PATHS TO A GREENER STEEL CITY

AUGUST 2021

TABLE OF CONTENTS

EXECUTIVE SUMMARY

- Steelmaking ranks first amongst heavy industries for CO2 emissions, and second for energy consumption, accounting for 7% of global CO2 emissions
- Steelmaking results in direct and indirect environmental impacts across the supply chain which must be addressed to mitigate the impacts of the climate crisis
- Achieving 'net-zero', 'carbon-neutral', or 'fossil-free' steel is an easier task than 'emissions-free' or 'CO2-free' steel due to the carbon content of steel
- Steel is the "most sustainable material of the 21st century" due to its recyclability, and will play a vital role in the transition to a greener future due to its use in renewable energy infrastructure and electric vehicles
- Canada is the 19th largest steel producer in the world, with over 30 facilities across 5 provinces (primarily in Ontario), contributing $4.2 billion to GDP annually
- The Canadian Steel Producers Association aims to reach net-zero steel by 2050, which will require significant economic investments, technological upgrades, research collaborations, and a levelled playing field supporting domestic steelmaking
- There are several promising environmental initiatives and investments in green steel occurring around the world, such as the HYBRIT program in Sweden
- There are several emission-reducing strategies that are already technologically and/or economically feasible, such as the use of biomass, direct reduced iron (DRI), and electric arc furnaces (EAF)
- Green hydrogen, in combination with renewable energy use, in the DRI-EAF production route, provides the most promising avenue to producing net-zero steel, but will not be economically viable unless green hydrogen prices decrease, or carbon prices are implemented and/or increased
- The transition to green steel requires significant government investments
- A $1.725 billion project to implement hydrogen-ready DRI-EAF production at ArcelorMittal Dofasco was announced in July 2021, which will become operational in 2028, reducing CO2 emissions by 60%
- There is no single technology or initiative that will allow for net-zero steel to be reached, but rather several technologies that must be used together across the supply chain to minimize the environmental impacts of the steel industry

ENVIRONMENTAL IMPACTS OF THE STEEL INDUSTRY

Steelmaking is an incredibly energy-intensive process. The steel sector is the second-largest global industry energy consumer,[1] and Dofasco's existing, traditional electric arc furnace was Ontario's largest single consumer of electricity in 2014.[2]

Three-quarters of the steel industry's energy use comes from coal - the 'dirtiest' fossil fuel.[3] In order to produce one tonne of steel, the traditional integrated steel mill uses an average of 780 kilograms of coal.[4]

Steelmaking creates substantial GHG emissions due to the necessary addition of carbon to iron in the steelmaking process. In 2018, producing one tonne of steel released 1.85 tonnes of CO2 emissions,[5] the majority of which are direct emissions from the steelmaking process compared to indirect emissions from energy use.[1] Overall, the steel industry accounts for 7% of global CO2 emissions.[5] While the GHG and energy intensity indices can vary widely between countries, no steel plant has achieved net-zero emissions to date.

Steelmaking also releases byproducts into the environment (primarily air emissions) that can pose risks to environmental and human health, such as particulate matter (PM2.5 and PM10), heavy metals (mercury, arsenic, cadmium, lead, etc.), benzene, nitrogen dioxide, and benzo(a)pyrene.[6]

There are direct and indirect environmental impacts throughout the steelmaking supply chain, many of which could be minimized or eliminated through technological innovation and infrastructural upgrades (see pages 9-20).

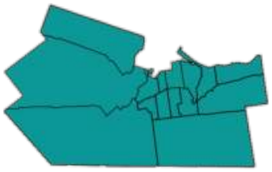
ENVIRONMENTAL BENEFITS & OPPORTUNITIES IN THE STEEL INDUSTRY

Steel provides several environmental advantages, and will be a vital part of the transition to a greener future. Renewable energy infrastructure is heavily reliant upon steel; 35 to 45 tons of steel are required for one megawatt of solar energy, while 120 to 180 tons of steel are required for one megawatt of wind energy.[7]

Steel is the most recycled material in the world, and called the "most sustainable material of the 21st century"[8] due to its ability to be continually recycled without loss of quality. A basic oxygen furnace can use up to 30% recycled steel when making new steel products, while electric arc furnaces can run using 100% scrap metal.[5]

New innovations in steelmaking (such as Advanced and Ultra High-Strength steels) have created stronger, lightweight materials.[9] Vehicles built using these steels can weigh 17-25% less while continuing to meet safety standards, resulting in an average 5.7% decrease in GHG emissions and 5.1% decrease in fuel consumption.[10] These steels can also increase the range of electric vehicles, which would eliminate a major barrier that has deterred consumers from switching to electric vehicles.[11]

Steel will be needed within our society for generations to come, but cannot continue to be produced in an unsustainable manner. Companies around the world are developing new technologies to combat these issues and strive for mass-scale net-zero steel production by 2050.



STATE OF THE STEEL INDUSTRY
HAMILTON

For over a century, the steel industry has been the backbone of the Hamilton economy. However, the steel industry has also significantly contributed to many of the key environmental issues in Hamilton.[12] The two steel plants in Hamilton are respectively operated by Stelco and ArcelorMittal (Dofasco).

STELCO HOLDINGS INC.

- Founded in 1905, currently employs 750+ unionized individuals[13]
- ~2 million tonnes of steel produced annually[14] (though the Hamilton plant is only involved in cokemaking and finishing, with no blast furnaces, basic oxygen furnaces, or electric arc furnaces in operation)
- Released an Environmental Policy in 2017 aiming to **reduce** air, water, and waste pollution, **improve** environmental performance and management system, and **comply** with environmental laws[15]
- Stelco is running several environmental initiatives, such as replacing coke with railway ties, and capturing 6300 tonnes of CO_2 a year for algae and bioplastics[16]

ARCELORMITTAL DOFASCO

- Founded in 1912, currently employs 5000 individuals[17]
- ~5 million tonnes of steel produced annually[14]
- Created 10 sustainable development outcomes in 2017 in the following areas: **people, products, infrastructure, resources, air/land/water, energy/carbon, supply chains, community, scientists/engineers, and impact measurement**[18]
- ArcelorMittal Dofasco has received a $400 million federal investment to transition to a DRI-EAF steelmaking process (see page 24), while ArcelorMittal plants around the world are implementing various environmental initiatives, such as piloting the use of biomass in place of coal[19,20]

STATE OF THE STEEL INDUSTRY
CANADA

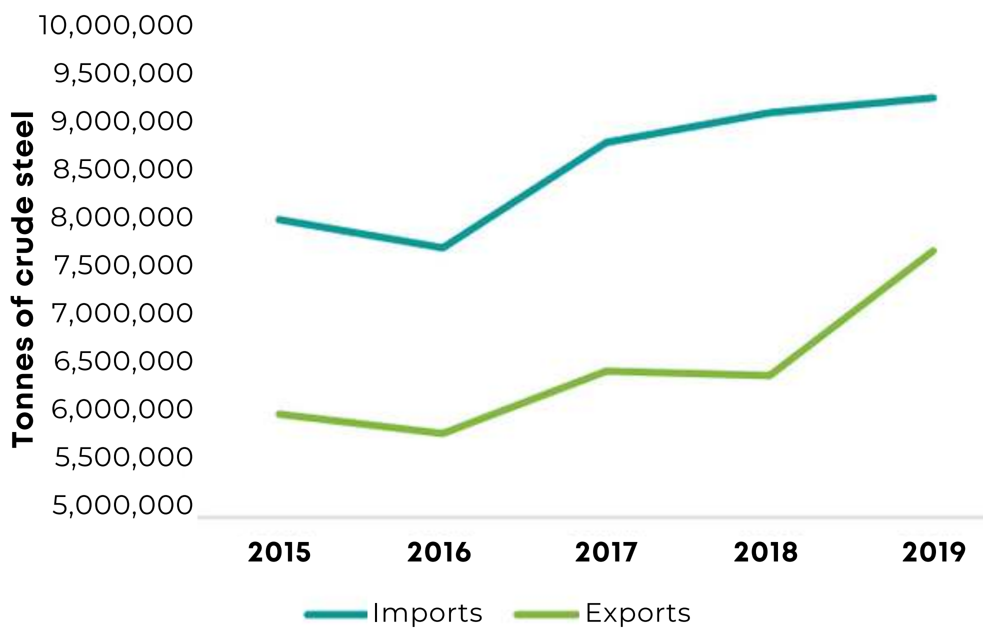
QUICK FACTS ABOUT THE CANADIAN STEEL INDUSTRY[21,22]

30+ STEEL FACILITIES ACROSS 5 PROVINCES

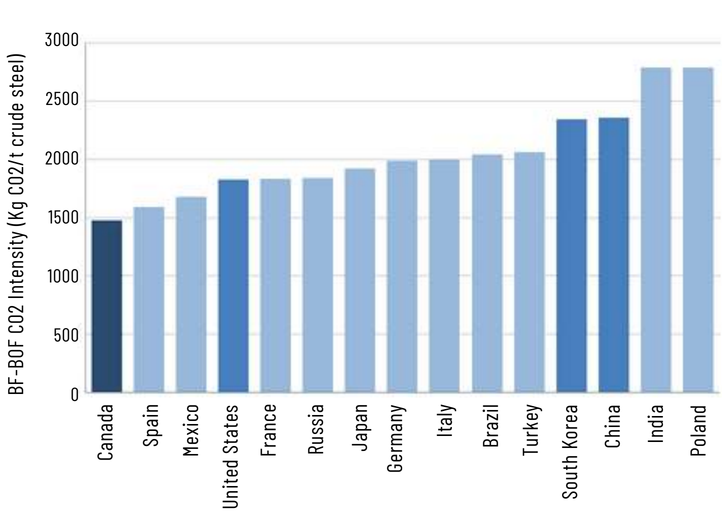
18TH LARGEST GLOBAL STEEL PRODUCER IN 2019 (12.89 MILLION TONNES)

$15 BILLION INDUSTRY CONTRIBUTING $4.2 BILLION TO GDP

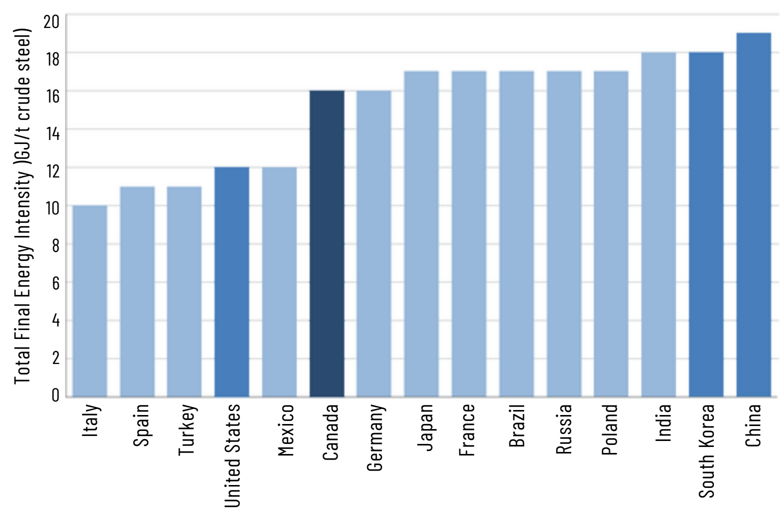
Canadian steel imports continue to surpass exports,[21] with steel primarily being imported from the US, South Korea, and China.[23] However, China and South Korea have the highest energy intensity per tonne of steel in 2019, while Canada had the lowest CO2 intensity for blast furnace/basic oxygen furnace steel production.[24] Canada's relatively low emissions can largely be attributed to its high proportion of renewable energy.[25] The Canadian Steel Producers Association is calling for protection of domestic markets through carbon border adjustments and procurement policies.[26]



Canadian Steel Imports and Exports from 2015-2019[21]



The CO2 intensity of blast furnace-basic oxygen furnace (BF-BOF) steel production (2016)[24]



Total final energy intensity of the steel industry (2016)[24]

STATE OF THE STEEL INDUSTRY
CANADA

Top 10 GHG-emitting iron & steel plants[20]

Canadian iron and steel mills emitting more than 100 kilotonnes of CO2 equivalent (2019)

Facility	Location	Emissions (tonnes)
ArcelorMittal Dofasco	Hamilton, ON	4784800
Algoma Steel Inc.	Sault Ste. Marie, ON	4312800
Stelco Holdings Inc.	Haldimand County, ON	3833700
ArcelorMittal Contrecoeur-Est	Contrecoeur, QC	1032900
Rio Tinto Fer et Titane	Sorel-Tracy, QC	842700
EVRAZ Inc.	Regina, SK	227600
Stelco Inc.	Hamilton, ON	270000
Quebec Silicon LP	Bécancour, QC	187400
Elkem Metal	Chicoutimi, QC	126200
Ivaco Rolling Mills	L'Orignal, QC	125400

In 2019, the Canadian steel industry had the highest highest emissions out of all heavy industries, releasing over 16 million tons of CO2 (2% of Canada's total emissions).[27] This percentage is lower than the international average due to substantial oil & gas sector emissions.[20] About 85% of steel emissions are from integrated mills, while the remaining 15% are from electric arc furnaces.[27]

EXAMPLES OF CURRENT ENVIRONMENTAL INITIATIVES

ArcelorMittal Dofasco: ArcelorMittal Dofasco is testing the use of Char Technology's biomass (SulfaCHAR and CleanFyre)[28] at an industrial scale, with the goal of replacing 40,000 tonnes of coal per year.[20] ArcelorMittal also recycles several waste products such as slag, and blast furnace/coke oven gas.[19]

Stelco (Lake Erie): In 2020, Stelco Holdings Inc. entered into a partnership with DTE Energy Services to create a 65-megawatt cogeneration plant, which is expected to be operational in 2022.[29] Cogeneration plants use byproduct gases from the blast furnace and/or coke ovens to produce electricity. The Lake Erie plant also has a partnership with Pond Technologies to sequester CO2 emissions with an algae bioreactor.[16]

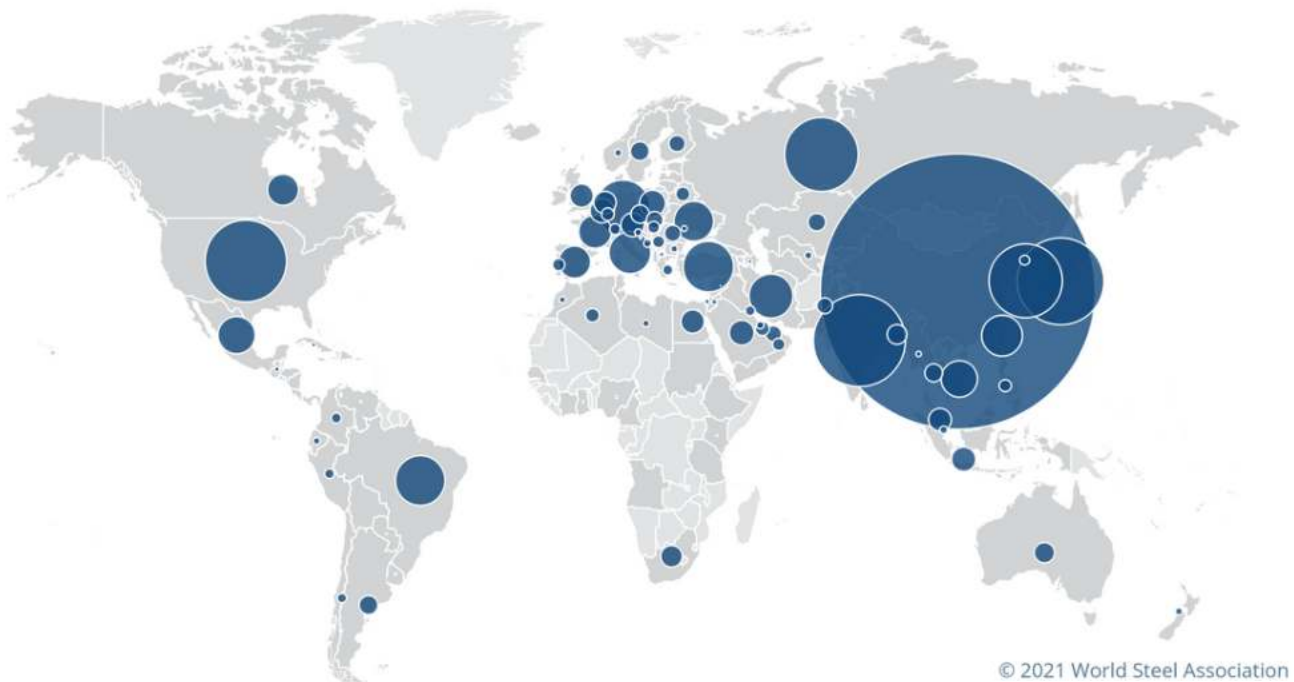
Algoma Steel: Algoma Steel aims to be the "greenest flat-rolled steel producer in Canada"[30] through constructing two electric arc furnaces (EAF) that will feed into existing finishing and hot-rolling infrastructure.[31] This transition could reduce annual GHG emissions by 3 million metric tonnes within the next decade.[31]

The Canadian steel industry has reduced GHG emissions by 25% since 1990, and the Canadian Steel Producers Association aims to reach net-zero steel by 2050.[22] Striving for net-zero will require significant economic investments, technological upgrades, research collaborations, and a levelled playing field supporting domestic steelmaking.[22] This transition is also vital to mitigating the impacts of the climate crisis and creating a more climate-resilient future.

STATE OF THE STEEL INDUSTRY
GLOBAL

2019

Total production of crude steel (thousand tonnes)[32]



Global steel production has been steadily increasing, with global demand tripling between 1970 and 2019.[1,21] The iron and steel sector is the largest producer of CO_2 emissions amongst heavy industries, releasing 2.6 gigatonnes of CO_2 each year.[1] Steel demand is expected to increase by 33% between now and 2050, and current projections show CO_2 emissions rising to 2.7 gigatonnes by 2050.[1] Actions must be taken across the supply chain to reduce environmental impacts while meeting global steel demand.

EXAMPLES OF CURRENT GLOBAL ENVIRONMENTAL INITIATIVES

DRI-EAF
ArcelorMittal (Hamburg)

ArcelorMittal Hamburg is the only DRI-EAF plant in Europe. In 2020, this facility became the first to use grey hydrogen as a reductant (produced using natural gas)[33] to produce direct reduced iron (DRI) for use in the electric arc furnaces (EAFs) at an industrial scale. The facility aims to use green hydrogen when there is sufficient supply and more affordable hydrogen prices.[33]

Zero CO_2 emissions
ArcelorMittal (Sestao)

In July 2021, ArcelorMittal announced its Sestao plant would be the first zero Scope 1 & 2 carbon-emissions plant in the world by 2025,[34] producing 100,000 tonnes of steel annually. The plant will increase the use of scrap metal, and use green hydrogen-produced DRI in its EAFs, which are powered by renewable energy. Biomass and green hydrogen will be used to eliminate remaining emissions. This project was made possible by a €1 billion investment from the federal government.[34]

HYBRIT (fossil-free steel)
SSAB, LKAB, & Vattenfall

Hydrogen Breakthrough Ironmaking Technology (HYBRIT) is a unique collaboration between three companies working to create fossil-free steel at all points of the supply chain: SSAB (steel), LKAB (mining), and Vattenfall (energy).[35] HYBRIT has been researching and testing the technology needed for fossil-free steel since 2017. Iron pellets are made using biofuel,[36] and renewable energy is used to create the hydrogen used in the direct reduction process. HYBRIT is also developing hydrogen storage systems to account for fluctuating solar and wind power.[37]

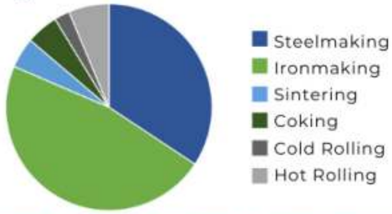
PATHS TO A GREENER STEEL CITY

OVERVIEW

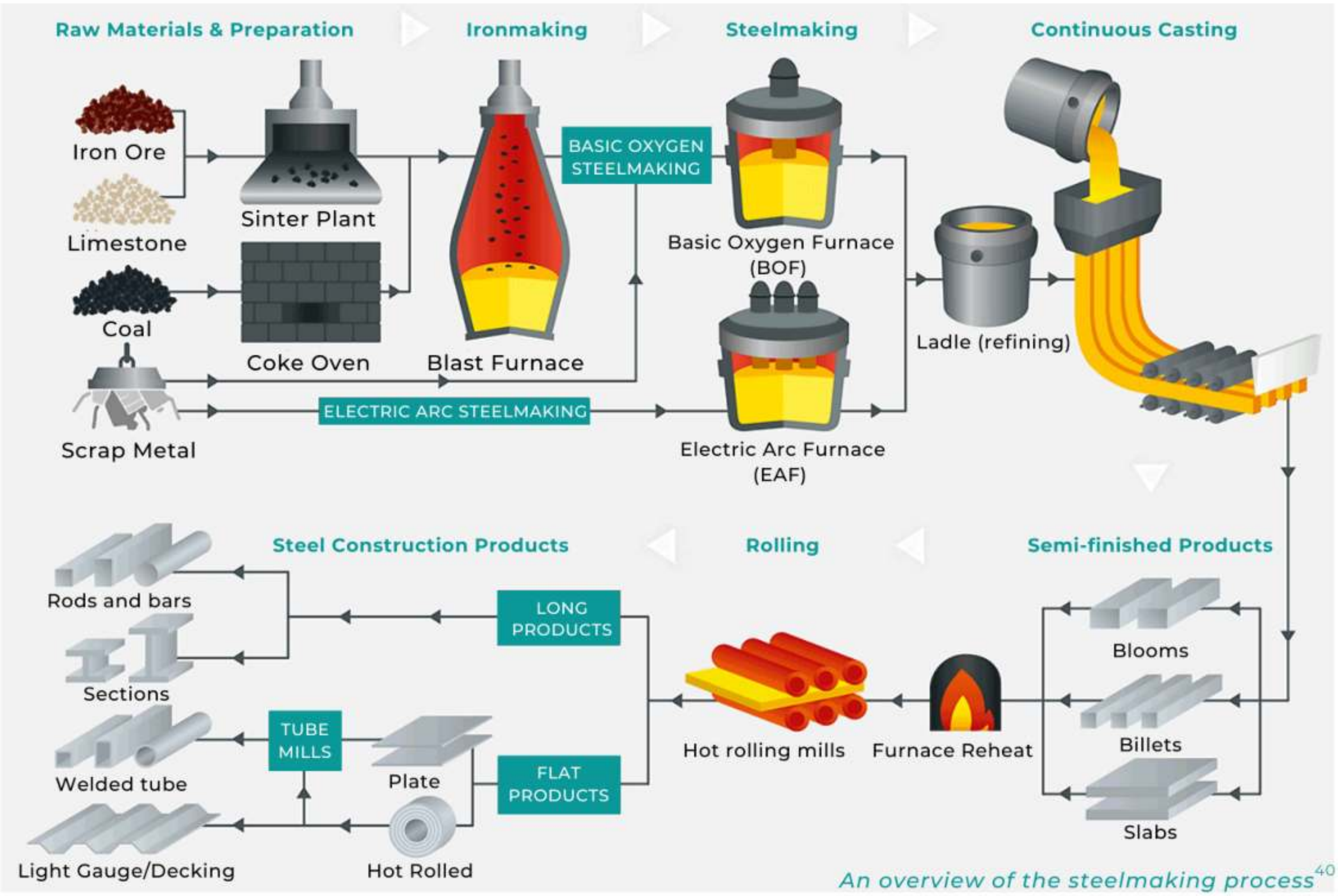
It is important to consider the environmental impacts of the steel industry across the supply chain, from initial material extraction to end-of-life product disposal, as the relative impacts and challenges in reducing impacts can vary widely. For example, a 2019 study found that 47% of wastewater released in the steelmaking process comes from the ironmaking stage, followed at steelmaking at 34% (though exact values can vary between steelmaking plants).[38] Carbon and energy intensities also vary widely between steelmaking processes, as seen below.[1] DRI-EAFs fuelled by green hydrogen and renewable energy could virtually eliminate CO2 emissions in the steelmaking process[5] (reduced by 97.2% compared to traditional BF-BOF).[39] However, carbon is a necessary component of steel, and thus CO2 will be released from either the blast furnace or the EAF. While it is feasible to achieve net-zero steel, carbon-neutral steel, or fossil free steel (using biomass and renewable energy), the creation of emissions-free or carbon-free steel on an industrial scale proves to be more challenging.

Energy and CO2 intensities of main steel production routes[1]
(in gigajoules per tonne of steel, and tonnes of CO2 per tonne of steel)

	BF-BOF	Scrap-based EAF	Natural gas-based DRI-EAF
Energy intensity	21.4-22.7 GJ/t	2.1 - 5.2 GJ/t	17.1-21.8 GJ/t
CO2 intensity	1.2-2.2 t CO2/t	0.04 - 0.3 t CO2/t	1.0 - 1.4 t CO2/t



Sources of wastewater in steelmaking[38]



An overview of the steelmaking process[40]

PATHS TO A GREENER STEEL CITY
IRON EXTRACTION

98% of usable iron ore (>58% iron content) is consumed by the steel industry, with approximately 2.28 billion metric tonnes of iron ore being mined annually. [41] The mining of iron ore impacts local wildlife, air quality, and water quality, with toxic tailings that can contain heavy metals such as mercury, lead, and arsenic.[42]

Stelco currently sources its iron ore from the Minntac mine in Minnesota, owned by US Steel,[43] and acquired 25% interest in Minntac in 2020.[44] This iron ore mine is the largest in the US, and its associated tailings basin have been called "the poster child for Minnesota's failure to control mining pollution, even when there is clear evidence that the pollution has violated Minnesota water quality standards and decimated downstream wild rice."[45] Minntac was found to be releasing 2000 gallons of wastewater per minute into the groundwater,[46] and emitting sulfate levels of 954-1320 mg/L despite their permit requiring respective basin and groundwater sulfate levels to be 800 mg/L and 250 mg/L by 2025.[47] In February 2021, the Minnesota Supreme Court reversed a lower court decision and ruled against US Steel, stating that regulators can in fact limit groundwater and surface water pollution through strict permit standards.[46]

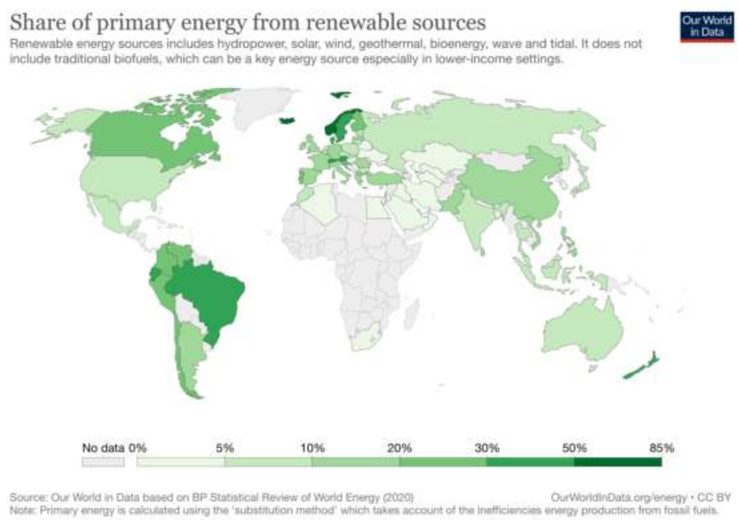
ArcelorMittal Dofasco sources its iron from two self-owned open-pit mines: Mont-Wright and Fire Lake.[48] These two mines have been given positive environmental ratings in the Towards Sustainable Mining progress reports, however, results are only externally verified every three years with self-assessment in between, and the 'good practices' listed under the assessment criteria emphasize tracking and reporting rather than concrete action or reductions.[49]

It is clear that the environmental impacts, and steps taken to improve environmental outcomes, vary widely between iron ore companies. Sustainable mining practices must be identified and better regulated to minimize these environmental impacts, while steel companies must critically assess their procurement policies and partnerships with iron ore mining and pellet manufacturing companies.

PATHS TO A GREENER STEEL CITY
RENEWABLE ENERGY

There is a reciprocal relationship between renewable energy and steelmaking - steel is a foundational component of renewable energy infrastructure, such as solar panels, wind turbines, and hydroelectric dams, and increased renewable energy allows for a significant reduction in emissions from steelmaking.

Steelmaking is an incredibly energy-intensive process, and thus the transition to net-zero steel will require a significant increase in renewable energy supply. Steel production is predicted to increase by 33% between 2020 and 2050,[1] and many of the 'greener' steelmaking methods that will be needed to achieve net-zero steel, such as direct reduced iron and green hydrogen, also require increased energy capacity. Direct reduction using hydrogen requires 3.48 MWh of electricity to produce one tonne of liquid steel[39]- this amount of electricity is equivalent to driving 20,000 kilometres in an electric vehicle, or powering the average home for four months.[50] In the context of a country, Germany would need 100 TWh (100 million MWh), which is approximately 20% of Germany's current electricity consumption, to decarbonize its steel sector completely.[51] Low-cost, accessible renewable energy is a critical component of decarbonizing steelmaking across the supply chain. However, many countries do not have the necessary renewable energy generation capacity, as seen in the map below.[52]



Failure to meet renewable energy demand and capacity could be major barriers to achieving net-zero steel, which further emphasizes the need to invest in the creation of low-cost, reliable renewable energy.

PATHS TO A GREENER STEEL CITY
COKEMAKING & SINTERING

Cokemaking is the process of heating coal in the absence of oxygen in cokemaking ovens, which removes impurities in the coal and results in a high-carbon fuel for the blast furnaces.[53] Sintering is the process of heating iron ore and additives such as limestone, creating a compact, solid mass known as sinter. Sinter and coke are fed into the blast furnace to create liquid iron as part of the integrated steelmaking process (see page 15). Many of the sintering plants in Ontario, such as Stelco and Algoma Steel, have closed, but these processes continue to occur in Canada. ArcelorMittal Dofasco's Hamilton plant does not have a sintering plant, as sintering occurs at their Quebec mining facilities. However, the steelmaking processes that do occur in Hamilton still pose numerous health risks.

Cokemaking and sintering are some of the most environmentally damaging parts of the steelmaking process. Cokemaking and sintering can account for nearly 40% of CO2 emissions and nearly 70% of emissions that pose human toxicity risks.[54] One study found that the sintering plant was the primary contributor to direct carcinogenic impacts potentially occurring in the area compared to the coke oven, blast furnace, and basic oxygen furnace, likely due to the emission of heavy metals, polychlorinated dibenzofurans, and dioxins from the sintering plant.[54] The production of dust and particulate matter are also a primary concern in the sintering process. Cokemaking and sintering have also been found to be the most significant contributors to freshwater toxicity and eutrophication, which can result in algal blooms that impact wildlife.[54] Cokemaking significantly impacts air quality, and poses numerous threats to environmental and human health through the release of particulate matter and carcinogens. Hamilton has the highest ambient air levels of benzo(a)pyrene in Ontario due to the cokemaking plants, which causes disproportionate severe health impacts in neighbourhoods closer in proximity to the steel plants.[55]

Cokemaking and sintering are both environmentally detrimental processes that are very difficult to decarbonize, but there are viable technologies to replace both processes. Coke can be replaced by biomass when using a blast furnace, or replaced by natural gas or hydrogen in a direct reduced iron process. Sintering can similarly be replaced by the DRI-EAF steelmaking route (see pages 16-17) or the sole use of scrap metal.[56]

PATHS TO A GREENER STEEL CITY
BIOCHAR & BIOMASS

Biomass: any renewable organic material used for fuel
Biochar: a carbon-rich solid that is made when biomass is heated in the absence of oxygen

Carbon is required in order to make steel, with most steel containing 0.04%-2.1% carbon.[57] In blast furnaces, carbon (in the form of coke) is used to reduce iron ore (iron oxides) into liquid iron with a carbon content of about 4% - the carbon (coke) reacts with the oxygen in the iron ore, creating carbon dioxide as a byproduct.[58] By using biomass as the carbon source rather than coal, the emissions intensity can be reduced by 31-57%.[59] Even a 80% coke/20% biomass mix used in a blast furnace could reduce CO2 emissions by 15%.[60] Biomass can also be used in the sintering or cokemaking processes (if coke is being used instead of biomass in the blast furnace) to further reduce emissions by a respective 5-15% or 1-5%.[60]

Biomass is being used around the world, producing 14,864 petajoules of energy - 85% of this energy is used by industries, while the remaining 15% is used in the transportation sector.[60] It is important to note that industrial-scale biomass use can heavily depend on local supply,[5] and may not be economically competitive compared to coal unless carbon pricing or incentives were put in place.[60]

Overall, incorporating biomass into an integrated steel mill poses minimal to no infrastructural barriers, and could result in significant emissions reductions. However, production costs may increase, and a reliable stream of biomass would need to be secured (ideally from a local source to reduce transportation emissions).

PATHS TO A GREENER STEEL CITY
PLASTICS

In addition to biomass, plastics have been proposed as an alternative reducing agent to coke in the steelmaking process. 360 million tonnes of plastic were produced in 2018, and the vast majority of plastics end up in landfills or the natural environment.[61] The accumulation of plastics in the natural environment and waterways, as well as their degradation into microplastics, create a multitude of environmental and ecological issues. Several solutions to the plastics crisis have been proposed, such as switching to more recyclable or compostable materials, creating bioplastics, incinerating plastics, plastic bans, or enzymatic degradation. One potential 'solution' pertinent to the steel industry is the use of plastic waste transformed into pellets and used as a reductant in blast furnaces. One study found a 30% reduction of carbon emissions when using plastics as the reductant compared to typical coke use.[62] The increased hydrogen content in plastics compared to coke acts as an additional reductant, and can reduce energy use through speeding up the reduction process.[62]

Despite the potential to reduce carbon emissions, incinerating plastics pose significant risks to human health. Plastic incineration releases multiple chemicals that can increase the risk of cancer, heart disease, respiratory diseases, or central nervous system damage, such as dioxins, toluene, formaldehyde, PCBs, and heavy metals (lead, mercury, cadmium, etc.).[63,64,65,66]

The use of plastics as a reductant poses significant risk, and there are several other alternative reductants, such as biomass, that also reduce carbon emissions without creating additional risks to human health. These alternative reductants should be prioritized when trying to lower emissions and coke use.

PATHS TO A GREENER STEEL CITY
INTEGRATED STEEL MILLS

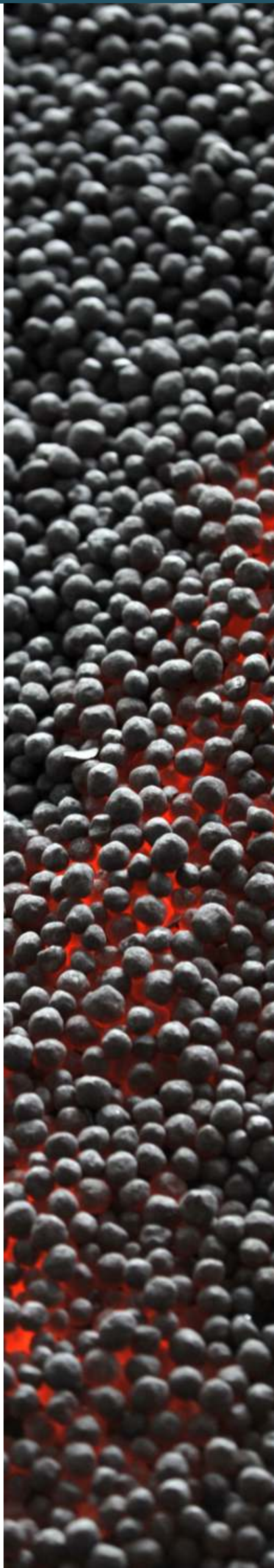
Stelco and ArcelorMittal Dofasco are integrated steel mills, which reduce sinter (compact iron ore) in a blast furnace (BF) which is fed into a basic oxygen furnace (BOF) to create liquid steel (also known as the BF-BOF production route).[67] Blast furnaces are responsible for most of the CO2 emissions in the steelmaking process due to the use of coke (coal).[10] Electric arc furnaces (see page 17) can be used in place of basic oxygen furnaces, which can result in reduced atmospheric, resource, and toxicity impacts, as seen in the case study below (values can vary between plants, and can be dependent on other processes in the plant).[68] The blast furnace is the most strenuous and harmful process within a steel mill, with the highest average energy consumption and CO2, methane (CH4), and carbon monoxide (CO) emissions in the integrated steel mill process.[55] EAFs, while energy intensive, can consume less energy, reduce pollutant release, and utilize more scrap steel than the BF-BOF route.[55, 68, 69]

Impacts of BOF vs EAF steelmaking per tonne of crude steel (case study)[68]

Impacts	BOF	EAF
Atmospheric Impacts		
CO2 emissions	17.03 kg	7.66 kg
Photochemical oxidant formation (e.g. ozone, NOx)	4.89 kg	1.39 kg
Particulate matter formation (e.g. PM2.5, PM10)	4.61 kg	0.78 kg
Resource Depletion		
Terrestrial acidification (SO2)	4.81 kg	2.48 kg
Freshwater eutrophication (phosphorous)	0.81 kg	0.46 kg
Marine eutrophication (nitrogen)	0.3 kg	0.14 kg
Metal depletion (iron)	850 kg	13 kg
Fossil fuel depletion (oil)	529 kg	143 kg
Toxicity Impacts (1,4-DB eq)		
Human toxicity	643 kg	347 kg
Terrestrial ecotoxicity	0.17 kg	0.06 kg
Freshwater ecotoxicity	12.77 kg	6.96 kg
Marine ecotoxicity	13.32 kg	7.1 kg

Transitioning away from BF-BOF plants will be necessary to reach net-zero or reduced-emissions steel. However, given the long lifespans of blast furnaces, coke ovens, and basic oxygen furnaces, companies may be hesitant to decommission functioning plants. As well, the transition to DRI-EAF plants can take years, and thus steelmakers should aim to improve the efficiency and minimize the impacts of BF-BOF production routes in the meantime. Examples include using coke/biomass mixes to reduce CO2 emissions, maximizing iron content in pellets to decrease the amount of coke needed, using pulverized coal injection (PCI), natural gas, or hydrogen as an additional reagent, utilizing renewable energy where possible, etc.[5]

PATHS TO A GREENER STEEL CITY
DIRECT REDUCED IRON



In traditional integrated steel mills, iron ore, coke, and limestone are added to a blast furnace at high temperatures. The carbon monoxide produced from the coke reacts with the oxygen in the iron ore, producing pig iron (crude iron) and carbon dioxide.[70] Blast furnaces are the primary source of emissions in the steelmaking process, and this process is incredibly difficult to decarbonize.[5] An alternative to the blast furnace is direct reduced iron (DRI), where the oxygen is removed from iron ore below iron's melting point, creating solid sponge iron that is subsequently fed into an electric arc furnace.[71] Both hydrogen and carbon can be used as a reductant to remove the oxygen from iron ore. In DRI, the reductant is either natural gas (CH4) or green hydrogen (H2); the former produces carbon dioxide and water as by-products, while the latter only produces water.[72] DRI is a more energy-efficient process than a blast furnace, and can reduce or eliminate CO2 emissions (depending on the reductant).[39] DRI does require a higher iron content in the ore than blast furnaces, which must be taken into consideration when switching to this technology. A carbon source is still required in the EAF due to the carbon content of steel,[58] however, this can be sourced from more sustainable means than coke (e.g., biomass).The DRI-EAF production route is one of the most promising alternatives to BF-BOF production in terms of energy efficiency, scalability, and reduced environmental impact.[5]

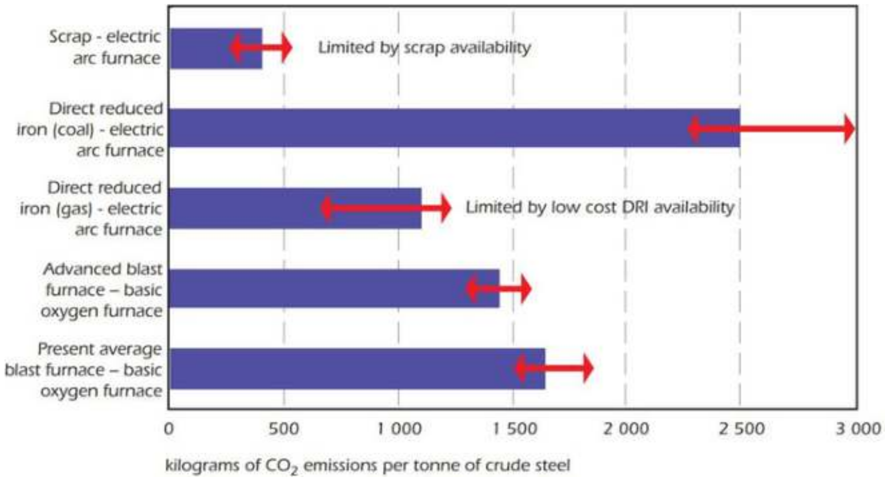
Hydrogen-direct reduction is still in its early stages, but natural gas DRI is already being used on an industrial-scale. ArcelorMittal's Contrecoeur plant is the first steelmaking facility in Canada, and one of four plants in the world, that uses DRI made in on-site DRI plants in its steelmaking processes.[73] DRI plants reduce the need for coal through the use of natural gases or hydrogen, which subsequently reduces emissions.[74] ArcelorMittal Dofasco in Hamilton will be building a DRI plant by 2028 that uses natural gas but will be 'hydrogen-ready' when green hydrogen technology becomes readily available.[75]

PATHS TO A GREENER STEEL CITY

ELECTRIC ARC FURNACES (EAF)

An electric arc furnace (EAF) produces liquid steel through melting of pig iron (end-product of a blast furnace), scrap steel, and/or direct reduced iron using electricity, and is the main alternative to the traditional integrated steel mill (BF-BOF) production route.[76] An EAF can be used in conjunction with a blast furnace (BF-EAF), or with direct reduced iron (DRI-EAF production route). The DRI-EAF production route can be a virtually zero-emission process if the energy used for the EAF is renewable, and green hydrogen is used as the DRI reductant.[5] As shown below, CO2 emissions can vary greatly depending on the other steps used in the EAF production route.[10]

CO2 emissions per ton of crude steel produced via various technologies[10]



EAFs are becoming increasingly competitive in terms of quality, cost, and energy use.[77] The proportion of steel made in an EAF worldwide is approximately 25%, with 75% made in an integrated steel mill.[51] The proportion of Canadian steel made in an EAF was 47% in 2017, compared to 41% in 2010 and 36% in 1993.[78] In the US, EAFs account for nearly two-thirds of all steel produced.[79] The difference in EAF use is largely dependent on scrap availability, energy costs and production costs.[51] EAFs will play an important role in reducing emissions, but its efficacy is dependent on the source of electricity and the ironmaking process (DRI, blast furnace, etc.)

Dofasco currently has one electric arc furnace, and recently received a $400 million federal investment to switch to a DRI-EAF production route (see page 24). Algoma Steel recently received a similar $420 million federal investment to transition to EAF use.[51]

PATHS TO A GREENER STEEL CITY
GREEN HYDROGEN

There are several 'types' of hydrogen, such as blue, green, and grey hydrogen, which are the same final product reached via different production methods. Green hydrogen is the only carbon-neutral and fossil-free type of hydrogen, as it is produced using renewable energy.[5]

<u>Green hydrogen</u>: produced via electrolysis of water using renewable energy
<u>Blue hydrogen</u>: produced by splitting natural gas into hydrogen and CO2 (which is captured and stored)
<u>Grey hydrogen</u>: produced by splitting natural gas into hydrogen and CO2 (which is released into the atmosphere)

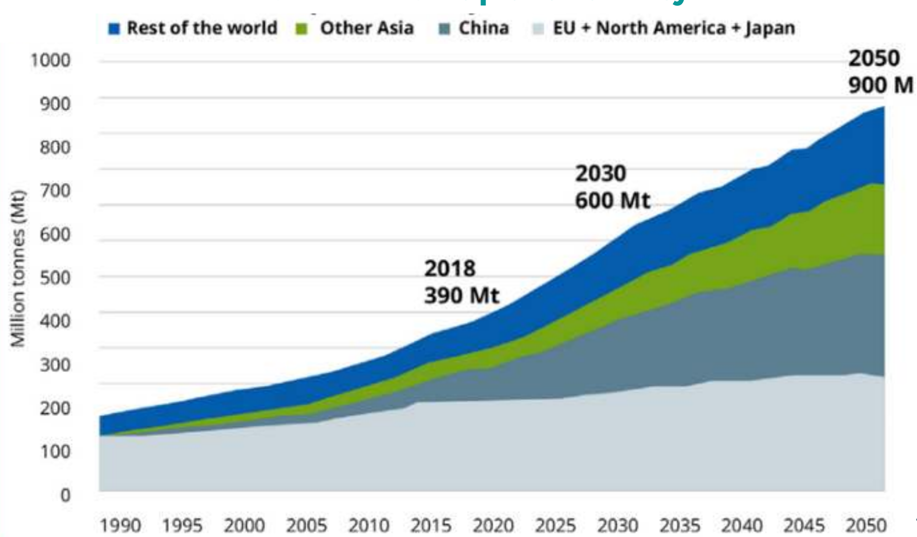
Green hydrogen can be used in two primary ways in the steelmaking process: as an alternative to pulverized coal injection (PCI), or as an alternative reductant to make direct reduced iron (DRI).[5] Pulverized coal injection is a process used to improve the performance of blast furnaces and speed up the production of liquid iron, which can reduce energy use, emissions, and the amount of coke required in the blast furnace.[80] Using hydrogen in place of PCI can reduce emissions by 20%, however, using hydrogen in this capacity alone cannot eliminate emissions due to the use of coke as a reductant. Hydrogen can also be used in place of coke as a reducing agent, which produces water as a byproduct rather than carbon dioxide.[81] Green hydrogen produced using renewable energy and used as the reductant in the DRI-EAF process could produce virtually fossil-free steel.[5]

Several barriers remain in the implementation of green hydrogen. One of the primary barriers is the cost of green hydrogen compared to coal and natural gas. In order for green hydrogen to surpass coke use, either a decrease in green hydrogen costs or implementation of carbon pricing would be required. Renewable energy capacity would need to be increased in order to power the electrolyzers, though energy use decreases as the percentage of scrap metal used increases.[39] Storage of green hydrogen must also be considered due to natural fluctuations in solar and wind energy generation. HYBRIT in Sweden[82] and H2Store in Australia[83] are both working on storage solutions, with the latter using sodium borohydride - a salt-like material that can absorb and release hydrogen as needed.

PATHS TO A GREENER STEEL CITY
SCRAP STEEL

Steel is the most recycled material in the world due to the lack of quality loss when recycling, and inherent magnetism which allows for easy separation in recycling facilities.[84] Currently, 650 million tonnes of scrap steel is recycled each year, and 30% of total metallic input in steelmaking is scrap steel (the other 70% being iron ore).[1] Unlike the flexible nature of iron ore supply and demand, scrap steel supply is dependent on past steel demand and when steel products reach their end of life. There was approximately 400 million tonnes of scrap steel available for re-use in 2019, compared to the 1.86 billion tonnes of steel produced.[84] By 2050, global demand for steel could be upwards of 2.5 billion tonnes per year,[1] while scrap steel availability is projected to be around 900 million tonnes.[84]

End-of-life scrap availability[84]



It is possible that with a rise in electric arc furnace use and continual increase in global steel production, there could be an even greater disparity between steel scrap supply and demand. Implementing stronger recycling regulations, or designing products with reuse and remanufacturing in mind could help secure a more reliable stream of scrap steel. However, scrap steel should not be relied upon completely. Iron ore mining and sintering will have to become more sustainable practices to meet global steel demand in an environmentally conscious manner.

PATHS TO A GREENER STEEL CITY
FINISHING & PRODUCT USE

Once the liquid steel has been produced, it undergoes a casting and finishing process to create the final steel product. The environmental impact from casting and finishing is minimal compared to the ironmaking and steelmaking processes, however, there are ways to make these processes more efficient. Steel can either be hot rolled or cold rolled. The hot rolling process requires the steel slabs to be reheated to 1200 degrees Celsius, often resulting in direct or indirect CO2 emissions (unless renewable energy is used).[85] One strategy that has been implemented by ArcelorMittal is re-using the gas from the blast furnaces to re-heat the slabs rather than using natural gas.[86]

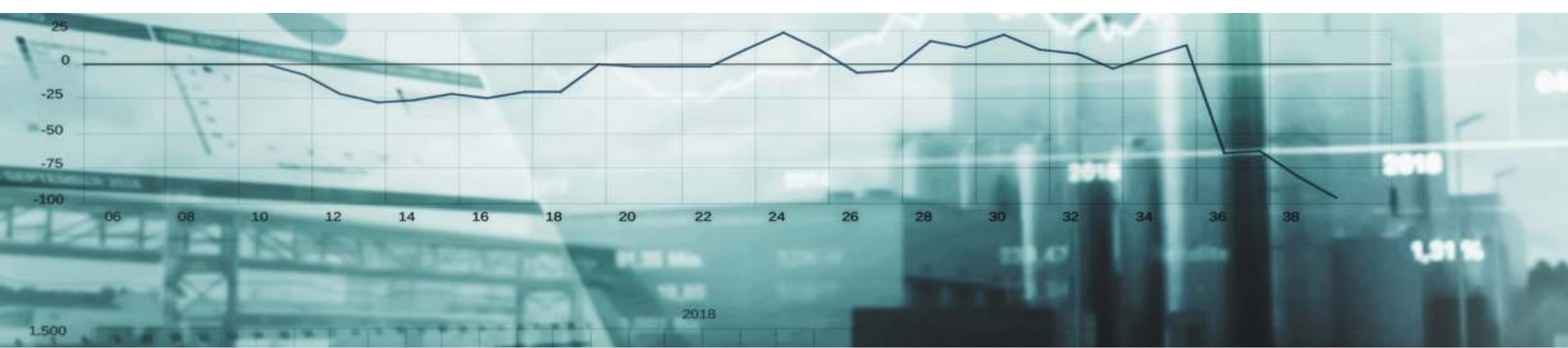
Finally, the steel undergoes one of many finishing processes, such as annealing, galvanizing, coating, etc. depending on the final product.[85] There is room for improvements in efficiency and reducing emissions, though these processes have minimal emissions contributions compared to ironmaking and steelmaking. For example, the ArcelorMittal Kessales plant in Belgium implemented a Jet Vapour Deposition line to coat steel with zinc in a process that has the "lowest global warming potential of any steel coating process."[86]

Steel is a vital part of the green transition and circular economy. Improvements in steel production and innovation can create lightweight, stronger electric vehicles, longer-lasting solar panels and wind turbines, and energy-efficient buildings with longer lifespans. Going forward, these products should be designed with re-use and recyclability in mind to make the steel recycling process more efficient and increase scrap supply.

IS A GREENER STEEL CITY POSSIBLE?
ECONOMIC FEASIBILITY

The transition to green steel provides many economic opportunities, but will not be possible without significant investments from companies and governments. ArcelorMittal estimates that reaching net-zero steel by 2050 in its European facilities would cost up to €40 billion.[87] Many of the current environmental initiatives were funded partially by federal investments: ArcelorMittal Sestao (€1 billion investment from Spanish government),[34] Algoma Steel ($420 million from Canadian government),[30] HYBRIT (51.3 million from Swedish Energy Agency),[88] and ArcelorMittal Dofasco ($400 million from Canadian government).[79] Many of these projects also include significant investments from the steel companies themselves. Additional measures should also be considered by federal governments to protect domestic steel production during these periods of significant economic investment, such as carbon border adjustments or tariffs on foreign steel.[26,89]

There are additional financial barriers to implementing certain green technologies. While the price of green hydrogen is expected to decrease by 50% over the next decade,[5] green hydrogen is not cost-competitive with natural gas or coal in many areas of of the world. One estimate is that green hydrogen would be economically viable with a carbon price set at $220/tonne,[90] while another predicts that hydrogen direct reduction can become viable at a carbon price of €34-68 ($50-100 CAD) and electricity costs of €40/MWh (~$60/MWh CAD).[39] To aid in the transition to net-zero steel, the federal government should determine the economic viability threshold for green hydrogen and set the carbon price accordingly, and continue to increase the availability and capacity of low-cost renewable energy sources. Overall, the transition to net-zero steel is economically viable with collaboration between federal (and provincial) governments and companies.



IS A GREENER STEEL CITY POSSIBLE?
TECHNOLOGICAL FEASIBILITY

CO2 reduction strategies[5]

Technology	Strategy	Current Outlook
BF and BOF efficiency	Make infrastructure upgrades and improvements to optimize operations	Technology readily available at competitive cost
Biomass as a reductant	Use biomass (wood chips, agricultural waste, etc.) as the reductant in place of coke	Technology readily available in areas with adequate biomass availability
Carbon capture, utilization, and storage (CCUS)	Capture CO2 emissions and recycle for other uses	Not currently available on an industrial scale, technologically premature and yet to be proven economically

Full decarbonization strategies [5]

Technology	Strategy	Current Outlook
Electric arc furnace (EAF) - scrap	Utilize and recycle more scrap steel in EAF	Technology readily available at competitive cost
DRI-EAF (natural gas)	Increased used of direct reduced iron in EAF instead of iron reduced in a blast furnace using coke	Technology readily available
DRI-EAF (hydrogen)	Replace fossil fuels (coal, natural gas) with renewable energy and hydrogen as the reductant	Technology available at a high cost

In 2020, McKinsey & Company outlined the current outlook of various CO2 reduction and full decarbonization strategies in the steel industry.[5] With the exception of carbon capture and usage (which has been widely contested as a viable practice in general), all of these strategies are readily available from a technology standpoint. Many of these strategies (BF/BOF efficiency, biomass, EAF) are already in use for many companies, or do not require major infrastructural upgrades. For example, ArcelorMittal Dofasco already has an operational EAF, and has been running an industrial-scale trial of biomass as a reductant.[19]

The technology needed to reach net-zero steel is within reach. Electric arc furnaces are already used across the world, often in conjunction with blast furnaces, though the DRI-EAF production method is becoming more common due to technological improvements and availability of renewable energy.[5] Most DRI plants currently use natural gas, but a net-zero process would require a reductant such as green hydrogen. The electrolyzer technology needed to produce green hydrogen is mature and can easily be scaled to create industrial-level quantities.[39] Storage of green hydrogen remains one of the primary technical barriers, especially when the electrolyzer is powered by variable renewable energy sources such as solar and wind. Companies like HYBRIT and H2Store hope to remove this technological barrier to improve the feasibility of widespread green hydrogen.[82,83] Carbon capture, utilization, and storage is discussed frequently in the transition to greener steel, however, there are growing concerns regarding its technological and economic feasibility,[91,92,93] and would not be necessary in a fossil-free green hydrogen DRI-EAF approach.

IS A GREENER STEEL CITY POSSIBLE?
SUMMARY

The goal to reach net-zero steel by 2050 is shared by many groups, such as the Canadian Steel Producers Association,[26] International Energy Agency,[94] and US Steel,[95] which is in line with the IPCC recommendation of a net-zero economy by 2050.[96] However, the IPCC also states that CO2 emissions must drastically decrease "well before 2030", reaching emission reductions around 45% by 2030.[97] Given that steel accounts for 7% of global emissions,[5] governments and the steel industry must be taking emission-reducing actions immediately while continuing to strive for the net-zero by 2050 goal.

Potential short term actions (few technological or economic barriers)

- Using coke/biomass mixtures, or switching to biomass completely if there is adequate local supply
- Implementation of carbon pricing and carbon border adjustments
- Sourcing more sustainable iron ore with higher iron content (to reduce energy consumption)
- Use of fuel injection (PCI, hydrogen, biomass, natural gas, etc.)
- Increased percentage of scrap metal used in BOF or EAF

Potential longer term actions (needs investments and technology upgrades)

- Transitioning away from BF-BOF, switching to DRI-EAF (directly to hydrogen DRI or building natural gas DRI plants that are 'hydrogen-ready')
- Increased capacity and use of low-cost, renewable energy
- Implementation of electrolyzer-produced green hydrogen as a reductant
- Fossil-free iron ore mining (see LKAB and HYBRIT)
- Designing steel products for re-use and recycling

There is no one single technology or initiative that can result in net-zero or fossil-free steel. The steelmaking process is complex, and environmental impacts across the entire supply chain must be addressed. These solutions are becoming increasingly viable at an industrial-scale, and actions must be taken as soon as possible to reduce the steel industry's immense carbon emissions.

WHAT'S NEXT FOR HAMILTON?

On July 30th, 2021, the federal government announced a $400 million investment to support ArcelorMittal Dofasco's transition to greener steelmaking processes.[98] This $1.765 billion project will transition the integrated steel mill to the DRI-EAF production route by 2028, resulting in the decommissioning of the blast furnaces and coke making facilities. ArcelorMittal Dofasco will be the "world's first producer to transition to a hydrogen-ready, direct reduced iron–fed electric arc furnace at this scale for the development of advanced steels that serve the automotive, medical and consumer packaging industries."[75] The direct reduction of iron will initially use natural gas as the reductant, but the plant is being built so that it is "hydrogen-ready", and can transition to green hydrogen once it is economically and technologically feasible to do so. This project will reduce CO2 emissions by 60%, or 3 million tonnes per year by 2028, and will create 2500 jobs during the engineering and construction process.[98] The transition to green hydrogen following this project, assuming renewable energy is used for hydrogen production, would allow Dofasco to create virtually net-zero steel. ArcelorMittal Dofasco will be researching other emission-reduction technologies, such as green hydrogen, biocarbon, and carbon capture, utilization and storage. This announcement is incredibly promising, and brings Hamilton within reach of producing net-zero steel by 2050.

SOURCES

1 International Energy Agency. (2020). *Iron and Steel Technology Roadmap*.
ArcelorMittal Dofasco. (2014, March 20). How steel is made at ArcelorMittal Dofasco [Video]. YouTube. https://www.youtube.com/watch?v=lzUygLWhn_Y

2 U.S. Energy Information Administration. (Updated 2021, June 1). *How much carbon dioxide is produced when different fuels are burned?* https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

3 World Steel Association. (2021, April). *Steel and raw materials*. https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact_raw+materials_2018.pdf

4 Hoffmann, C., Van Hoey, M., & Zeumer, B. (2020, June 3). *Decarbonization challenge for steel*. McKinsey and Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel#

5 Van Caneghem, J., Block, C., Cramm, C., Mortier, R., & Vandecasteele, C. (2010) Improving eco-efficiency in the steel industry: The ArcelorMittal Gent case. *Journal of Cleaner Production*. 18(8), 807-814. https://doi.org/10.1016/j.jclepro.2009.12.016

6 ArcelorMittal. (Updated 2021). *Steel is the power behind renewable energy*. https://corporate.arcelormittal.com/media/case-studies/steel-is-the-power-behind-renewable-energy

7 World Steel Association. (2009, September). *The three Rs of sustainable steel.* https://www.mbma.com/media/WorldSteelAssociation.pdf

8 World Steel Association. (2008, October). *2008 Sustainability Report*. https://www.worldsteel.org/en/dam/jcr:e6f75b6a-5c2a-4690-94f8-72f82bb674a0/2008.pdf

9 Nidheesh, P. V., & Kumar, M. S. (2019). An overview of environmental sustainability in cement and steel production. *Journal of Cleaner Production*, 231, 856-871.

10 Adhikari, M., Ghimire, L. P., Kim, Y., Aryal, P., & Khadka, S. B. Identification and Analysis of Barriers against Electric Vehicle Use. *Sustainability,* 12(12), 4850. https://doi.org/10.3390/su12124850

11 The Hamilton Spectator. (Updated 2020, February). *Hamilton's steel industry from birth, to boom and beyond*. https://www.thespec.com/news/hamilton-region/2012/02/11/hamilton-s-steel-industry-from-birth-to-boom-and-beyond.html

12 Stelco. (Updated 2021). *Our Facilities*. https://www.stelco.com/about-us/our-facilities

13 Rubin, J. (2021, March 6). The Faceoff: Steel prices are taking off and Stelco is on a tear – but rival Dofasco still dominates the auto market. *The Toronto Star.* https://www.thestar.com/business/2021/03/06/the-faceoff-stelco-is-closing-the-gap-but-rival-steelmaker-dofasco-still-dominates-crucial-auto-market.html

14 Stelco. (2017, July). *Environmental Policy*. https://www.stelco.com/sites/default/files/2018-07/STELCO_ENV_POLICY_2017.pdf

15 Ellmen, E. (Updated 2021, March 14). Climate change and steel in Hamilton. *The Hamilton Spectator*. https://www.thespec.com/opinion/contributors/2021/03/13/climate-change-and-steel-in-hamilton.html
16 ArcelorMittal. (Updated 2021). *At a Glance*. https://dofasco.arcelormittal.com/who-we-are/at-a-glance/about-dofasco.aspx
17 ArcelorMittal. (Updated 2021). *Our 10 outcomes*. https://canada.arcelormittal.com/en/sustainability/our-10-outcomes
18 ArcelorMittal. (2015). *Sustainable Development Report 2015*. https://canada.arcelormittal.com/~/media/Files/A/Arcelormittal-CA/canada-files/signpost-pdf/corporate-responsibility-report-2015.pdf
19 Ellmen, E. (2021, July 5). Can Steel Town clean up its act?. *Corporate Knights*. https://www.corporateknights.com/channels/climate-and-carbon/can-steel-town-clean-up-its-act-16254810/
20 Worldsteel. (2021). *Steel Statistics*. https://www.worldsteel.org/steel-by-topic/statistics.html
21 Canadian Steel Producers Association. (2021). *Manufacturing*. https://canadiansteel.ca/manufacturing
22 International Trade Administration. (2020, May). *Steel Imports Report: Canada*. https://legacy.trade.gov/steel/countries/pdfs/imports-Canada.pdf
23 Hasanbeigi, A., Springer C. (2019, November). *How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO2 Intensities*. Belfer Center. https://www.belfercenter.org/publication/how-clean-us-steel-industry-international-benchmarking-energy-and-co2-intensities
24 Ritchie, H. & Roser, M. *Renewable Energy*. Our World in Data. https://ourworldindata.org/renewable-energy
25 Canadian Steel Producers Assocation. (2019). *Canada's Steel Industry: A Sustainable Choice*. https://canadiansteel.ca/files/resources/CSPA_Climate_Final.pdf
26 Hamilton Industrial Environmental Association. (2021, April). *Recording of Spring 2021 Public Meeting*. http://www.hiea.org/community/presentations.aspx
27 CHAR Technologies Limited. (2018, October 22). *CHAR commissions biocarbon production facility*. https://www.canadianbiomassmagazine.ca/char-commissions-biocarbon-production-facility-7084/
28 Stelco Holdings Inc. (2020, June 18). *Stelco Announces Entering into of Energy Services Agreement with DTE Energy Services, Inc*. https://www.newswire.ca/news-releases/stelco-announces-entering-into-of-energy-services-agreement-with-dte-energy-services-inc--816636227.html
29 Algoma Steel Inc. (2021, July 5). *Government of Canada Endorses Algoma Steel's Transformation Plan for Green Steel*. https://www.newswire.ca/news-releases/government-of-canada-endorses-algoma-steel-s-transformation-plan-for-green-steel-875175226.html
30 Helwig, D. (2021, July 25). Algoma Steel digs into the details on upgrading to electric arc furnaces. *Northern Ontario Business*. https://www.northernontariobusiness.com/industry-news/technology/algoma-stee-digs-into-the-details-on-upgrading-to-electric-arc-furnaces-3984880

31 World Steel Association. (Updated 2021). *Economic and social impact of the steel industry*. https://www.worldsteel.org/steel-by-topic/statistics/steel-industry-economic-impact.html
32 ArcelorMittal. (Updated 2021). *Hydrogen-based steelmaking to begin in Hamburg*. https://corporate.arcelormittal.com/media/case-studies/hydrogen-based-steelmaking-to-begin-in-hamburg
33 ArcelorMittal. (2021, July 13). *ArcelorMittal Sestao to become the world's first full-scale zero carbon-emissions[1] steel plant*. https://corporate.arcelormittal.com/media/press-releases/arcelormittal-sestao-to-become-the-world-s-first-full-scale-zero-carbon-emissions-steel-plant
34 Vattenfall. (2020, October 27). HYBRIT - Episode 2: Research [Video]. YouTube. https://www.youtube.com/watch?v=wWH_DYQALhQ
35 Automotive World. (2020, August 5). *HYBRIT: Successful trials using fossil-free fuels in the pellet process*. https://www.automotiveworld.com/news-releases/hybrit-successful-trials-using-fossil-free-fuels-in-the-pellet-process/
36 Hybrit. (Updated 2021). *A fossil-free future*. https://www.hybritdevelopment.se/en/a-fossil-free-future/
37 Sun, W., Xu, X., Lv, Z., Mao, H., & Wu, J. (2019). Environmental impact assessment of wastewater discharge with multi-pollutants from iron and steel industry. *Journal of Environmental Management*. 245, 210-215. https://doi.org/10.1016/j.jenvman.2019.05.081
38 Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, 203, 736-745.
39 Nieto, V. (2019, September 18). Steel production: from iron ore to functional industrial products. *Vepica*. https://www.vepica.com/blog/steel-production-from-iron-ore-to-functional-industrial-products
40 Mining Engineering. (2017). *Global iron ore production data; Clarification of reporting from the USGS*. https://www.usgs.gov/media/files/global-iron-ore-production-data-clarification-reporting-usgs
41 Gleekia, A., Pradhan, D., & Sahu, H. (2016). Impacts of Iron Ore Mining on Water Quality and the Environment in Liberia. *In 6th Asian Mining Congress*. pp. 371-380. Kolkata, India: The Mining Geological and Metallurgical Institute of India (MGMI).
42 The Canadian Press. (2020, May 1). *Stelco signs 8-year deal with U.S. Steel to buy iron ore pellets from mine*. Canadian Broadcasting Corporation. https://www.cbc.ca/news/canada/hamilton/stelco-iron-ore-1.5551925
43 Stelco. (Updated 2021). *Stelco Announces Option to Acquire 25% Interest in Minntac, the Largest Iron Ore Mine in the United States, and Entry into Long-Term Extension of Pellet Supply Agreement with U.S. Steel*. https://investors.stelco.com/2020-04-30-Stelco-Announces-Option-to-Acquire-25-Interest-in-Minntac-the-Largest-Iron-Ore-Mine-in-the-United-States-and-Entry-into-Long-Term-Extension-of-Pellet-Supply-Agreement-with-U-S-Steel
44 WaterLegacy. (Updated 2020). *Minntac Tailings Basin*. https://waterlegacy.org/minntac-water-pollution/
45 The Associated Press. (2021, February 10). *Minnesota Supreme Court deals blow to Minntac iron mine*. https://apnews.com/article/north-america-minnesota-environment-courts-water-pollution-0b9abe274f291388c5ff5a31e5fc9c3c

46 Lovrien , J. (February 10, 2021). Court: Regulators were correct in applying drinking water standards to groundwater in Minntac permit. *Duluth News Tribune and Forum Communications Company*. https://www.duluthnewstribune.com/business/ energy-and-mining/6879870-Court-Regulators-were-correct-in-applying-drinking-water-standards-to-groundwater-in-Minntac-permit
47 ArcelorMittal. (Updated 2021). *What we do*. https://canada.arcelormittal.com/en/arcelormittal-in canada/what-we-do
48 Towards Sustainable Mining. (2019). *2018 Progress Report*. https://mining.ca/wp-content/uploads/2019/02/Progress-Report-2018-English-Final.pdf
49 Nussey, B. (2019, June 23). What can you do with a megawatt-hour? https://www.freeingenergy.com/what-is-a-megawatt-hour-of-electricity-and-what-can-you-do-with-it/
50 Baker Institute. (2020, May 15). *Steel, Hydrogen And Renewables: Strange Bedfellows? Maybe Not…* https://www.forbes.com/sites/thebakersinstitute/2020/05/15/steel-hydrogen-and-renewables-strange-bedfellows-maybe-not/
51 Ritchie, H., & Roser, M. *Renewable Energy*. https://ourworldindata.org/renewable-energy
52 Encyclopaedia Britannica. *Carbonization (cokemaking)*. https://www.britannica.com/topic/coal-utilization-122944/Carbonization-coke-making
53 Renzulli, P. A., Notarnicola, B., Tassielli, G., Arcese, G., & Di Capua, R. (2016). Life cycle assessment of steel produced in an Italian integrated steel mill. *Sustainability, 8*(8), 719.
54 Hu, J. Y., Gao, F., Wang, Z. H., & Gong, X. Z. (2014). Life cycle assessment of steel production. In Materials Science Forum (Vol. 787, pp. 102-105). Trans Tech Publications Ltd
55 Hamilton Spectator. (2020, March 1). *Province pitches new pollution standards for Hamilton*. https://www.thespec.com/news/hamilton-region/2017/11/15/province-pitches-new-pollution-standards-for-hamilton.html
56 Babich, A., & Senk, D. (2013). Coal use in iron and steel metallurgy. In *The coal handbook: towards cleaner production* (pp. 267-311). Woodhead Publishing.
57 McHone Industries, Incorporated. (2020, June 3). *A Guide to Carbon Steel Grades*. https://blog.mchoneind.com/blog/carbon-steel-grades-chart
58 Just Have a Think. (2020, December 13). Fossil free steel. Another giant step towards net carbon zero? [Video]. *YouTube*. https://www.youtube.com/watch?v=ywHJt88H5YQ
59 Norgate, T., Haque, N., Somerville, M., & Jahanshahi, J. (2012). Biomass as a Source of Renewable Carbon for Iron and Steelmaking. *ISIJ International*. 52(8), 1472-1481
60 Mousa, E., Wang, C., Riesbeck, J., & Larssona, M. (2016). Biomass applications in iron and steel industry: An overview of challenges and opportunities. *Renewable and Sustainable Energy Reviews. 65,* 1247-1266. https://doi.org/10.1016/j.rser.2016.07.061
61 Plastics Europe. (2019). *Plastics – The Facts*. https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf
62 Devasahayam, S., B haskar Raju, G., & Mustansar Hussain, C. (2019). Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry. *Materials Science for Energy Technologies*. https://doi.org/10.1016/j.mset.2019.08.002

63 Verma, R., Vinoda K.S., Papireddy, M., Gowda, A.N.S. (2016). Toxic Pollutants from Plastic Waste- A Review. *Procedia Environmental Sciences*. 35, 701-708. https://doi.org/10.1016/J.PROENV.2016.07.069
64 Alabi, O.A., Ologbonjaye, K.I., Awosolu, O., Alalade, O.E. (2019). Public and Environmental Health Effects of Plastic Wastes Disposal: A Review. *Journal of Toxicology and Risk Assessment*. 5(2). https://doi.org/10.23937/2572-4061.1510021
65 Trinkel, V., Kieberger, N., Bürgler, T., Rechberger, H., & Fellner, J. (2015). Influence of waste plastic utilisation in blast furnace on heavy metal emissions. Journal of Cleaner Production, 94, 312-320.
66 Ágnes, N., & Rajmund, K. U. T. I. (2016). The environmental impact of plastic waste incineration. AARMS–Academic and Applied Research in Military and Public Management Science, 15(3), 231-237.
67 International Energy Agency. (2013, July). *Iron and Steel CCS study (techno-economics steel mill).* https://ieaghg.org/docs/General_Docs/Reports/2013-04.pdf
68 Burchart-Korol, D. (2013). Life cycle assessment of steel production in Poland: a case study. Journal of cleaner production, 54, 235-243.
69 Martelaro, N. (2016, December 4). *Energy Use in US Steel* Manufacturing. http://large.stanford.edu/courses/2016/ph240/martelaro1/
70 Hu, J. Y., Gao, F., Wang, Z. H., & Gong, X. Z. (2014). Life cycle assessment of steel production. In Materials Science Forum (Vol. 787, pp. 102-105). Trans Tech Publications Ltd
71 Encyclopaedia Britannica. (last updated 2016). *Blast Furnace.* https://www.britannica.com/technology/blast-furnace
72 Science Direct. *Sponge Iron – An Overview.* https://www.sciencedirect.com/topics/engineering/sponge-iron
73 Midrex. (2018, April 12). *The Midrex Process.* https://www.midrex.com/wp-content/uploads/MIdrex_Process_Brochure_4-12-18.pdf
74 ArcelorMittal. (2013, September 26). *A Dream That Became Reality: Employees and Retirees Celebrate the 40th Anniversary of the ArcelorMittal Reduction Plant in Contrecoeur.* https://long-canada.arcelormittal.com/en/news-media/dream-became-reality-employees-and-retirees-celebrate-40th-anniversary-arcelormittal/
75 Encyclopedia of Energy. (2004). *Direct Reduced Iron*. https://www.sciencedirect.com/topics/engineering/direct-reduced-iron
76 Government of Canada. (2021, July 30). *Government investing in Hamilton's steel industry to support good jobs and significantly reduce emissions*. https://www.canada.ca/en/innovation-science-economic-development/news/2021/07/government-investing-in-hamiltons-steel-industry-to-support-good-jobs-and-significantly-reduce-emissions.html
77 Greenspec. *Steel Production and Environmental Impact.* https://www.greenspec.co.uk/building-design/steel-products-and-environmental-impact/
78 Cavaliere, P. (2019). Electric Arc Furnace: Most Efficient Technologies for Greenhouse Emissions Abatement. In Clean Ironmaking and Steelmaking Processes (pp. 303-375). Springer, Cham.
79 Hites, B.E. (2016, June 10). *North of the Border: The Future of Canadian Steelmaking*. https://cari-acir.org/wp-content/uploads/2016/07/Hites-Presentation-CARI-2016.pdf

80 American Iron and Steel Institute. *Steel Production*. https://www.steel.org/steel-technology/steel-production/
81 The Institute for Industrial Productivity. (2012, May). *Pulverized Coal Injection*. http://www.iipinetwork.org/wp-content/Ietd/content/pulverized-coal-injection.html
82 Homann, Q. (2019, November 25). Hydrogen as a Clean Alternative in the Iron and Steel Industry. *Fuel Cell and Hydrogen energy Association*. https://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry
83 Svenskt Stål AB. (2021, April 7). *HYBRIT: SSAB, LKAB and Vattenfall building unique pilot project in Luleå for large-scale hydrogen storage investing a quarter of a billion Swedish kronor*. https://www.ssab.com/news/2021/04/hybrit-ssab-lkab-and-vattenfall-building-unique-pilot-project-in-lule-for-largescale-hydrogen-storag
84 Collins, L. (Updated 2020 March 11). World first for solid-state green hydrogen at hybrid solar project. *Recharge*. https://www.rechargenews.com/transition/world-first-for-solid-state-green-hydrogen-at-hybrid-solar-project/2-1-771319
85 World Steel Association. (2021, May). *Scrap use in the steel industry*. https://www.worldsteel.org/en/dam/jcr:2a96b408-325e-4691-ae50-10c43c3a90fd/scrap_vf.pdf.
86 ArcelorMittal. *Making Steel*. https://corporate.arcelormittal.com/about-us/making-steel?backToSlide=true
87 ArcelorMittal. *What's being done to make steel finishing more sustainable?* https://corporate.arcelormittal.com/about-us/making-steel/what-s-being-done-to-make-steel-finishing-more-sustainable-finishing
88 Russell, C. (2020, July 9). *ArcelorMittal's Path to Carbon Neutrality*. https://www.massifcap.com/content-library/2020/7/9/arcelormittals-path
89 BioEnergy International. (2018, June 18). *Swedish Energy Agency awards record funding to HYBRIT*.https://bioenergyinternational.com/research-development/swedish-energy-agency-awards-record-funding-to-hybrit
90 Taylor, K. (2021, June 3). LEAK: EU's carbon border tariff to target steel, cement, power. https://www.euractiv.com/section/energy- environment/news/eus-carbon-border-tariff-to-target-steel-cement-power/
91 Pooler, M. (2021, February 15). 'Green steel': the race to clean up one of the world's dirtiest industries. *The Financial Times*. https://www.ft.com/content/46d4727c-761d-43ee-8084-ee46edba491a
92 Canadian Broadcasting Corporation. (2021, January 15). *How carbon capture technology can add to the emissions problem*. https://www.cbc.ca/news/science/what-on-earth-carbon-capture-enhanced-oil-recovery-1.5873431
93 Sekera, J., & Lichtenberger, A. (2020). Assessing Carbon Capture: Public Policy, Science, and Societal Need. *Biophysical Economics and Sustainability*, 5(3), 1-28.
94 Drugmand, C., & Muffett, C. (2021, April 22). Confronting the myth of carbon-free fossil fuels: Why carbon capture is not a climate solution. *Environmental Working Group*. https://www.ewg.org/news-insights/news/confronting-myth-carbon-free-fossil-fuels-why-carbon-capture-not-climate
95 International Energy Agency. (2021, May). *Net Zero by 2050*. https://www.iea.org/reports/net-zero-by-2050

96 Coyne, J. (2021, April 21). US Steel aims to achieve net-zero emissions by 2050. *S&P Global Platts*. https://www.spglobal.com/platts/en/market-insights/latest-news/coal/042121-us-steel-aims-to-achieve-net-zero-emissions-by-2050
97 Intergovernmental Panel on Climate Change. (2018, October 8). *Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments*. https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/
98 Berwyn, B. (2019, August 27). What Does '12 Years to Act on Climate Change' (Now 11 Years) Really Mean?. *Inside Climate News*. https://insideclimatenews.org/news/27082019/12-years-climate-change- explained-ipcc-science-solutions/
99 Peesker, S. (2021, July 30). ArcelorMittal Dofasco getting $400M from Ottawa to cut greenhouse gas emissions. https://www.cbc.ca/news/canada/hamilton/dofasco-investment-1.6123829

ABOUT ENVIRONMENT HAMILTON

Environment Hamilton (EH) is a community-focused non-profit that was incorporated in 2001 to help Hamiltonians develop the knowledge and skills they need to protect and enhance the environment around them. EH is working towards a city that is a carbon-neutral community with secure local food sources, sustainable transportation, and healthy, clean air, water, and land. Environment Hamilton inspires people to protect and enhance our environment through leadership, education, and advocacy.

Over the past 20 years, Environment Hamilton has worked on dozens of projects and activities in collaboration with a variety of funders and many local partners to build a sustainable future for Hamilton. We also work alongside residents to deal with pressing environmental issues, making frequent use of the Environmental Bill of Rights and other legal tools. In 2003, EH began their StackWatch initiative, which helps Hamiltonians to observe, document, and report problem emissions from Hamilton's industrial core.

CONNECT WITH US

www.environmenthamilton.org

/EnvHamilton

@environmenthamilton

@envhamilton