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INNOVATION AND DE-CARBONIZATION IN THE CANADIAN STEEL INDUSTRY

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Abstract

Purpose - 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 of change. This study discusses policies and initiatives in the Canadian steel industry to achieve net zero emissions in the coming decades.

Design/Methodology/Approach - This is a case study. It relies on the domain expertise of the authors, company and industry documentation, current literature references and a number of key informant interviews with senior steel executives currently engaged in the effort to identify the potential future technology pathway to achieve the objective of net zero carbon emissions.[1]

Findings – The Canadian steel industry has had a 50 year research alliance, the Canadian Carbonization Research Association, which was established to increase the volume and efficiency of metallurgical coal in the Canadian steel industry, as well as to expand exports of metallurgical coal. The industry association, the Canadian Steel Producers Association, is now turning to this pro-carbon research group to be the leaders in de-carbonization. This would appear to be counter-intuitive.

Originality/Value - The paradoxical case of using the resources of the pro-carbon group to identify the future de-carbon technology roadmap for steel is explained by fact that the technology challenge is exactly to the 'hot end' furnace processes of the steel mill. It is here that the expertise required for the future is to be found. Further, the Canadian steel industry has an advantage over the steel industry of the EU for example, in that there is also a large Canadian forest industry, which can be the required source of biomass for future production of biocarbon steel.

[1] Interviews were conducted with five individuals totalling three hours of discussion followed up by personal correspondence for further clarification.

Steel biocarbon developments can be considered not just as a technological innovation but also as a social innovation. Technological innovations require complementary ones in organization, production processes, policies, and society, a relationship which is poorly understood outside of innovation studies.

In the Canadian steel biocarbon case, the relevant factors include:

1. Technological innovation in steel has traditionally been an endogenous development within the industry as a standalone. For reasons of environmental concern and social legitimacy, steel in public policy discussions is now constantly situated as an energy-intensive industry (steel, aluminum. chemicals, cement).

2. The change required to decarbonize comes down to people and skills if it is to be successfully implemented. As does digitalization.

3. The increased price level for Green Steel in the marketplace will only be viable if it is supported by a high-level carbon tax.

4. The new decarbonized steel production processes involve a fundamental shift in industrial organization from batch mode physical commodity production to continuous flow chemical processes.

5. The transition to biocarbon and carbon capture can only be achieved by the steel industry entering into co-operation and joint production with inter-industry partnerships with the forest and chemical industries. This will require R&D and cross-sectoral collaboration in a country which has historically excelled at neither.

Keywords: Steel, Carbonization, Biocarbon, Technology, Transition

Paper type: Research Paper

1. Introduction

The role of carbon and specifically coal continues to be a challenge for the environmental and economic sustainability of the global steel industry. Further, if measured by tonnage, iron ore and metallurgical coal production also account for over 75% of the physical output of the global mining industry. CO2 emissions, particularly from integrated steel producers, are a major challenge to environmental policies according to the UN Paris Agreement 2015 (Natural Resources Office of Energy Efficiency 2007; House of Commons. Report of the Standing Committee on International Trade 2017; Government of Canada 2017; Government of Canada 2020; Industry Canada 2020; Hoffmann 2020; Turner 2020).

Carbon and steel have historically been inseparable. For the highest quality, high strength steels for such things as automotive applications, iron ore and metallurgical coal are the indispensable raw material inputs at the ‘primary end’ of an integrated steel mill: the coke ovens, blast furnace and basic oxygen furnace. For every ton of steel produced, another ton of coal is consumed. While enormous progress has been made in the last 30 years in reducing physical discharges from steel mills, CO2 emissions are the largest remaining physical discharge from these facilities. To solve this environmental challenge will require replacing the fundamental iron production technology, i.e. the blast furnace that are currently tied to fossil fuel carbon, with alternative strategies such as bio-based carbon with carbon capture (CCUS), hydrogen reduction and electricity based iron/steelmaking. In Canada 45% of crude steel production is by Electric Arc Furnaces (EAF), both scrap based and DRI (Direct Reduction Iron) based. It is true that the blast furnace is the biggest source of CO2 but the decarbonization challenge extends beyond to the EAF sector as well. The research question in this paper is how does the steel industry reduce and eliminate metallurgical coal and subsequently fossil fuels from steelmaking? This paper surveys the possibility of the transformation of the steel plant into a chemical plant as a key answer to this question.

On the other hand, the steel industry occupies a major positive position in the circular economy. Due to key properties of steel (strength, durability, magnetic properties) it is well placed to contribute to a circular economy, a critical part of the solution in addressing environmental concerns about the future of the industrial economy. The circular economy refers to a move from linear business models, in which products are manufactured from raw materials and then discarded, to circular business models where products or parts are repaired or remanufactured, reused, returned and recycled (Word Steel Association (2018), How Steel is Helping to Achieve a Global Circular Economy). This reduction in the amount of manufactured products will contribute to reduction in GHG emissions. However, recycling by itself cannot provide the answer for steel which is already the most reused material in the economy.

The purpose of this paper is to identify an important emerging policy area in the global steel industry, while describing a fundamental technology change requiring inter-industry linkages between the steel, chemical and forest industries. First, the paper reviews some of the existing literature, from different aspects related to emission reductions: its correlation to the circular economy is explained as well as the current practices for CO2 reduction. Then, with reference to the Canadian steel case, it introduces two industrial organizations, the Canadian Carbonization Research Association (CCRA) and the Canadian Steel Producers Association (CSPA). Their missions and plans for reaching the goal of net zero emission will be discussed. Finally, the paper suggests a framework for this technological change, transforming steel mills into chemical plants.

2. Literature Review

The Canadian steel industry, as in other countries, has been faced with the on-going challenge of carbon emissions for many years, with significant but differential success (Griffin, B. 2019). However, these efforts fall short of policy and regulatory requirements, ultimately aimed at achieving full de-carbonization.

2.1 Redefining Steel as a Separate Industry

The steel industry is but one of the energy intensive industries (EII) including pulp and paper, cement, non-ferrous metal and glass. Many of these industries require transformative technologies to significantly reduce GHG emissions (Elkerbout, M. 2017). As described by Wesselinga *et al*. (2017) structural components of EII are different and so the policies and innovations in these industries will be unique as well.

The steel industry has witnessed many changes and innovations over time. Most of these innovations have been internal innovations from within the industry directly related to efficiency and production improvements, embodying smaller changes, incremental innovations. On the other hand, some have been of a radical nature leading to totally new designs and processes, such as the introduction of the Electric Arc Furnace (EAF). The current challenges related to reduction of GHG emissions are of a more radical nature but currently remain at an experimental scale.

Some of the CO2 reduction technologies currently on offer include CDA (Carbon Direct Avoidance), CCU (Carbon Capture and Utilization), CCS (Carbon Capture and Storage) as well as other novel technologies or policies. From a technology perspective, CCS offers the greatest opportunity for carbon dioxide reduction within the EII industries. The viability of this approach, both technologically and economically, varies between sectors, with ammonia production, steel and the chemical industries being best suited to its early adoption.

However, more radical changes in this industry are possible, primarily finding the best alternative to the blast furnace (BF). Some incremental innovations, such as the ULCOS projects, have been implemented in blast furnaces, which are modifications of standard BF designs, but the reduction values of these technologies cannot meet the global needs of, for instance, the Paris Agreement on climate change. As blast furnaces are the main emission source in the steel industry (70%), more radical changes to the process are necessary to reduce GHG emissions to the required extent. Rather than changing the technology from BF to EAF, some other alternative processes are introduced which are typically referred to as breakthrough technologies, such as electrowinning and hydrogen direct reduction (H-DR). These radical innovations point exclusively at the iron and steel industry.

2.2 Steel and De-Carbonization Today

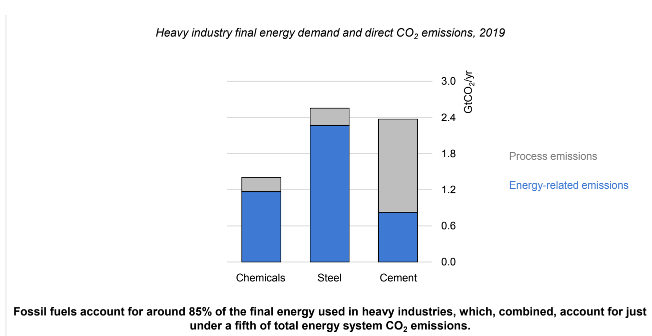
The leading policy discussion of decarbonization of steel is currently taking place in the context of the reduction of global steel overcapacity. For example, the Global Forum on Steel Excess Capacity sponsored a conference on Decarbonization on April 22, 2021. The industry perspective is summarized in the overview of the meeting agenda:

> The steel industry is now facing one of the biggest adjustment challenges of its time: the need to move towards decarbonisation of steel production. But global excess capacity represents a major barrier to the needed adjustment. Investing in costly breakthrough technologies, which may require hundreds of millions or possibly billions of dollars/euros requires a robust long-term business case, as well as certainty that the new steel plants that are capable of producing low-carbon steel will be economically sustainable once the investments are in place. By distorting markets and competition, excess capacity drastically reduces the returns on and incentives for making such investments. A consistent policy framework committed to sustaining reductions in excess capacity and ensuring a level playing field for steel producers over the long run could therefore play an important supporting role in accelerating the industry's move to decarbonisation. (GFSEC April 22, 2021)

A key overall factor is the required policies to support the steel industry in making the transition to climate neutrality (Neuhoff 2021).

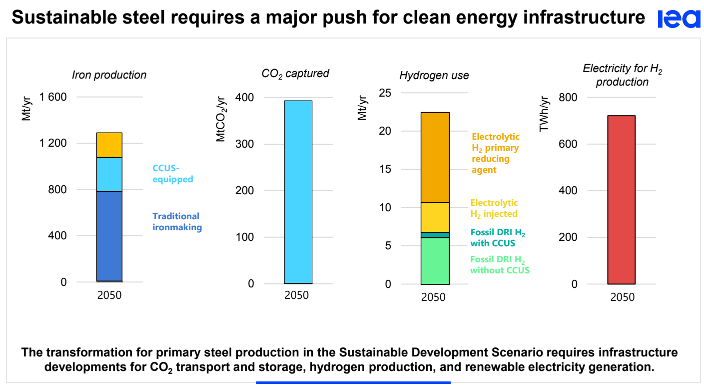
The European Steel Industry view as stated by EUROFER (2021) aims to reduce CO2 emissions from EU steel production by 30% by 2030 compared to 2018 or 55% compared to 1990 and up to 95% by 2050, ultimately becoming totally CO2 neutral. However, the challenges include creating new product markets where breakthrough technologies would increase steel prices significantly. Breakthrough technologies also require access to low carbon energy, estimated at ~ 400 TWh of electricity. The development of the new technologies will require an estimated 50-60B Euro of investment.

For the purposes of this paper, the most critical perspective comes from the International Energy Agency "Iron and Steel Technology Roadmap" (Levi 2021). It is summarized in the following two graphics. First, the final energy demand and direct CO2 emissions from key heavy industries indicate that emissions from heavy industry are hard to abate.



Source (Levi 2021)

In addition to process improvements and new technologies within the steel industry, major new infrastructure investments are required for CO2 transportation and storage, hydrogen production and renewable energy generation.



Source (IEA 2019)

2.3 Steel and the Circular Economy

The World Steel Association, the industry association for the global industry, has stated the ambitious policy goal of net zero emissions by 2050 (World Steel Association (2015). The CSPA also aspires to this goal. It builds on the core idea that steel, almost alone among materials, is 100% recyclable. It can be recycled over and over again to create new steel products in a closed-material loop. The recycled steel maintains the inherent properties of the original steel. For this reason, in policy terms, there should be a unique alignment of steel producers and the circular economy.

For the WSA, the circular economy is a move from linear business models, in which products are manufactured from raw materials and then discarded at the end of their useful lives, to circular business models where advanced design leads to products or their parts being repaired, reused, returned and recycled. A circular economy aims to rebuild capital, whether it is financial, manufacturing, human, social or natural. This approach enhances the flow of goods and services.

In the steel industry perspective, the concept of the circular economy drives optimal resource efficiency. It makes sure that resources are efficiently allocated to products and services in such a way as to maximise the economic well-being of everyone. In addition, products need to be designed to be durable, easy to repair and, ultimately, to be recycled. But the cost of reusing, repairing or remanufacturing products has to be competitive to encourage these practices. Simply replacing a product with a new one should no longer be the norm.

A circular economy ensures that value is maintained within a product when it reaches the end of its useful life while at the same time reducing or eliminating waste. This idea is fundamental to the triple-bottom-line concept of sustainability, which focuses on the interplay between environmental, social and economic factors. Without a life cycle approach, it is impossible to have a genuine circular economy.

The WSA states that in a well-structured circular economy, the steel industry has significant competitive advantages over competing materials. Within the WSA policy document (Word Steel Association, 2015), four keywords define these advantages as summarized below:

Reduce. Reducing the weight of products, and therefore the amount of material used, is key to the circular economy.
Reuse. Because of its durability, steel can be reused or repurposed in many ways, with or without remanufacturing. Rates of reuse will increase as eco- design, design for reuse and recycling, and resource efficiency become more commonplace.
Remanufacture. Many steel products, such as automotive engines and wind turbines, can be remanufactured for reuse to take advantage of the durability of steel components.
Recycle. Recycled steel maintains the inherent properties of the original steel. It is the most recycled material in the world. Over 650 Mt of steel are recycled annually (WSA, 2020).

The World Steel Association (WSA) has recently published a position paper on climate change and the production of iron and steel (WSA 2021).

They point to the fact that steel is a permanent resource; it is 100% and infinitely recyclable without any loss of properties. Further, the industry fully supports the aims of the Paris Agreement. The WSA also supports the IEA's Iron and Steel Technology Roadmap for transformation of the industry.

The position of the WSA is that there is no single solution to drastically reducing CO2 emissions from the steel industry. There are three components to reducing steel's environmental impact.

First, a new industry-wide efficiency review process based on leading practices that focus on the key efficiency levers of raw material quality, energy efficiency, process yield and process reliability. The successful implementation of this methodology has the potential of reducing direct and indirect emissions by up to 20% at the average ore-based steelmaking site and up to 50% at the average scrap-based facility.

Second, maximizing scrap usage. Every steel plant should be considered a recycling plant. All scrap that is collected is recycled, and the overall recycling rate today is estimated to be about 85%. But, this high level of recycling means that going forward there is limited room for improvement.

Third, breakthrough technology. For the World Steel Association there is no single technology solution to low-carbon steelmaking, and a broad portfolio of technological options will be required to be deployed alone or in combination which will vary by country and region:

> In areas rich in low-carbon energy, one might expect to see the deployment of water electrolysis and hydrogen reduction.
>
> In areas with access to CO2 storage, for example the UAE, the USA or the Netherlands, CCS or blue hydrogen reduction may emerge as the most appropriate choice.
>
> In areas offering potential access to biomass resources, such as Australia or Brazil, sustainable biomass and biochar may be used to substitute coal in existing steelmaking processes.
>
> Carbon capture and utilisation (CCU) can combine carbon-rich waste gases with renewable energy to create synthetic fuels and chemicals such as acetone and isopropanol that can be used as feedstock by the chemicals sector.
>
> (WSA 2021)

It is against this background that the Canadian steel industry's efforts can be assessed.

2.4 Harvesting Steel By-Products

As a point of reference for the Canadian steel industry's efforts, one of the leaders of the European discussion of net zero steel is the German steel company Thyssenkrupp. At its Carbon2Chem pilot plant in Duisburg, they transform CO2 and other exhaust gases from steel production into new products, such as chemical raw materials. These can then be used to produce many useful products such as fuel, fertilizer or synthetics (Wich *et al.*, 2020).

The longer term Thyssen iron and steelmaking strategy is based on the use of "green" hydrogen, which will augment and later replace coal as a reducing agent, so that in the long term no CO2 will be produced during steel production. The federal government of Germany and the state of North Rhine-Westphalia are supporting both technologies. In addition, they continue internal programmes to increase Thyssenkrupp-wide energy efficiency and promote the use of renewable energies in their own production, particularly conversion of steel mill process gases into chemical products. They are supported by the German Ministry of Education and Research and a consortium of other companies. The next step is to extend the solution to other industries, supported by additional funding from the federal government through the period to 2024.[2]

The German government provided more than 60 million Euro in funding for the first phase of the project in 2016. Since then, important milestones have been reached: shortly after the pilot plant in Duisburg started operation in March 2018, ammonia, methanol and higher alcohols were successfully produced from steel mill process gases for the first time. In addition to the CO2 from these gases, Carbon2Chem also uses hydrogen. To pave the way for climate-neutral production, a two megawatt alkaline water electrolyzer from ThyssenKrupp Uhde Chlorine Engineers was operated in the pilot plant. It has been shown that the water electrolyzer could be operated with highly volatile renewable energy without suffering damage. The implementation of chemical synthesis using commercially available catalysts and gas cleaning using commercially available process stages by ThyssenKrupp Industrial Solutions is proof of the high technology readiness level of the project. In addition, commercial viability as well as the positive ecological effect were confirmed by all project partners.

[2] Thyssen Krupp. The Carbon2Chem Project. Available at: https://www.thyssenkruppsteel.com/en/company/sustainability/carbon2chem/carbon2chem.html

In the newly launched second phase of the project, the aim is to demonstrate long-term stability in the complex interactions between steel production and chemical synthesis and to show that the Carbon2Chem technology can be upscaled quickly in an inter-industry network, for instance by pairing a steel mill and a chemical plant. In addition, the focus will be on transferability to other industries besides steel production. To this end, additional sectors are to be included in the project as major CO2 sources – for example cement and lime producers and waste incineration plants. Finally, the second phase of the project will serve to bring the project to market readiness.

Carbon2Chem is already an integral part of ThyssenKrupp Steel's strategy for climate-neutral steel production. As well as avoiding CO2 emissions through the use of hydrogen in steel production, the company is banking on the technology to utilize and avoid residual emissions. Carbon2Chem is expected to help reduce CO2 emissions at ThyssenKrupp's steel mill 30 % by 2030 on the path to complete climate neutrality by 2050. This appears to be a project with much potential in the future.

2.5 CO2 and Alternate Steel Production Technologies

Iron and steel plants producing steel via the blast furnace-basic oxygen furnace (BF-BOF) route constitute among the largest single point CO2 emitters within the European Union (EU) (Lechtenböhmer *et al*. 2018).

As described in Mandova *et al*. (2018), the iron ore reduction process in the blast furnace is completely dependent on carbon mainly supplied by coal and coke. Bioenergy is the only renewable source that presents a practical possibility for their partial substitution. EU steel policy discussions have advocated that biomass integration for European steelmaking should be seriously considered, but only when its sustainable sourcing is ensured. Studies on biomass availability for integrated steel plants have already been done for Finland, Sweden and France. The findings indicate that a sufficient amount of biomass for their iron and steel plants could be supplied using their national resources, even though competition from other industries will take place. The high cost of the biomass product was identified as the most significant drawback, where the current CO2 allowance prices do not make the solution economically feasible. However, when optimising the whole system based on cost, integrated steel plants in Belgium, Germany, Spain, Great Britain, Italy and Netherlands would heavily rely on imported biomass from other EU countries (European Commission, 2017; Suopajärvi, 2013; Mousa, 2016; Wang, 2015; Wei, 2013).

The conclusion is that integration of biomass, with the aim to reduce CO2 emissions, would be economically feasible only after imposing a relatively high CO2 price, which would in turn significantly impact the production cost of steel.

3.0 Research Methodology

This paper concerns how construction and other basic industries like steel and mining adapt to the imperatives of a circular and sustainable economy. This is fundamentally about how industrial operations must change to operate and have legitimacy in a fundamentally different policy environment. These issues are complex and have lots of uncertainty. In these situations, case studies using qualitative methods have an established place and contribution to make (Johansson 2007; Noor 2008). This case study primarily relies on direct interviews with the most senior management teams in the industry association and steel companies directly involved in the Canadian decarbonization initiative. The Canadian case in relevant because of the presence of a large forestry industry makes a biomass intermediate strategy a possibility and a major new industry research programme is required, despite the historically low level of R&D spending by Canadian businesses. An interview guide was composed based on the literature review (see appendix). Three confidential interviews were conducted by Warrian with senior association representatives and two with steel company executives and technology managers using Zoom meetings plus written responses to the questionnaire. The key informant interviews took place over the course of three hours on four occasions. Factual accuracy was confirmed in follow-up correspondence. In addition, secondary data was accessed through desktop research using policy documents and reports, company and industry documentation and analysis of current literature references. In addition, a validation workshop with innovation studies specialists was held March 5, 2021 at the Innovation Policy Lab, Munk School of Global Affairs and Public Policy, University of Toronto with 12 participants.

4.0 Findings

This is a narrative case study of the decarbonization initiatives in the Canadian steel industry addressing four variables: the activities of the Canadian Carbonization Research Association (CCRA), the role of the Canadian Steel Producers Association (CSPA), the Decarbonization Alliance and Inter-Industry Co-operation.

The Canadian steel industry is comprised of integrated and electric steel producers producing approximately 12 MMT of CO2, with about 90% coming from the big three integrated mills. The EAFs account for roughly 1.0-1.3 MMT. All three integrated producers run blast furnaces that are coke based. The integrateds all have coke plants and BF's that have a certain life expectancy after which no further investment in these facilities will take place. These companies will face re-investment decisions before and after 2030. This will determine the timing of possible change to hydrogen-based steel if this route is chosen:

> Some might just stay with the same technology and use CCUS to meet targets or pay the carbon tax. I cannot say what others will do and can't say what we are planning at this time.
>
> However, no one is going to throw away good assets. It has been proven that the BF is the most energy efficient way to make hot metal for steelmaking compared to all the other methods that have been tried and not really taken off over many years.[3]

4.1 The Canadian Carbonization Research Association (CCRA)

4.1.1 The Canadian Carbonization Research Association

The Canadian steel industry does not have a strong tradition of industrywide research and development partnerships, though individual steel companies do have partnerships with universities and government laboratories on specific problems. The major exception is the Canadian Carbonization Research Association (CCRA). The CCRA was formed in 1965 and was incorporated under the Canadian

[3] Interview Jan 5, 2021

Corporations Act on July 16, 1981 as a not-for-profit research association.[4] Its purpose is to conduct research and development of importance to the coal and carbonization industries in Canada, to co-ordinate and support Canadian carbonization research in and related to the steel, foundry, smelting and coal industries, as well as to affiliate with national and international organizations or associations having similar objectives.

At the policy level, the CCRA is a unique co-operative research and development effort between private industry and the federal government. CCRA members and the government laboratory network CANMET participate in a consensus-based program that has and continues to meet its members' needs over many fruitful years.[5] Numerous company members have and continue to perform many individual, confidential test programs at CANMET to meet their companies' issues directly. The government CANMET lab provides the critical technical capacity beyond the steel companies' internal capacity to support the innovation curve moving forward. Having a dedicated laboratory to conduct carbonization research is beyond the feasibility of any one steel company.

The fields of R&D covered by the joint CCRA/CANMET program include energy and fuel conservation and efficiency, stabilization of supply, GHG reduction, mining, processing, transportation, production of iron, environment and safety. At any specific time, the R&D program places priority on the most immediate problems in the industry while also addressing the longer-term work necessary to progress in the future.

Historically, the CCRA had a major focus on developing the Canadian coal industry. In figure 1, the history of metallurgical coal production in Canada is shown. Western Canadian coals are unique in their coking nature and produce excellent coke, but require specialized engineering and technology. The CCRA has been instrumental in establishing technical programs to showcase the technical merits of Western Canadian coals on a global scale and, as a result, the coal industry has grown to reach the 30 mt levels of today.

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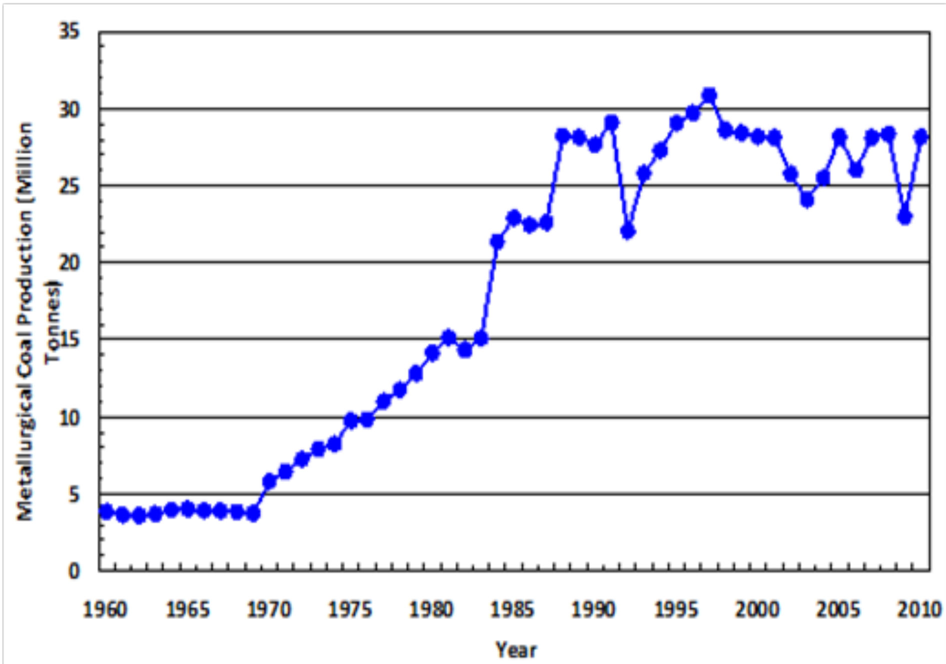
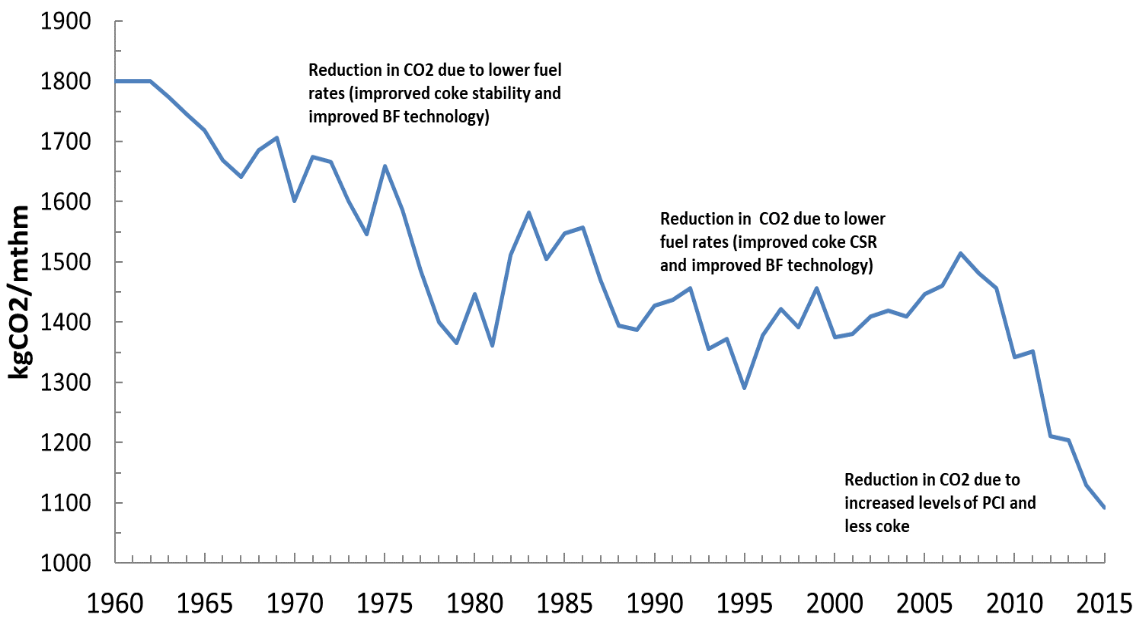
[4] Canadian Carbonization Research Association. History. Available at: http://www.cancarb.ca/about/history/
[5] Confidential interview, Dec. 22, 2020

History of Metallurgical Coal Production in Canada



Source: Canadian Carbonization Research Association data

The steel industry, along with the CCRA, have also been studying ways to improve energy efficiencies in ironmaking. Some of these improvements are industrial and equipment based, but the CCRA programs have also contributed to the steel sector's success in lowering fuel rates by understanding how to improve coke quality for Canadian blast furnaces. Figure 2 shows CO2 reduction in steel and iron making since 1960 due to increases in coke quality and furnace technology.



Source: Canadian Carbonization Research Association data

4.1.2 CCRA from Carbon Optimization to Decarbonization

In the early 1980's, CCRA research studies focused on the correlation of coke and processing conditions from the movable wall oven with that from industrial ovens. Gas and wall pressure measurements in pilot and industrial coke ovens were emphasized. The CCRA was able to take advantage of the Algoma Steel No. 6 coke oven battery, which was scheduled to be demolished, to carbonize very high pressure coking blends to determine what the high coking wall pressures would do to an oven and if it could even cause wall failure. One of the technical highlights of the CCRA at the time was the CCRA/NKK Technical Exchanges between Canada and Japan, where both sides presented papers on their research work.

By the later 1980s, the international energy crisis had subsided, coal and steel prices fell and both industries were entering a period of intense competition. Coal injection into the blast furnace was seen as an important productivity advantage and was introduced in Europe and Japan. The CCRA Technical

Committee oversaw the upgrading of the coking quality of Canadian coals through wash plant control, CSR (Coke Strength after Reaction) and carbon texture, vertical temperature distribution in a coke oven, and the effect of partial aging/weathering of component coal on coke quality.

A project to study blast furnace coal injection (PCI) was approved and a special federal government facility was built at Bells Corners near Ottawa. CCRA and the Canadian Steel Industries Research Association co-sponsored a study on strategic ironmaking with CANMET to review how technologies on ironmaking could evolve in the next 20 years. That study was completed in 1990 and became the ironmaking technology road map for the Canadian steel industry.

Because the government was seeking to support both the coal industry as well as the steel industry, another Ottawa-based federal research agency was moved to Alberta. Its activities centered on coal pipelining, additives to coking charges, hot briquetting, formed coke and petrographic methods for all coals. A coking facility to accommodate the Western Canadian Coal producers was built, with Algoma Steel arranging to donate their Koppers pilot coke oven. A mini fluidized bed was constructed for heating coal for hot briquetting as part of the formed coke project and, by 1974, the facility was operational. Researchers from the Edmonton facility gained international recognition as coal carbonization scientists.

In pursuit of national policy, from the 1970s, a major focus for research was to offset the fact that Western Canadian coal contains a significant amount of reactive semi-fusinite compared to traditional Appalachian coals from the USA. During this period, R&D programs focused on petrographic analysis and coking tests to improve coking behaviour, producing excellent coke quality. CCRA has spent much effort explaining the benefits of these coals by using its research program to develop technical projects and has presented numerous research papers supporting the technical merits of Western Canadian coals. As a result, once the technical and quality issues were resolved, Canadian metallurgical coal exports doubled over the 1980s and now account for 95% of exports, though Canada ranks only 13^{th} in the world with 1% of global coal production (NRCAN 2021).

For several years prior to 2008-09, greenhouse gases (GHG) became a major thrust of the joint R&D program. In 2009, CCRA spent a significant amount of time and effort gathering information on the development and financing of an energy recovery pilot coke oven for the joint CCRA/CANMET program to examine this alternative/new cokemaking technology. The high cost of building such a facility led the CCRA to seek government participation at both the federal and provincial levels and include other parties such as Ontario Hydro Generation as partners.

The 45th anniversary of CCRA's foundation was celebrated in 2010. The association began a very ambitious project to carry out the engineering, design, construction and commissioning of an Energy Recovery Pilot Coke Oven (ERCO) at the Bells Corners coal and coke facilities. The ERCO technology is an alternate approach to traditional slot coke oven technology and the fact that pilot facilities using ERCO technology were previously unavailable meant that R&D could not be carried out in Canada. CCRA's goal for this project was to put Canada at the leading edge of this technology by having a facility where its members would be able to investigate how coal behaves in this type of oven. This facility would also be used to showcase the cokemaking merits of Western Canadian coals using this technology globally as well as making use of it to conduct research on the incorporating of coal blends for assessing coke quality.

As mentioned in the CCRA annual report of 2012-2013, in that year a major project was started to add an Energy Recovery Pilot Coke Oven (ERCO) which would put Canada on the leading edge of a new coke oven technology with Hatch being contracted to develop a preliminary design for the facility. The engineering design study was financed by contributions from CCRA member companies and a forgivable loan from Natural Resources Canada. With the design complete, planning on the location and support facilities got under way with one of the existing movable wall ovens being relocated to facilitate the ERCO.

According to the CCRA Annual report of 2016-2017 fiscal year, the CCRA pursued a number of other coal-related research initiatives. The association continued work on the ISO Inter Laboratory Study on Coal Dilatation initiated in 2015-2016 and entered into a new research funding arrangement with Geoscience B.C. to support a study aimed at producing clean coal from Western Canadian coal fields using the water-based Roben Jig process. In addition, further studies on coal stamp charging and small-scale coking were developed to meet members' future needs.

During the 2017-18 fiscal year, the new PCI experimental rig at CanmetENERGY-Ottawa was upgraded to allow for better control of the coal feeding rate and hot blast composition (Annual Report 2018-2019). A new approach was developed in processing the experimental data including the introduction of two new parameters to quantify the extent of gasification of coal. A new approach using TGA was developed to quantify the reactivity of combustion residues. Going forward, work would focus on enhancing the rig's capability in terms of NG/COG co-injection, blast gas moisture control and off-gas analysis.

4.1.3 The Current CCRA Research Programme

Looking at the medium to longer term, the CCRA is pursuing significant GHG reduction initiatives with both the coal and steel sectors as this is fast becoming a very significant global directive for these industries. In brief, the CCRA is examining ways to achieve carbon-neutral ironmaking in the middle to long-term (2030-2050) by partnering with Canadian and international partners. A steel company executive summarized the CCRA's role in the following way:

> *The history of the CCRA has shown that it can adapt to the changing needs of its members, the coal sector and the steel sector. Innovation takes time, and the CCRA program structure that brings both industry and government together in a mutually beneficial arrangement, [allowing] for the development and growth to support Canadian industry. In the short to medium timeframe, much research is needed to decarbonize the integrated steel sector as steel companies that operate coke plants and blast furnaces need to reduce fossil fuel carbon using renewable biobased carbon, but what will be the limit that can be used needs to be determined. CCUS technology will play an important role in the future as the steel sector assets will be utilized until their end of life.*
>
> *In future, to make steel, reduction using carbon, hydrogen and electrons are the only methods. As the steel world shifts to reduce and eliminate GHG emissions by 2050, the CCRA in partnership with other partners is positioned to develop these new technologies required to support the CSPA and its members*

Association representative

The CCRA is pursuing this research but with a special emphasis on the use of sustainable biomass based energy for the steel industry. The Canadian research includes (1) Pyrolysis Technology Evaluation (2) Bio-Carbon for EAF Steelmaking (3) Bio-Briquette Formation (4) Bio-Carbon for Direct Injection in Blast Furnace Ironmaking and (5) Biochar Production and Handling.

Again in 2018-19, the CanmetENERGY Bioenegy group was an active partner and made contributions in assessing existing biomass conversion technologies in handling, cleaning, processing and carbonization. The biocarbon for iron and steel production and other large emitters' project successfully secured research funding until March 2022. In 2018-19, four meetings of the CCRA-Biocarbon for Steel Working Group were held at CanmetENERGY-Ottawa. These meetings were successful in advancing the discussion and interest level among the numerous project partners. Going forward, the CCRA Biocarbon for Steel Working Group and its members are working to better define their plan and vision to 2025 around biomass production, supply, utilization, etc., including potential barriers at each level.

4.2 The Canadian Steel Producers Association

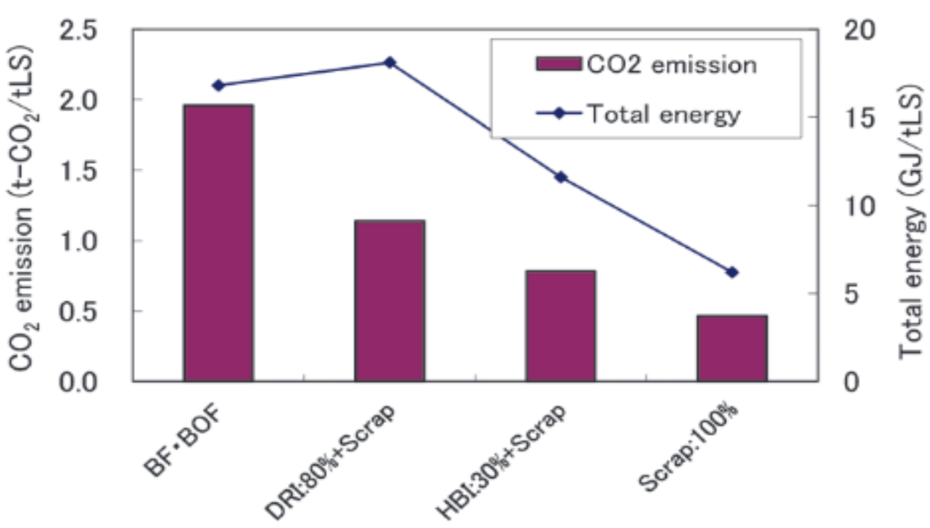
The Canadian Steel Producers Association was founded in 1986 after the Canadian steel companies, who had been long term members of the American Iron and Steel Institute (AISI), found that they could no longer rely on the industry-wide body to defend their interests in the face of rising American steel trade protectionism. Today, the CSPA represents 100% of Canada's domestic steel producing industry. For most of its 35 years, the CSPA has functioned as a traditional industry lobby group, primarily directing its activities at trade policy, taxation and regulatory issues. It has not played any significant coordination role in research and technology development. This is what makes the recent shift to a leadership role in research and technology development in emissions-related public policy to be of keen interest for students of innovation policy

Most R&D was performed within the companies' internal departments and lab facilities. The exception in the industry was the activity of the CCRA as described above, where active research collaboration amongst a small number of steel industry players was pursued largely with the federal government.

In 2020 this profile is beginning to change. While the CSPA has never itself been a centre of research activity, it did prepare a bold new vision for the steel industry with its aspirational net-zero climate action plan. This plan sets a new course for Canada's steel industry that requires a significant amount of research and technology development to achieve net zero. Given the long history of collaboration at the CCRA, it was natural for the CSPA to turn to that organization to become the leading research partner for the Canadian industry's future effort to achieve net zero carbon emissions by 2050.

The CCRA is currently chaired by ArcelorMittal Dofasco. This is important because Dofasco alone among the major steel companies retained its internal research capacity throughout the restructuring and downsizing of the Canadian steel industry in the 2000-2010 period. In addition to the technical capacity in the coal companies, the CCRA, on the steel side, was led by the internal R&D expertise for the primary production technology and processes in the steel mills. Some different processes in steel making and their part in CO2 emission are shown in figure 3. This core technology knowledge base and personnel were key to the otherwise ironic development that sees the previous pro-carbon CCRA organization being able to pivot to become central to the future strategy of de-carbonization of Canadian steel. The other development however requires the steel industry to develop a relationship with the completely unrelated forest industry, and its research network, in order to succeed in development of the required biocarbon supply.

Energy consumption and carbon emissions for steelmaking route



Source: Griffin (2019)

In achieving the CSPA's GHG objectives, other national and international policies can significantly impact the costs and benefits of different approaches. For instance, the Canadian domestic steel industry emits less CO2 compared to other steel producers that export their steel products to Canada like China.

If Canada wants to remain an environmental leader, examining the import and export policies on the upstream and downstream steel products and their impacts on the environment seems to be crucial. Therefore, the current complex discussion of a border carbon tax can directly impact the policy progress towards net zero steel.

4.3 The De-Carbonization Alliance

How does the industry assess the value proposition of moving to biocarbon?

> Value in use is the way to look at this. If the carbon content is high enough and residuals are low enough, but the material is expensive, then is the steel industry needs to look at its value in the BF itself and balance this against the carbon tax savings.
>
> [It] would be good to use material that is transparent to coal itself. The same could be said for others that use fuel pellets. The forest/pulp & paper sector needs to reinvent their investments. Could they or should they be a biocarbon provider to different users – steel, power, soil, metal refining as mentioned in our call? We all have different specs, but carbon is carbon ,so why not make a high value added product to improve [the] replacement ratio in various applications?[6]

What are the processing implications and limits of moving to biomass carbon?

> We are trying, but this will be difficult to incorporate more than say 5% in the coal blend. The biocoal does not have coking properties that are required to make coke, so [we] need to build around this with really good coal and or look at briquetting or stamping technology which is not cheap to install.
>
> In the end, if we stay carbon based and look at biocarbon to transition to 2030 with existing facilities, we can have some reduction in CO_2, but this will have an upper limit as we still will need the BF coke to perform, which will allow for coke rates <300 kg/thm. This is where CCUS will be needed.
>
> With DRI for the EAF, the demand for DRI with either blue or green hydrogen will increase if steelmakers look at EAF in the future to replace coke plants' BF technology. ...we could lower our carbon footprint also by using DRI in transition with our current BF's.
>
> It all comes down to cost of the [DRI + reduced coke rate - carbon tax] vs [iron ore pellets + coke rate – carbon tax] in a back of the envelope way of thinking.[7]

CCRA-CSPA Action Plan

[6] Interview Jan 5, 2021
[7] Interview Jan 5, 2021

The shift to green steel is of a scale and complexity, with major technical financial risks, that the Canadian industry, like others, requires a technology roadmap for its multi-year transition. The CSPA and CCRA have now published their technology roadmap for net zero steel (CSPA, 2020):

> Background
>
> As an industry with fixed-process emissions of greenhouse gases, the steel industry will need to research, develop and implement major technology changes in the future to drastically reduce its emissions. Significant innovation and technology breakthroughs will be essential for the industry to achieve its aspirational goal of net zero carbon emissions by 2050. The Canadian Steel Producers Association (CSPA) and the Canadian Carbonization Research Association (CCRA) have developed a R&D action plan following a stepwise transition approach.
>
> (2020-2025) Near future R&D and implementation: Implementation of technologies to reduce GHG emissions of ironmaking and steelmaking using existing production facilities.
>
> (2020-2050) Long term R&D: Potential reduction of fixed-process emissions. Pursuit of net-zero carbon emission steelmaking technology.
>
> Goal Statement
>
> To achieve significant reduction in GHG emissions in ironmaking and steelmaking processes with existing production facilities.
>
> To research and develop non-fossil carbon based iron and steelmaking processes to replace existing fossil carbon based technology to achieve net-zero carbon emissions in steel production.
>
> To improve the productivity and global competitiveness of the Canadian steel sector during this transition.
>
> Specific Objectives
>
> Near future R&D and implementation
>
> To substitute fossil carbon reductants by renewable biocarbon in blast furnace ironmaking and EAF steelmaking
>
> To substitute combustion of fossil fuel by alternate low carbon fuel for heating
>
> To explore potential of electrification in steel production
>
> To improve management and utilization of low grade waste heat
>
> To explore potential of carbon capture, utilization and storage in steel production
>
> Long Term R&D
>
> To advance alternate ironmaking technologies, in particular H2 DRI and electrolytic ironmaking
>
> To advance steelmaking technologies in order to utilize the alternative iron sources
>
> To develop technologies for production, storage and delivery of gaseous reducing agents to support DRI processes

To develop technologies for renewable electricity generation to support alternate ironmaking technologies in the steel industry

To apply CCUS in iron and steelmaking processes for establishing circular carbon pathway and long term carbon sequestration

4.4 Inter-Industry Cooperation between Steel and Forestry

However, the Canadian technology trajectory may be different because Canada has a much more advantageous position in forestry and biocarbon. This is a major potential competitive advantage in assisting the steel industry in making the transition to net zero carbon. The move away from blast furnaces can use biomass as a substitute for coal as a transition step while preparing for the eventual shift to hydrogen-based steelmaking. However, this requires research and the development of exogenous inter-industry partnerships from an industry whose past has been overwhelmingly characterized by incremental endogenous innovation pathways.

The other country which has a combined prominent steel and forest industry and is pursuing the biocarbon strategy is Sweden (Toktarova, 2020). In addition, Nordic countries are seen within the innovation studies literature to have uniquely successful traditions of inter-industry innovation (Ornston, 2012).

5.0 Discussion

5.1 A Framework for Transition to a Net Zero Steel Industry

As stated in the introduction, the steel industry faces a unique challenge in that the pathway to a net zero CO2 future requires more than just major changes to the environmental externalities that many other industries face. In steel, what is required is a fundamental transformation in the core production technology itself.

The history of the Canadian Carbonization Research Association illustrates several distinctive characteristics of extractive and primary metals industries. The traditional distinction in innovation studies of manufacturing has been between product innovation and process innovation. In primary metals, almost all product innovation takes place in process innovation. In the case of the steel industry adapting to the environmental and economic dimensions of the net zero economy, the intimate connections between environmental discharges and the 'hot end' of steel mills (coke oven, blast furnaces, oxygen furnace) changes its fundamental production function.

However, there are reasons to believe that Canada has critical advantages that position its steel industry to successfully make this transition. First, Canada has abundant supplies of low cost natural gas and high quality iron ore reserves. It also has a large forest industry, from which an important output historically has been to supply newsprint to the US newspaper industry. The latter, facing the disruptive challenge of digital media, has generated a surplus of biomass in the pulp and paper industry that can be a significant source for producing biocarbon for steel.

In terms of the research and innovation capacity to make this change, the largest Canadian steel company ArcelorMittal chairs the Canadian Carbon Research Association. This fifty year partnership that has joined coal producers, steel company primary research and development facilities, and dedicated Federal CANMET lab facilities, comprise a world leading knowledge hub for the primary metallurgy of steel production. The Dofasco research organization follows the lead of global ArcelorMittal's carbon capture, CUS and technology development strategy. However, the unique potential role of biocarbon is a point of differentiation.

Public Policy, Green Steel Markets and Carbon Taxes

Inevitably, moving to net zero or green steel will entail issues external to the firms. Prices for the new products will rise by an estimated 30-50%. How will product markets adjust? Of critical importance is the role of carbon tax policy. Integration of biomass with the aim to reduce CO2 emissions would be economically feasible only after imposing a relatively high CO2 price, which would in turn significantly impact the production cost of steel (Wesselinga, 2017). The modelling for Europe suggests that, based on current prices and near term technology, the maximum 42% attainable fossil fuel substitution by biomass would increase steel production cost by a minimum of 50%. Further, there will be competition to access biomass supply. Steel requirements alone would amount to 15% of the overall potential biomass supply, while other industries including the energy, transportation and chemical sectors among others will also be seeking biomass input materials.

There are two implications of this for public policy that support the proposition that this transition is a social innovation process as well as a technological change process. First, for the purposes of regulation and public support, the steel industry will no longer be regarded as a standalone industry, but part of a family of energy intensive industries which do not have a history of common identity or collaboration. Second, the price mechanism in steel markets will have limited to little effect in supporting the transition unless assisted by an external carbon tax.

From Steel Mill to Chemical Plant

Following up on the previous point, to fully implement the transition, the physical appearance and technical composition of a steel mill will change. The classic landscape of a steel mill is dominated by the 'hot end': Coke ovens which make metallurgical coal into coke; the blast furnace that combines iron ore and coke to produce molten iron (pig iron); the basic oxygen furnace that converts the iron to steel. In the future, all of those probably go away. They will be replaced with a set of basically chemical plants: An H-DRI, hydrogen-based, direct-reduced iron facility feeding a smaller EAF (electric arc furnace) and also an on-site hydrogen plant, a methanol plant and an electrolysis plant.

Steel production in the past has been driven by classic metallurgy. In the future, it will be driven by hydrogen, biocarbon and electrons.

A graphic representation of the transitional pathway to bio-mass steel is suggested below. As this figure shows, for each tonnage of hot metal, assuming 30% yield of raw biomass in pyrolysis process, 700 kg of raw mass is required.

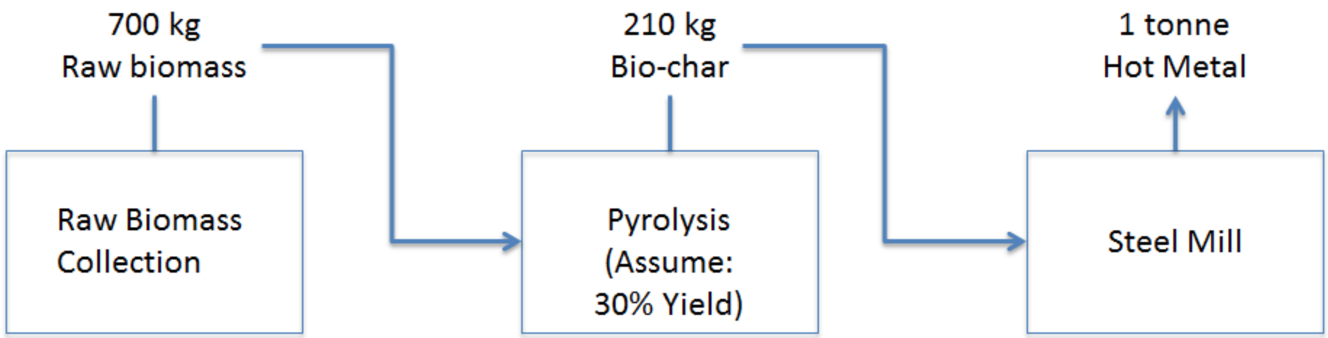


Figure 4. Pathway to bio-mass steel

To repeat, the change in the steel mill as an industrial organization will probably not be feasible without support of a carbon tax and probably other financial assistance. Also, it will involve the relevant human factors of skills and people. Otherwise, it will not happen.

Conclusion

The theoretical contribution of the paper is to identify a gap in the emerging literature about the general challenge of making a successful transition to a zero carbon economy. All industries and economic sectors face issues and challenges. However, in extractive and primary industries where the traditional innovation literature, mostly based on manufacturing, distinguishes between product and process innovation, this distinction collapses: Product innovation takes essentially takes place within the primary production processes. The practical, but ironic, implication is to turn to the technical expertise and technologies within the primary 'hot end' facilities of the integrated steel producers, the very sources that led the Canadian companies to expand and entrench carbonization, to now lead the de-carbonization effort. Finally, success in making the transition to net zero steel will require an extending of the lens to include the interaction with the forestry and chemical industries.

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Appendix

Interview Guide

Technical Questions

1. If the CCRA shifts from a carbon improvement to a carbon elimination policy objective, how might change the organization's functioning or will it?

2. How do you assess the European industry's approach to carbon neutrality as represented by the Thyssen case with the Biomass effort in Canada?

4. The lead Federal government partner of CCRA has been CANMET. Will the shift to an environmental policy objective involve different Federal partners?

5. Thyssen carbon project suggests a technology path where new technologies will dramatically impact the production technology configuration of existing integrated facilities e.g. BF goes away? new DRI/BOF configuration? Other EAF + ? And, will the steel mills become 'twinned' with external chemical plants?

6. For HSS steel grades 850+, do they require iron ore as an input and cannot be made from an EAF?

7. What does it mean to say that the only input options for steelmaking are Coal, hydrogen and electrons?

Policy Questions

1. What lessons can be drawn from your Forest Industry experience that might inform the Steel Industry approach to innovation in the coming years?

2. If the CCRA takes the technical lead on the goal of Carbon neutrality in the coming years, does this have implications for new forms of technology transfer, licensing and IP in the Canadian steel industry?

3. How do you assess the European industry's approach to carbon neutrality as represented by the Thyssen case with the Biomass effort in Canada?

4. Could you see the Federal government creating an equivalent of the Forest Innovation Program in the steel industry?

5. Could movement to natural gas/hydrogen DRI technologies eliminate the traditional distinction between Integrated and EAF steel producers?