CANADA'S PATHWAY TO HYDROGEN STEELMAKING

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INNOVATION POLICY LAB WORKING PAPER SERIES 2023-04

Introduction[1]

The global steel industry, along with governments, has committed itself to decarbonizing steel production. The presumed future primary steel production technology, based on current technological feasibility, is a switch to hydrogen from fossil-based reductants as an energy source. However, there is still some level of uncertainty as to whether this will be the final route to decarbonization. For instance, heat balance is critical in maintaining quality in the conversion of iron ore to molten iron. The case is not yet fully proven.

The steel industry has faced pressure to reduce emissions for over 50 years in response to increasingly strict regulatory standards and to maintain its social legitimacy. It now faces a qualitatively different challenge to meet the new industry policy objective of Net Zero Carbon by 2050. Unlike in other industries, the transition is not simply a matter of addressing externalities or supplementary processes, but rather the core production technology for carbon steel itself. Further, it is precisely the highest value-added steel products for such products as electric vehicles and energy-efficient buildings that pose the greatest challenge.

The steel specific issues include: Hydrogen as a reducing agent for iron ore and a fuel to replace fossil-based carbon; carbon capture and storage as well as carbon capture and utilization; electrification of fossil fuel processes such as reheat furnaces, stoves, ladle preheat furnaces, boilers and building heat; biomass and other wood residues as reducing agents to replace coal; andiron ore reduction by electrolysis.[2]

Decarbonization is a challenge for many industries, however, because it challenges the core metallurgical processes, the policy ask of the steel industry exceeds most others.

[1] The authors wish to acknowledge the invaluable comments and suggestions received from three independent reviewers.

[2] CSPA (2023) "Hydrogen and the Decarbonization of Steel production in Canada", Canadian Steel Producers Association. Ottawa, June 2023

Decarbonization in Mining and Metals

Decarbonization of the mining and metals industries as a whole, including iron ore and steel, has been the subject of an important recent paper by Ashok Dalvi.[3] Ashok argues that there are several pathways to decarbonize the industry, including making incremental improvements to current production methods or switching to different technologies. The former includes methods such as the use of hydrogen as a fuel in blast furnaces as partial carbonization and adopting CCUS technology. The latter would shift to hydrogen as the reductant in DRI production. This section of the current paper draws on the work of Ashok, as evidenced in his published paper.

To determine the feasibility and necessity of these approaches, one should consider the importance of excess production capacity in the steel industry. Global steel production is growing at a rate of 3% per year and is expected to reach 2.5 billion tonnes by 2050, a 33% increase from 2021. So, the transition to Net-Zero could lead to a large portion of stranded assets. Therefore, the choice between improving current assets or adopting new technologies requires further investigations for each plant individually. Critical for such capital intensive facilities, it is essential to identify the assets which are of advanced age and need to be replaced. Among the different types of steelmaking facilities, the blast furnace has the longest life (15- 20 years) between relines and replacing it with newer assets with a low-carbon footprint is best scheduled at the time of the next reline to minimize wasted capital and stranded assets.

Considering the different available strategies to use in different plants and Dalvi's arguments, the pathways to the decarbonization of steel industries can be categorized into three stages:

- The first stage focuses on short-term solutions that can be implemented quickly without major facility changes, such as the gradual shift from natural gas to hydrogen utilization and the partial injection of hydrogen in blast furnaces.
- In the medium term, it is recommended to make incremental improvements using best practices and switching to scrap melting in EAF or DRI-EAF processes. Strategies at this stage need changes in the core technology of the plant, which will lead to a less CO2-

[3] Dalvi, A. (2022). "Decarbonization of Mining and Metals Industry: A Critical Overview". Proceedings of the 61st Conference of Metallurgists, COM 2022: The Canadian Institute of Mining, Metallurgy and Petroleum, 2022.

intensive process. It can fit the BF/BOF plants, which are closer to their relining date and would justify the investment. Moreover, changing to scrap from DRI in an already running plant can be placed in this category, as it will require modifications in the infrastructure, as well as the equipment.

- Finally, in the long term, facilities such as CCUS can be added where feasible and economical. Moreover, switching to low-carbon electricity power, such as the models in Ontario or France, can be considered.

By categorizing these strategies based on their timeline and required changes, it can be easier to evaluate the feasibility and necessity of utilizing each method for each plant individually, taking into account the importance of excess production capacity in the steel industry.

However, the following challenges should be addressed to make these pathways feasible and successful:

- There are technical issues related to EAF steel operation with carbon-free DRI, and the infrastructure for the production of H2 and its delivery is not in place.
- Expanding hydrogen generation capacity and increasing zero-carbon power generation capacity is essential to achieve the net-zero goal in the steel industry.
- Scrap generation in developing economies is low since the infrastructure is new and is not at the end of life. Moreover, steel recycling rates are lower in countries such as China, Japan and South Korea. Therefore, currently, there is not enough steel scrap to satisfy global steel demand. However, we expect to see a growth of more than 500 Mt in scrap availability to reach 1.3 billion tonnes in the next 30 years. Scrap quality will also be important.
- Based on the International Energy Agency (IEA) report, for equipping steel plants with hydrogen-based DRI, electricity demand will rise by 720 terawatt hours by 2050, equivalent to 60% of the sector's total electricity consumption today. Furthermore, the concurrent deployment of CCUS-equipped plants requires around 0.4 Gt CO_2 capture globally in 2050, equivalent to the deployment of a large CCUS installation (1 million tonnes of CO_2 capture per year) every 2-3 weeks from 2030.

Additional overview considerations in the transition include: The energy supply to the EAF must be clean energy, and Scope 3 emissions, in general, should be considered. DRI or other reduction pathways are critical to keeping the steam of virgin iron into steelmaking, particularly for high-grade steels. Scrap scarcity will also be an issue. However, the most underappreciated challenge will be electricity supply, both for hydrogen supply and for steel production.

Organization of the Paper

The paper is organized as follows: The first section discusses and clarifies the distinction between hydrogen steel making and hydrogen iron making. The second section briefly profiles Canada's integrated steel companies, to which the discussion of hydrogen steelmaking most applies. The third section describes the divergent approaches each of the three companies is pursuing within the industry-level premise that the steel industry is going hydrogen in the future. The fourth section identifies some major technical challenges that could complicate and delay the development of hydrogen steelmaking. The final section draws some initial conclusions from these developments.

Hydrogen Steelmaking vs. Hydrogen Ironmaking

Many industrial actors, such as ArcelorMittal Dofasco or Algoma and organizations, such as National Research Council (NRC) or Canadian Carbonization Research Association (CCRA), believe that the hydrogen plant should be considered the first priority in greening the iron and steel industry, and that the steel plant would be the anchor tenant in the hydrogen energy economy. However, the utilization of hydrogen is not mentioned as a definitive plan in any of the announced approaches. Although every member of this ecosystem, including government and private actors, has insisted on the essential role of hydrogen and how we are moving toward a hydrogen steel world, no practical assessment of this move has been yet done.

The use of hydrogen has been discussed broadly in two aspects, as a reductant and as a fuel source. Hydrogen can be the reducing agent and replacement for pulverized coal injection (PCI) in the blast furnace in the BF-BOF route (H2-BF); or, as a substitute for natural gas injection as an energy source in the blast furnace (BF). It will primarily be a case of natural gas replacement. All three integrated producers in Canada inject natural gas, but only Arcelor-Mittal Dofasco uses coal injection. The achievable target price for hydrogen steelmaking is <$3/kg H2, which is still three to four times the industry's current natural gas price. Green hydrogen is not viable at this stage. Producing H2 via electrolysis would require 6.5% of Ontario's current power generation. The industry projects an energy cost equivalent of $7.46/KG H2 or $36/GJ. Natural gas is currently $5.50/GJ. Green H2 is not a cost-effective pathway. Blue hydrogen has a better outlook.[4]

In the media and in government policy pronouncements about H-DRI, reference is constantly made to "hydrogen steelmaking". In fact, it is more accurate to describe it as hydrogen ironmaking. In this process, while total CO2 emissions are lowered compared to a conventional blast furnace or DRI-EAF system, the EAF does not directly affect this emission reduction; the reduction in this technology will be by the reduction in electricity production and not the steelmaking process itself. So, at the end of the day, it will reduce emissions, but not through steelmaking technologies. On the other hand, H2 use in ironmaking will lead to increased energy demand in the EAF and potentially higher emissions. Without carburization from CO as a reducing gas, the melting point of the iron increases and more carbon is needed to promote slag foaming in the EAF. That is, the fundamental change will be how to produce iron, which will then be made into steel. The blast furnace, which now produces liquid iron from iron ore and coking coal, will be replaced by a new hydrogen process to produce DRI (Directly Reduced Iron) in the form of briquettes, which are then processed into molten steel.

Another option to utilize hydrogen in iron or steelmaking is as a fuel source, as an alternative to fossil fuel. The potential applications of hydrogen or hydrogen-rich gas as fuels mainly involve processes like pellet production, sinter production, and heating ladle and reheating furnaces. If the furnaces and ladle heaters are gas-fired, then substitution with hydrogen will directly reduce process emissions. Due to the dominant concern with emissions from the process, the main focus on using hydrogen in the steel and iron industry will remain on its application as a reducing agent.

[4] CSPA (2023)

For these reasons, the discussion of hydrogen steelmaking relates only to integrated steel producers who source iron ore and not the recycled steel that is used in Electric Arc Furnaces (EAF).

Profile of Canadian Integrated Steel Companies

Before analyzing the emission reduction efforts, first, it is important to classify the emission sources in such steelmaking into three categories:

a) Emissions from the steelmaking process.
b) Emissions due to the electricity grid.
c) Emissions due to transportation of both product and raw material.

Steelmaking plants mainly focus on the first source of emissions, as it contributes to approximately 70% of total emissions. Changing the leading technology of ironmaking from an integrated BF-BOF plant to DRI is one of the efforts taken in this category. The emission amounts from the electricity grid are lower than the process; however, the sources of electricity make process decarbonization strategies feasible. Depending on the carbon intensity of the local grid, they may not yield deep decarbonization, although in the Ontario context this would not be applicable.

<u>Algoma</u>

With a raw steel production capacity of approximately 2.8 million tons per year,[5] Algoma is one of Canada's three main steel plants in Ontario. Algoma Steel is an integrated steel plant with two blast furnaces (BFs) and a Direct Strip Production Complex (DSPC) mill which produces hot and cold rolled steel sheets and plates, mainly for construction applications.

This plant is now invested in converting its integrated design to Electric Arc Furnace (EAF) steelmaking and has chosen Danieli as its as sole technology supplier for its transition.[6] The mill will have a nameplate capacity of 3.7 million tons of liquid steel with two 250-ton EAFs

[5] "Corporate Profile," Algoma Steel Inc., April 8, 2021, https://algoma.com/about-algoma/corporate-profile/.
[6] Algoma Steel selects Danieli Digimelter for full transition from integrated to electrical ' Danieli, accessed June 11, 2023, https://www.danieli.com/en/news-media/news/algoma-steel-selects-danieli-digimelter-full-transition-integrated-electrical-steelmaking_37_683.htm.

at its core, powered by two Q-One digital power systems with a rated capacity in excess of 190 million volt-amps each. Q-One is a patented technology that can continuously vary the frequency during each melting phase, yielding improvements in energy efficiency and electrode consumption, the company says.[7] The company says it determined that Danieli's AC-Digimelter technology powered by Q-One digital power systems was the best choice for its needs. The transition to EAF steel production is expected to reduce Algoma's carbon emissions by approximately 70 percent.

Another advantage of this plant is the DSPC facility used for casting and rolling the products. This direct strip rolling plant has a high productivity energy efficient design compared to the conventional rolling mills.

ArcelorMittal Dofasco

ArcelorMittal Dofasco is Hamilton's largest private-sector employer, with 4.5 million net tons annum production.[8] It currently uses two routes for its steelmaking, one through 2BF-1BOF and one through 1EAF.[9] In its transition, the BF-BOF will be replaced by one DRI, and one 2.4 million tonnes EAF will be added to reduce the CO2 emission together. The new DRI will be natural gas driven but will be constructed 'hydrogen ready' so it can be transitioned to utilize green hydrogen as a clean energy input when a sufficient, cost-effective supply of green hydrogen becomes available.[10] This transition will reduce annual CO2 emissions at Ontario's operations by approximately 3 million tonnes, which represents 60% of plant emissions.[11] Moreover, ArcelorMittal Dofasco believes that by this method, besides lowering the need for coal or coke, they eliminate the need for transportation for the raw material, as they will produce it at the same site.This will reduce emissions even more.

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[7] Danieli to supply technology for Algoma Steel's new EAF Steel Mill ..., accessed June 12, 2023, https://www.recyclingtoday.com/news/algoma-selects-danieli-eaf-technology-supplier/.
[8] "ArcelorMittal Dofasco: ArcelorMittal North America," Home Page, accessed June 11, 2023, https://northamerica.arcelormittal.com/our-operations/arcelormittal-dofasco.
[9] https://www.gem.wiki/ArcelorMittal_Dofasco_steel_plant
[10] "Arcelormittal Breaks Ground on First Transformational Low-Carbon Emissions Steelmaking Project: ArcelorMittal," Home Page, accessed June 11, 2023, https://corporate.arcelormittal.com/media/press-releases/arcelormittal-breaks-ground-on-first-transformational-low-carbon-emissions-steelmaking-project.
[11] "ArcelorMittal Dofasco: ArcelorMittal North America," Home Page, accessed June 11, 2023, https://northamerica.arcelormittal.com/our-operations/arcelormittal-dofasco

ArcelorMittal Dofasco is the one remaining primary steel producer owned by ArcelorMittal based in Luxembourg. One of the largest steel producers in the world, it is active pursuing virtually every steel decarbonisation process and technology. The Hamilton facility is able to draw on the resources and technology experiments across the global ArcelorMittal platform. The other two Canadian producers do not have these resources and advantages. For this reason, we characterize the ArcelorMittal Dofasco case as essentially technology transfer.

Stelco

Stelco is a leading producer of flat rolled sheet steel in North America, with 75% domestic use and 25% export to the USA. This plant has done several upgrades since 2017, with investments of over $800 million, such as coke battery upgrades, electricity co-generation project, and electric vehicle battery recycling initiative, with its most significant upgrade to be the blast furnace relining. In 2020, Stelco upgraded its blast furnace at its Lake Erie Works facility, increasing its production by an additional 300,000 net tons per annum.[12] It created what is believed to be the first smart blast furnace of its kind in North America, meaning that the furnace utilizes deep learning with an automation system that monitors and auto-controls the inside conditions of the furnace.[13] Stelco also added a pig-iron production facility more than a year ago.[14]

Three Different Bets on Hydrogen Steelmaking

Our research has revealed that the three integrated steel companies are pursuing different technological and organizational strategies all eventually aimed at achieving the transition to hydrogen steelmaking by 2035. They are taking different pathways, with different risk profiles.

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[12] "Stelco Announces Successful Completion of Blast Furnace Upgrade Project," Stelco Holdings Inc. - Stelco Announces Successful Completion of Blast Furnace Upgrade Project, accessed June 11, 2023, https://investors.stelco.com/news/news-details/2020/Stelco-Announces-Successful-Completion-of-Blast-Furnace-Upgrade-Project-10-20-2020/default.aspx.
[13] "Blast Furnace Anatomy #2 – Posco's Smart Blast Furnace: 'I Think, Therefore I Am.,'" – Official POSCO Newsroom, August 5, 2019, https://newsroom.posco.com/en/blast-furnace-anatomy-2/.
[14] Josh Rubin, "The Faceoff: Steel Prices Are Taking off and Stelco Is on a Tear - but Rival Dofasco Still Dominates the Auto Market," thestar.com, March 6, 2021, 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?rf.

We characterize this as three different “bets” on hydrogen steel.

Bet 1: Algoma: Fundamental Technology Change

Due to the time that passed since Algoma’s BF reline and upgrade, there was a need to revamp the whole BF-BOF plant. So, Algoma had two options: Whether to bring a new facility and switch to the new technology or to re-invest a considerable amount of money, which was its largest ongoing capex expense, to revamp the old, CO2-intensive equipment.. Therefore, Algoma chose the first option and leveraged the necessity of revamping old equipment into changing its steelmaking process to a low-emission one.

As the first step, Algoma has invested in constructing a new melt shop with an EAF. It will eliminate its current blast furnace and move over a four-year cycle to a twin EAF. With the technology transition to an EAF, Algoma will reduce the process emissions for the entire plant by up to 70% of the total emissions. The remaining 30% of process emissions are released from the secondary furnaces, such as reheat furnaces of plate and strip complex, as well as equalizing furnaces of the DSPC. This emission portion will be reduced by changing the nature of these furnaces from natural gas to electricity-based and synthetic biogas (syn gas) furnaces.

The other two sources of emissions are insignificant for Algoma and most probably for other plants in Ontario. Algoma is fed through the Ontario electricity grid, which is 93% non-emitting. This clean grid almost eliminates the second source of emissions for Algoma. In addition, the amount of GHG that trucks emit is negligible compared to the first two sources. However, it can also be shrunk by using green trucks, which are not equipped with fossil fuel engines.

Considering the above explanations, the Algoma team believes they can easily meet the target of CO2 reduction just by switching to the scrap-based EAF. Still, it is essential to take a deeper look into Algoma’s transition and assess its plans for reducing process emissions.

Algoma estimated that its complete transition from BF/BOF integrated plant to the EAF plant would take seven years until 2030. While the civil work for the EAF shop has already started and the necessary design and logistics behind the transition are complete, the required electricity to fully support the EAF facility will not be available until 2030. Therefore, the EAF needs to work partially and in parallel to one of the blast furnaces, until the grid can provide its electricity to the required level.

The furnace planned for the transition is scrap-based. Direct emissions from the EAF would be marginally different for scrap vs DRI based on input feeds. The emission differences are more related to the DRI production stage rather than the melting process of scrap or DRI within the EAF. Scrap-based EAFs are proven to have lower emissions than DRI-based, and the only downside to them is the availability of the scrap in the region. However, Algoma contracted a study regarding future scrap requirements that reported that there would be no long term scrap shortage in North America. Therefore, Algoma opted for a 100% scrap EAF with the lowest expected emissions. As the furnace will not depend on DRI, it will not need to rely on concentrate or pelletize DRIs. This eliminates the necessity of any other utility plants with potential CO2 emissions on site.

Compared to other Ontario plants, a competitive advantage of this plant is the geographical location and scrap access. The Algoma plant is located in Sault Ste. Marie, close to key steel-consuming regions of the U.S.-Midwest and Northeast and Canada - Southern Ontario. It also has geographic proximity to significant scrap trade flows, including prime scrap. Toronto, Chicago and Detroit, the three main scrap resources in North America, are located close to this plant and would provide enough scrap for the future EAF.

Furthermore, in 2021, Algoma entered into a joint venture with Triple M Metal, one of North America's largest privately-owned ferrous and non-ferrous metal recycling companies, to source prime scrap metal and other iron units to meet Algoma's business needs, including in connection with its potential transformation to electric arc steelmaking. Using scrap steel always raises issues of quality, particularly residual metals in the in-bound material. For high quality steelmaking, identification and sorting of the scrap is crucial in contracting with suppliers.

Algoma has another geographic leverage regarding accessibility to biomass. Powders and dust from sawmills like wood shops, stumps, and all not-prime lumber are available. In their future plan, erecting a pilot plant using biochar is foreseen to be used in the furnace. Moreover, the outlet gas from this biochar plant will be used as fuel for the secondary furnaces.

Other technologies, such as carbon capture utilization and hydrogen, are not foreseen as a priority in Algoma's plan in the near future. The extremely high price of CCUS is one of the reasons behind the reluctance to use this technology. However, the Algoma team also believes that considerable emissions will be reduced through switching to EAF technology, and Algoma will meet the emission reduction goal. Therefore, there is no need to reach net zero in its emissions, as the price will be phenomenally high, and it may not be worth the investment. So, no further emission-cutting strategy may be required in the first stage.

They will re-evaluate their options once they have utilized EAF, electric secondary furnaces and biomass. For instance, using hydrogen may depend on the results of the commissioning of the new plant. It should be noted that the new generation EAF planned for Algoma is not precluded from using hydrogen-based inputs in the future.

Nonetheless, Algoma believes that to support their financial and technological investment, the most effective policy which government can introduce and modify is the carbon tax. It will bring a 'change of behaviour' and can guarantee that high investment in green transition will be worth it. Cross border adjustment must also be in place to prevent carbon-intensive steel from unfairly competing with low-carbon-produced steel.

In parallel, Algoma has made efforts to widen its R&D and collaboration with other institutes and universities. They are engaged in various associations such as CSPA, CCRA, and Compass of the University of Toronto and McMaster University. Also, some arrangements have been made with Sault and Algoma University to hire educated workforces and train new students.

Our assessment is that Algoma, from a business perspective, is making the most radical change in the fundamental configuration of their steel plant and taking the biggest risk. There is no backup plan. However, from a strictly technical perspective, they are taking a more modest risk, in that the technology itself is familiar in the industry. They have done this before in dramatic fashion: In the 1970s in totally eliminating their Open Hearth furnaces and going to Basic Oxygen Furnaces in one fell swoop. And in the 1990s, they made a radical shift to thin slab casting in the form of the Direct Strip Production Complex (DSPC). The latter was also done with Danieli as the technology leader.

In summary, the emission objective will be reduced by changing the nature of these furnaces from natural gas to electricity-based, synthetic biogas (syn gas) furnaces, although 100% green steel will require the use of carbon capture. Other technologies, such as carbon capture utilization and hydrogen, are not foreseen in the near future as a priority in Algoma's decarbonization efforts. The extremely high price of CCUS is one of the reasons behind the reluctance to use this technology in the near-term. Algoma estimates its complete transition from BF/BOF integrated plant to the EAF plant to take seven years from 2022 until approximately 2029.

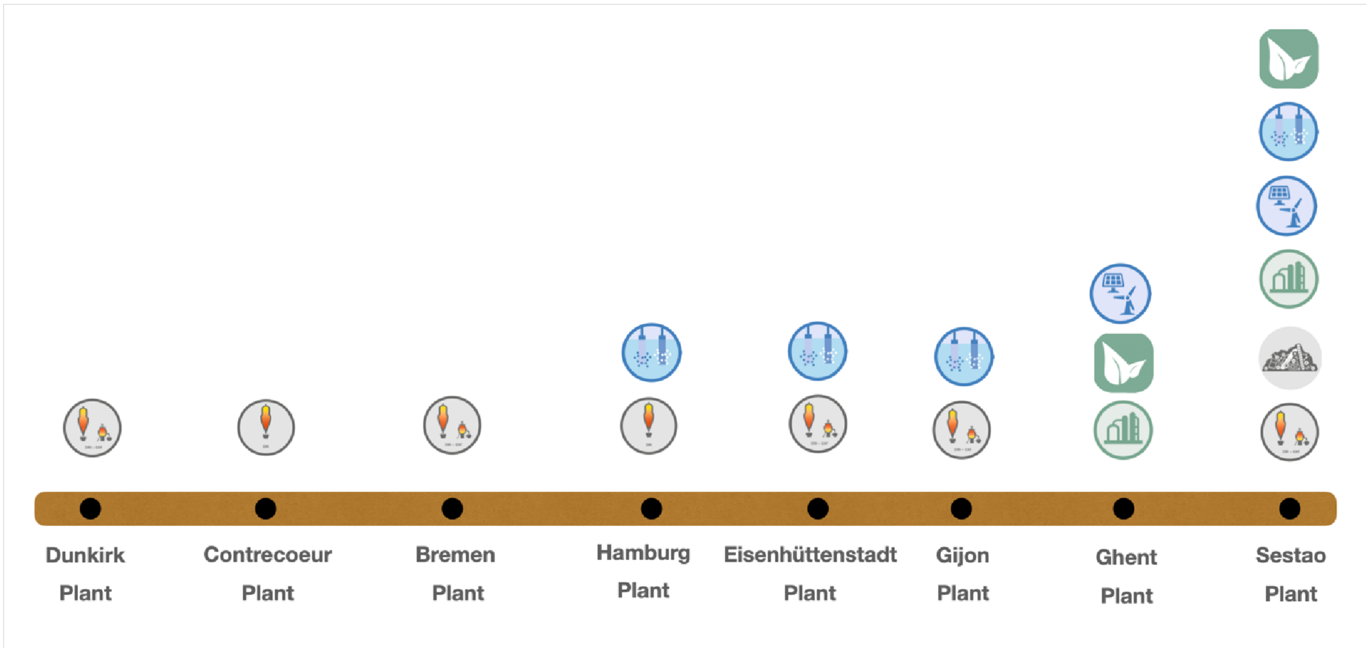
Bet 2: ArcelorMittal Dofasco: Technology Transfer

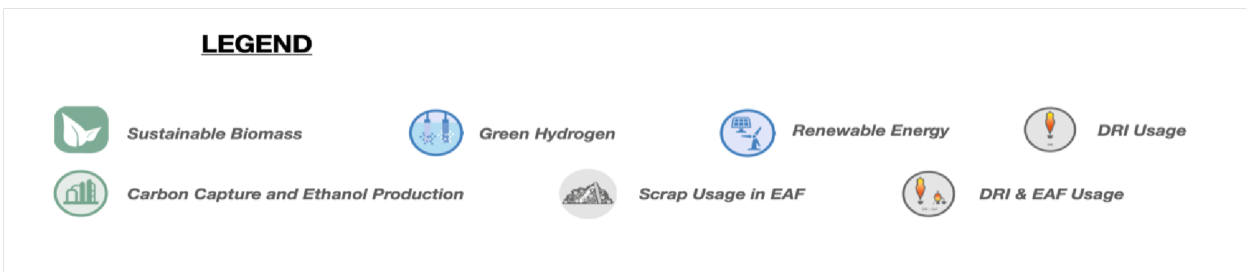
This transition from coke oven blast furnaces to EAFs at ArcelorMittal Dofasco is another project that also demonstrates the power of public and private partnerships to accelerate technology adoption, which is vital if the target of limiting the average global temperature increase to 1.5 degrees is to be achieved. The governments of Canada and Ontario have committed CAD$400 million and CAD$500 million, respectively, to the overall project cost.[15]

Our assessment is that ArcelorMittal Dofasco is able to take advantage of the global efforts of ArcelorMittal, which is active in all the competing technologies and processes to achieve net zero carbon across the global steel industry, to evaluate different options and therefore reduce their risk compared to the concentrated risk being taken at Algoma Steel. For this reason, we characterize their initiative as more a question of technology transfer.

As shown in the figure below, ArcelorMittal has adopted various sets of decarbonization strategies in its worldwide plants. While in some of them, including Dunkirk in France, Contrecoeur in Canada, and the Bremen plant in Germany, a single technology such as H-DRI or transition to EAF will be trialed, some other ArcelorMittal plants will face major changes. ArcelorMittal will implement multiple technologies in its plants in Hamburg or Ghent, and its Sestao plant has the potential to become a good showcase of what green steel has to offer.

[15] "Arcelormittal Breaks Ground on First Transformational Low-Carbon Emissions Steelmaking Project: ArcelorMittal," Home Page, accessed June 11, 2023, https://corporate.arcelormittal.com/media/press-releases/arcelormittal-breaks-ground-on-first-transformational-low-carbon-emissions-steelmaking-project.





Different from the other steel producers, ArcelorMittal Dofasco has for several years been investigating, in partnership with the CCRA, another effort to curb GHG emissions and support ArcelorMittal's Climate Action Plan. ArcelorMittal Dofasco has experimented using biochar as a replacement for coal in its blast furnaces. In partnership with CanmetENERGY, the Canadian Biocarbon for Heavy Industry Working Group, McMaster University Advanced Controls Consortium,[16] and several suppliers and government agencies, the ArcelorMittal Global R&D (Hamilton) team has successfully trialed up to 15% replacement of coal with biocarbon, which would displace more than 40,000 tonnes of coal annually.[17] Although they have mentioned the

[16] "Solving Ecological Challenges: Arcelormittal," ArcelorMittal Dofasco is part of the world's leading steel and mining company, accessed June 11, 2023, https://dofasco.arcelormittal.com/smarter-future/innovation/solving-ecological-challenges.

[17] "Advancing Products, Processes and Solutions: Arcelormittal," ArcelorMittal Dofasco is part of the world's leading steel and mining company, accessed June 11, 2023, https://dofasco.arcelormittal.com/smarter-future/innovation/advancing-products-processes-and-solutions.

role of biocarbon and biofuels in EAF and in achieving Dofasco's Journey to Net Zero emissions by 2050,[18] no specified plan to use it in EAFs is yet suggested.

ArcelorMittal Dofasco is also working with McGill University to evaluate the feasibility of implementing the European SIDERWIN project in Canada. ArcelorMittal is one of seven partners and the coordinator of the "SIDERWIN" project based in Maizières, France. The project is developing a technology using electricity for the direct electrolysis of iron, bypassing the use of carbon or hydrogen with no direct CO2 emissions. The prototype of this project in France showed that this process can operate in a highly flexible start/stop mode, which is ideal for power grids dependent on large amounts of intermittent renewable power. Moreover, less power is required compared to hydrogen electrolysis. Therefore, once affordable clean power is abundantly available, such as in the case of Ontario, direct electrolytic iron ore reduction becomes a very attractive route.

Another missing issue, at least from information available in the public domain, is that ArcelorMittal Dofasco's decarbonization initiatives lack a feasibility study for the required electricity. Algoma, as an example, estimated that the electricity grid cannot provide the required power until 2030 and designed the transition based on this duration. Dofasco, however, has not mentioned any specific plan for delivering the added electricity for the EAF. Moreover, while ArcelorMittal has mentioned the CCUS as one of the possible methods in future, it has not considered it as one of its certain plans for the North America region at the time being.

Bet 3: Stelco: Optimization of Current Assets

Taking into account past investments and upgrades to its coke ovens and blast furnace, it seems Stelco is not motivated to accelerate the movement to DRI/EAF anytime soon. It appears that the company's view is that with their improved technologies, they can focus on CCUS and recycling the off-gas, with the expectation that their overall emissions outcomes will at least match the BF to EAF competitors at least over the next five years. They can afford to wait and watch, while the other experiment. For this reason, we characterize Stelco's strategy as the

[18] "Solving Ecological Challenges: Arcelormittal," ArcelorMittal Dofasco is part of the world's leading steel and mining company, accessed June 11, 2023, https://dofasco.arcelormittal.com/smarter-future/innovation/solving-ecological-challenges.

optimization of current assets. It is conceivable that Stelco could, in future, utilize hydrogen in their blast furnace to substitute natural gas to significantly improve their environmental performance while keeping the original technology.

Stelco will construct a carbon capture utilization and storage facility through collaboration with Pond Technologies Holdings, Inc. They state that they are at the forefront of CCUS in the industry through partnerships and collaborations aimed at not only capturing the CO2 but also finding productive uses and markets for alternative products, such as fish feed and bioplastics. Pond Technologies Inc. has developed what they describe as a universal algae-growing platform that converts CO2 from virtually any source into algal-based commercial products. As a pollution abatement technology, the algae growing platform converts the CO2 in the untreated stack gas of industrial emitters into biofuels, animal feeds, and natural fertilizers.[19]

The engineering and construction work is supposed to be done by SNC-Lavalin Inc, and Pond states that they have already completed process engineering and are currently commissioning the first algae bioreactor for this project.[20] New updates on this process are expected from Stelco. The true test will be in the details. The carbon captured in the algae is not biogenic, so if it is reused somehow as fuel or reductant it is not carbon neutral but has 50% intensity. This may limit the degree to which large amounts of carbon can be sequestered

Moreover, updates about using the off-gas are also important. In 2020, Stelco Holdings, Inc. entered into a partnership with DTE Energy Services to create a 65-megawatt cogeneration plant, which was expected to be operational in 2022.[21] Stelco affirmed that, in early 2022, they expected to complete their new electricity cogeneration facility that will recycle the process off-

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[19] "Solving Ecological Challenges: Arcelormittal," ArcelorMittal Dofasco is part of the world's leading steel and mining company, accessed June 11, 2023, https://dofasco.arcelormittal.com/smarter-future/innovation/solving-ecological-challenges.

[20] Pond Technologies Holdings Inc., "Pond Technologies Receives Binding Commitment from Inventiv Capital to Fund up to CDN $7 Million for Phase 1 of Its Stelco Project and up to CDN $13.5 Million for Phase 2," Cision Canada, April 15, 2019, https://www.newswire.ca/news-releases/pond-technologies-receives-binding-commitment-from-inventiv-capital-to-fund-up-to-cdn-7-million-for-phase-1-of-its-stelco-project-and-up-to-cdn-13-5-million-for-phase-2-842520864.html.

[21] Paths to a Greener Steel City Final, accessed June 12, 2023, https://d3n8a8pro7vhmx.cloudfront.net/environmenthamilton/pages/1310/attachments/original/1634602997/Paths_to_a_Greener_Steel_City.pdf?1634602997.

gases, reducing both emissions and dependence on the provincial power grid.[22] While more detail about this facility is needed, it does not significantly loweri the consumption of fossil fuels in the furnace and only reduces the downstream outlet.

However, the capacity for the CCUS facility is reported as 6,300 tonnes per annum, which is considerably lower compared to the emission reduction amounts announced by Algoma and ArcelorMittal Dofasco. Considering this variance, Stelco may not play an essential role in achieving the net zero goal in the Canadian steel industry, and the project would be considered a trial case or a pilot plant for using CCUS in other North American steel plants. Looking at the funding received from the Ontario Center of Excellence (OCE) and the target GHG program, Stelco's decarbonization activities seem to be a moderate bet, as funding is secure and the scale of the project is small.

Based on the above summaries, we believe each one of these steelmaking companies has undertaken different sets of risks. Each plant has chosen a special and unique approach. Although it is not guaranteed which approach will be the safest or will combat the GHG emissions the most, the combination of all three approaches may shape the ideal roadmap for the Canadian steel industry as a whole. In other words, there are ‘small differences that matter’, and each steelmaking plant in Canada is making that small difference which is compatible with its circumstances.

Among these plants, Algoma has taken the biggest business risk. They are changing the core technology of the steelmaking plant and moving beyond a partial revamping or adding another facility. The changes Algoma is implementing in its shop create value in the Canadian steel industry. It creates this value with the help of its recent revamp and its geographical leverage, such as access to the market and raw materials, e.g., scrap and biomass. However, plants like Algoma are recognized as ‘adopters, not innovators.’ They will not have a high investment in R&D to innovate new methods to reduce CO2 emissions, but will instead use their funds to cut emissions through already-established methods.

[22] Stelco Inc. – Hamilton Works Environmental Management System and ..., accessed June 12, 2023, https://www.stelco.com/sites/default/files/2022-06/EMS%20and%20Community%20Engagement%20Report%202021%20HW.pdf.

ArcelorMittal Dofasco, on the other hand, relies on the technology transfer from the ArcelorMittal group as a tool to contribute to this collective action. ArcelorMittal group has started several decarbonization initiatives all over the world based on the requirements and advantages of each region. Therefore, it is equipped with various technology options (although in the early stages), and pilot plants and the results of these trials and approaches can benefit all members of its global team. One can say that ArcelorMittal has invested in multiple bets to mitigate the risk and uncertainties of decarbonization initiatives in the iron and steel industry. ArcelorMittal Dofasco, with its transition to the EAF and probability of utilizing hydrogen in future, is one bet among many.

The case of Stelco is different compared to the other two, and this difference majorly stems from the recent revamp and modification in this plant. It has the financial and efficiency advantage based on previous investments and modernization, with the most modernized facilities among all three steelmaking plants in Ontario. This makes Stelco take the least risky bet, as it has already invested in its current technology and cannot apply a huge change. However, Stelco tries to mitigate its risk by relying on pre-existing equipment. Stelco is not completely neglecting the hydrogen steel theme. They have recently announced a partnership with Utility Global from Texas to use the steam and off gas from the furnace to split water into hydrogen. The process doesn't use any external energy source, so basically, it's a way of energy recovery from the waste stream. It appears to be aimed at CO2 reduction through process efficiency gains.

Another considerable issue in Stelco's announcement is the usage of CCUS. This cutting-edge technology is a massive risk to take, and Stelco is the only plant in Canada that has invested in this system. As CCUS is a system that would be applied downstream, that is CCUS could be used 'downstream' of the process units to capture the emissions from the main process.

Technical Issues in the DRI-EAF Transition

The first major steps on the road to hydrogen steel is the current conversions at Algoma and ArcelorMittal Dofasco from BFs to EAFs. Completing the transition from coke-based to hydrogen steelmaking will be complex, as has been the case with any such fundamental change in production technology. Therefore, the possible timelines and contributing parties may not be what is currently assumed in public policies as well as interactions within the industry players themselves.

Examples of technical challenges include the following, without claiming to be exhaustive or definitive.

Dofasco makes steel for many applications which require low residual elements, such as copper (Cu), nickel (Ni), chromium (Cr), etc. If a 100% scrap charge were used, these residual impurity levels would be exceeded. Therefore, they will need to use some form of virgin iron units to achieve acceptable levels.

In converting from BFs to EAFs, the company's plans are to use scrap and DRI as their charge materials. The ratio of DRI will vary based on the grades being produced but will probably average about 70%. DRI is an iron reduction process which uses natural gas as a reductant to remove oxygen from DRI-grade iron ore pellets. The reaction is carried out at a low temperature, so the iron pellets feed into the process and remain solid, and only the oxygen associated with the Fe is removed. Other gangue materials, such as silica and alumina, which are in the iron ore pellets, do not react in the DRI unit, so they will enter the steelmaking process and must be removed in the slag in the steelmaking process.

Some iron ores can have high P content, and this impurity is not removed during DRI processing and is not easily removed in EAF processing. Typically, the pellet quality used in a DRI process is higher grade than pellets used in a blast furnace. DRI-quality pellets are less available and more expensive. Low-quality pellets can be used in DRI units, but the higher gangue content requires additional processing, which needs higher slag volumes in the EAF, more electrical energy, longer processing times, and lower yield, resulting in significantly higher steel production costs.

The EAFs will have a gas cleaning system to remove particulate materials. There are a variety of cleaning systems used, which can be ESP (Electrostatic Precipitator), bag houses, and scrubbers. Most of the new EAFs use bag houses to remove the dust. These dusts can be hazardous, depending on their chemical analysis. Because EAFs can charge a wide range of input materials as compared to blast furnaces, they can have dust which are considered toxic.

Galvanize scrap has zinc coating and such dust, depending on zinc concentration, can be considered toxic and needs a special disposal site to minimize leaching or processing of the dust to remove the zinc.

There are still issues with hydrogen DRI, today DRI pellets have some level of residual carbon when produced by natural gas. The carbon is used to reduce unreacted FeO in the DRI during the steelmaking process. In addition, the EAF process relies upon high power input into the EAF to achieve high productivity; to do this, a foamy slag practice is used, which shields the furnace walls from the electric arc and keeps the heat inside the bath. This foaming is created by reacting C+O in the slag to foam it to bury the arc. This is another source of CO2 that has not been addressed but could require carbon capture. If the carbon used is bio-based, then this will be a positive form of CO2 to allow for net zero to be achieved.

Whereas the conversion from blast furnaces and BOF to EAF reduced carbon emissions by about 30%, hydrogen ironmaking can reduce CO2 emissions by about 90%. However, this method faces some limitations. First of all, it is shown that using fossil carbon such as coke is inevitable in blast furnaces. Its structural abilities to allow for the counter current reactor to be fuel efficient cannot be understated. Released heat from hydrogen combustion is not enough to reach the required heat balance in the chemical reaction happening inside the furnace, and coke/coal should be present as one input of the reaction to provide enough heat. Moreover, massive amounts of green hydrogen and sufficient green electricity are required in this method, which imposes a huge cost. The assessment of a hydrogen direct reduction steelmaking process shows that total energy demand is similar to the traditional steelmaking route (blast furnace - basic oxygen furnace), but instead of coal and coke the process runs on electricity. This is particularly the case if H2 production is included. Then the electricity required to support steel production would increase significantly.

At current price levels, replacing coal with hydrogen would drive up the price of a ton of steel by about one-third. Studies show that the production cost of the H-DR route are generally higher than those of the integrated BF/BOF route but are close to competitive at a very low electricity cost (20 EUR/ MWh) and a carbon price of 62 EUR per tonne of CO2. The economic viability of the hydrogen-based process is thus highly dependent on the availability of low-cost clean electricity or, conversely, higher prices for carbon emissions.

Conclusions

The steel industry and governments have identified hydrogen steelmaking as central to achieving green steel, a critical material for the low carbon economy. What is clear from the Canadian case is that the path to success will be diverse with different companies pursuing different technologies and processes. The larger policy lesson here may be that innovation at the industry level is more than the sum of the parts.

There is not sufficient attention being paid to whether we will have enough power to completely electrify the iron and steel processes. Production of low-carbon hydrogen does not exist at scale today in comparison to the future need. The required supply chains for biocarbon do not yet exist. Neither does carbon capture infrastructure exist in Ontario, the home of the integrated steel producers at scale, and there are no pipelines for CO_2 transportation. R&D funding and activity are insufficient for the task at hand.[23]

However, in addition to the efforts of the individual companies, there are additional public policy and public infrastructure conditions required for technical and commercial success. First, the movement to EAF production will produce major new demands for electric power generation and transmission at a time when other industries like mining are also undergoing electrification. The Ontario government and Ontario Hydro are squarely challenged to find solutions to the electricity supply issue. Second, ArcelorMittal Dofasco plans to build its own DRI facility. The other producers do not in any of the publicly announced plans. The Quebec government, by contrast, is very active on the DRI sourcing issue. Finally, the Federal government will be crucial in development of a border carbon tax policy to ensure that Canadian industry is not placed in an unsustainable competitive position relative to other more polluting steel-producing countries.

[23] CSPA (2023)