and oxygen content of the flue gas, it can be determined if there are leaks within the furnace [45]. Benefits of this practice includes increased productivity, decrease in production costs, reduced energy consumption, reduced refractory wear etc.

102 MultiGas Analyzer

The MultiGas Analyzer system provides on-line process tuning of combustion related processes to improve continuous emission monitoring (CEM) [3]. The technology uses Fourier transform infrared spectroscopy in combination with advanced software and electronics to provide real time measurements including hazardous air pollutants.

103 Engineered refractories

Due to the extreme thermal and chemical conditions within iron/steelmaking vessels, specially engineered refractory materials have been developed to better withstand these harsh conditions [3]. Specific places these refractories can be incorporated include in EAFs to reduce ladle leakages/reduction in slag formation, in BOFs to increase the life of critical components as well as provide energy savings, or the use of ceramic low-thermal mass insulating materials in reheat furnaces.

104 Laser Contouring System (LCS)

The LCS utilizes high speed laser-based distance measuring equipment to perform rapid measurements of the vessel wall, bottom-lining thickness, bath level measurements, lance height calculations, optimal tapping angles etc. [3, 42]. The LCS system can be used on a BOF, EAF, Argon oxygen decarburization (AOD) etc.

105 Rapidfire™ edge heater

Often in traditional hot strip mills, the steel slabs are overheated to maintain high enough edge temperatures for the entire process [54]. However, once the slab is exposed to open air a rapid drop in temperature occurs, resulting in uneven cooling and possibly cracks or dimension variations. The Rapidfire edge heater addresses the edge related defects that occur during the production of steel sheet coils through the use of oxygen-natural gas burners [54].

106 Post combustion optimization

Carbon monoxide makes up the majority of the flue gas produced in an EAF or BOF and can be combusted to CO2 to produce additional heat for melting (this reaction is known as post combustion) [3, 32]. This is achieved through the injection of additional oxygen and can provide significant energy savings. Increases in productivity are also observed in EAFs. In order to optimize the post combustion process, computational fluid dynamic models (CFD) have been developed. A novel post combustion method involves the use of thermal regenerators and laminar-flow burners to achieve optimal reheat furnace operations [3]. The system uses low-calorific fuel gases (process gases, biogas etc.) and aims to create a reheat furnace with low energy demand, variable fuel input and a long lifespan.

107 Ultra High Power (UHP) transformers

Due to electrical transformer losses being as high as 7%, EAFs can be converted to operate at higher power by using ultra-high power transformers [3]. This can be achieved either by installing new transformers or using existing transformers in parallel. However, increased cooling is necessary at higher power to mitigate increased wear to the refractory lining. Increased transformer reactance and increased electrical arc stability were observed for these high powered EAFs.

108 Solar thermal generation for use in plant

Many processes within a steelmaking facility require the use of steam or the heating of air for hot blasts in a blast furnace etc. Numerous studies have been undertaken that look at using solar thermal or concentrated solar thermal plants to generate some of the heat necessary in the steelmaking process [87, 88].

109 Geothermal heat generation for use in plant

Many processes within a steelmaking facility require the use of steam while low grade heat is often used for administrative building heating etc. Geothermal heat in suitable locations can be used to produce low grade heat (< 150 degrees Celsius) that can replace boiler or space heating operations [89].

110 Facility wide integrated waste heat recovery system

There are many locations within a steelmaking facility whereby heat can be recovered such as from hot off-gases, cooling water, hot intermediate products such as slabs, hot slag etc. [90]. Systems such as Tenova's iRecovery can be installed that recover the waste heat and convey it to a central location to utilize the thermal energy through the creation of steam, electricity, heat for district heating etc. [90, 91].

Material Substitution/Process Options

111 Oxy-fuel burners

Oxy-fuel combustion involves carrying out the combustion process without any nitrogen in the oxidizer [68]. This is achieved through using pure oxygen or a mixture of oxygen and recycled flue gasses as the oxidizer. After combustion of the oxy-fuel, the resulting flue gas comprises mainly of CO2 and H20 and therefore allows for easier implementation of CCS or CCU [69]. Oxy-fuel burners can be used in a wide variety of locations across a steel facility (i.e., anywhere traditional burners are used).

112 Burning of biomass for thermal generation

Many processes within a steelmaking facility require the use of steam or the heating of air for hot blasts in a blast furnace etc. Biomass can both be used as a substitute for carbon bearing material, such as using charcoal as a partial substitute for wood, however it can also be burnt to provide thermal energy to replace sintering solid fuels, the production of steam, district heating etc. [74, 92].

Innovative Controls/Technologies

113 Bio H2 and renewable natural gas production

Renewable natural gas is the gaseous product of organic material decomposition (biogas) that has been processed to meet specified purity standard [93]. It can be used as a direct replacement for natural gas and is carbon neutral over its lifecycle therefore drastically reducing emissions compared to conventional natural gas [94]. Similarly, bio hydrogen is derived from organic material and can often even have a carbon negative influence over its lifecycle [95]. Both of these carbon neutral bio gasses can be used as a replacement for such things as natural gas injection in a blast furnace therefore reducing emission and in the case of bio hydrogen, improve reaction kinetics [75].

114 Hydrogen production

Hydrogen can be produced on site via natural gas cracking with carbon capture or water electrolysis with low emission electricity to produce low emission hydrogen [96]. This hydrogen can be used as a clean emission free fuel or reactant source in the blast furnace, as a fuel in coke batteries or reheat furnaces etc. This can drastically reduce emissions while also improving reaction kinetics in some cases [75].

115 Carbon Capture and Storage (CCS)

This process involves capturing CO2 from large point sources, transporting it and then storing it in such a way that it doesn't re-enter the atmosphere [3]. There are a variety of Carbon Capture (CC) techniques including chemical absorption using aqueous amine solutions, adsorption including novel fluidized and moving beds structures, chemical looping combustion, membraned based technologies etc. [70]. These techniques can be classified as pre-combustion, oxy-combustion and post-combustion processes depending when/where the capturing occurs. Many of the new BF or BOF technologies include systems to extract CO2 from the flue gas or involve techniques that allow for easy integration with CC. CC can be incorporated into most of the steelmaking processes with the Top Gas Recycling Blast Furnace (TGRBF) being one of the most promising technologies to reduce emissions in steelmaking. However, the sequestering/storing of the captured CO2 is much more challenging and sequestration is limited to areas with appropriate geological conditions that are not necessarily located at the plant sites. This technology will require the development of a carbon pipeline to connect the plants to sequestration locations.

116 Carbon Capture and Utilization (CCU)

CCU involves the utilization and conversion of the captured CO2 into a marketable product rather than sequestering/storing the captured carbon [70]. One of the major uses for captured carbon is Enhanced Oil Recovery (EOR), a technique that extract the remaining oil after conventional methods have reached their limits [71] the same limitations with regard to the plant locations and suitable EOR sites noted above apply. Other CCU techniques include carbon mineralization, concrete curing, algae cultivation, synthetic fuel production, chemical feedstock and urea yield boosting. All of these technologies would require transportation of the CO2 to the utilization site or co-location at the plant site.

POWER PLANT

Energy Efficient Options

117 Combined Cycle Power Plant (CCPP) using recycled process gasses (e.g., COG)

During the steelmaking process there are many process gasses produced and often facilities will use these gasses within the site with excess gas being flared. Instead of flaring the excess gasses, they can be used in a CCPP to produce the site's required steam as well as produce electricity to reduce electrical consumption from the grid. This will reduce and/or eliminate gas flaring while also producing steam/electricity therefore reducing facility wide scope 1 & 2 emissions.

118 Landfill gas for electrical generation

As garbage in landfills decomposes, they release landfill gas which consists of mainly methane (~55%), carbon dioxide (~40%) and nitrogen (~5%) [97]. This landfill gas is collected, processed, and then used in combustion engines (biogas generators) to produce electricity. As landfill gas is responsible for 20% of Canada's methane gas emissions, utilizing it for electrical generation rather than it being emitted to the atmosphere results in a decrease in emissions [97].

119 Electrical storage (batteries, electrolyser etc.)

Electrical storage (primarily batteries) is crucial for the integration of renewable electricity assets. As we know, two of the main renewable energy sources (solar and wind) are intermittent and do not provide a consistent power output. As a result, batteries are needed to capture excess electrical and to provide a power output during times of reduced or no power generation. Batteries can also be used to lower the costs of buying electricity from the grid by consuming and storing electricity from the grid during cheaper times of the day and then using/discharging the batteries during the expensive times of the day.

120 Solar photovoltaic

Solar photovoltaic utilize the photovoltaic effect to convert sunlight (in the form of photons) to electricity [98]. They provide emission free electricity while also drastically reducing the electricity costs of a site per year. There are however operational and maintenance costs associated with solar.

121 Wind turbine

Wind turbines capture a portion of the kinetic energy of wind in its blade which then turns a rotor connected to a generator to produce electricity [99]. They provide emission free electricity while also drastically reducing the electricity costs of a site per year. There are however operational and maintenance costs associated with wind turbines.

122 Geothermal electrical generation

Superheated water (i.e. water above the boiling point due to being pressurized) is extracted from the earth crust to produce steam. This steam drives a turbine or generator to produce electricity [100]. These systems provide emission free electricity while also drastically reducing the electricity costs of a site per year. There are however relatively higher operational and maintenance costs associated with geothermal depending on the chemical composition of the ground water.

123 Low-head hydro

Low head hydro typical refers to a change in elevation (head) of less than 20 meters between the intake and discharge points [101]. As a result, they have relatively small power outputs but have less environmental impacts due to the small infrastructure and the fact a dam isn't usually required [102]. Instead, the facilities are often run-of-river whereby a swift moving often steep river is utilized to generate power with a turbine. These facilities provide emission free electricity while also drastically reducing the electricity costs of a site per year. There are however operational and maintenance costs associated with low-head hydro as well as some environmental concerns compared to other renewable energy sources.

124 Fuel cells for electrical generation

A fuel cell generates electricity through a chemical reaction of a fuel (often hydrogen) and an oxidizing agent (often oxygen) rather than through combustion [103]. As a result, emission free electricity is produced along with water. As fuels and oxidizers are required to produce electricity it is not expected that there will be a cost savings due to consuming less electricity from the grid.

125 Small Modular Nuclear Reactors (SMRs)

Small Modular Reactors (SMR) are defined as nuclear reactors that produce less than 300 MWe of electrical power [104]. These modular reactors are often built as modules in a factory and are transported to the generation site with built in safety features [105]. SMRs produce emission free electricity while having a small land footprint and have a competitive cost with other forms of electricity generation [106].

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