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IRENA INNOVATION DAY

23-24 March 2022 • Canada

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Session 4:
Innovative Solutions To Decarbonize Iron And Steel Sector

THURSDAY, 24 MARCH 2022 • 10:00 – 11:15 EDT / 16:00 – 17:15 CET

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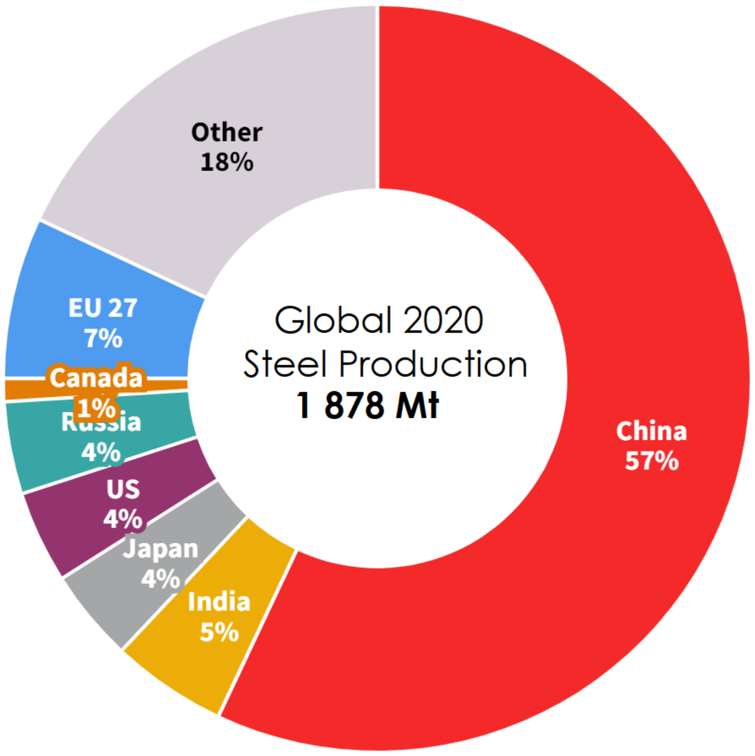
Global perspective

Martina Lyons

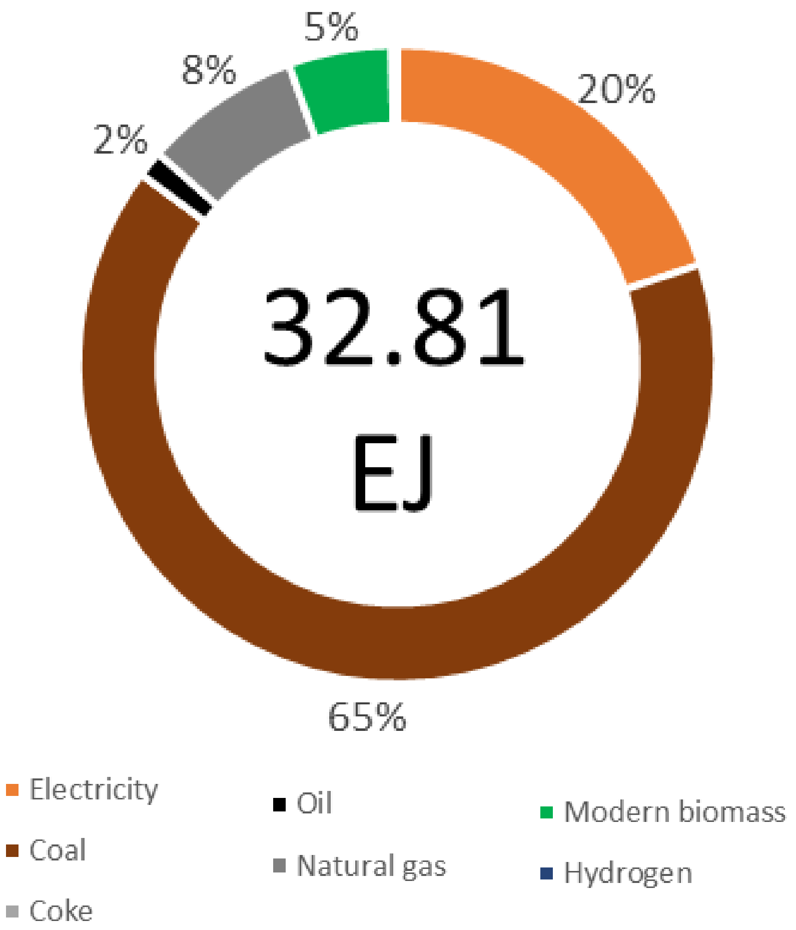
Associate Programme Officer
Innovation and End-Use Sectors
IRENA

Global Iron and Steel Production Today

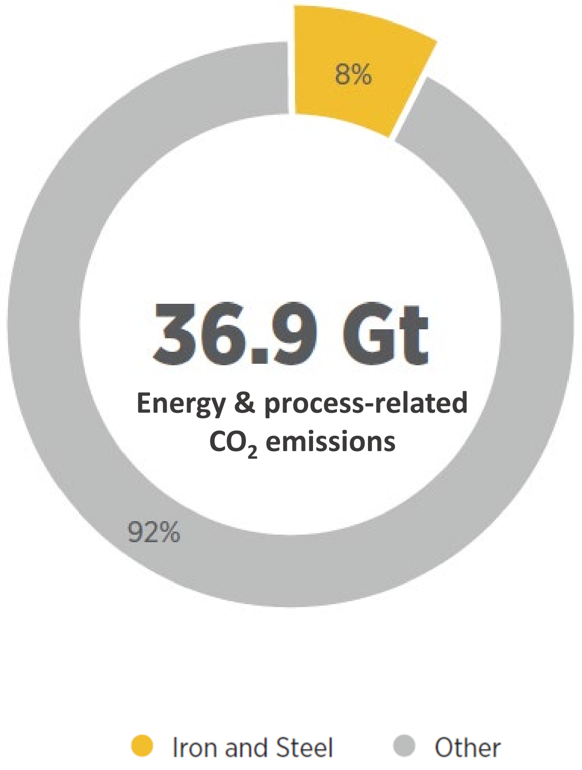
Steel production 2020



Energy usage 2020



CO_2 emissions 2018



Source: IRENA calculations

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Iron and Steel Production Existing Technologies

Iron - Steel production technologies (2020)

- 72% BF-BOF
- <1% SR-BOF
- 7% DRI-EAF

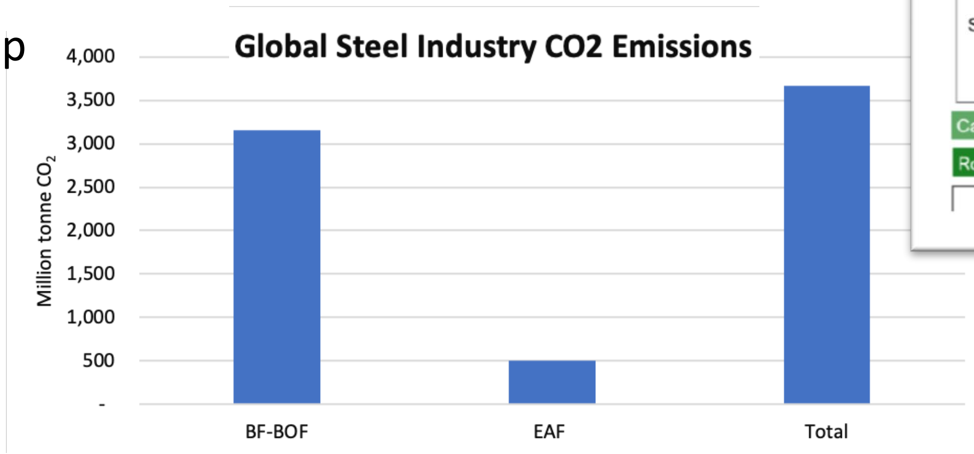
→ **Primary route**

- 22% Scrap-EAF

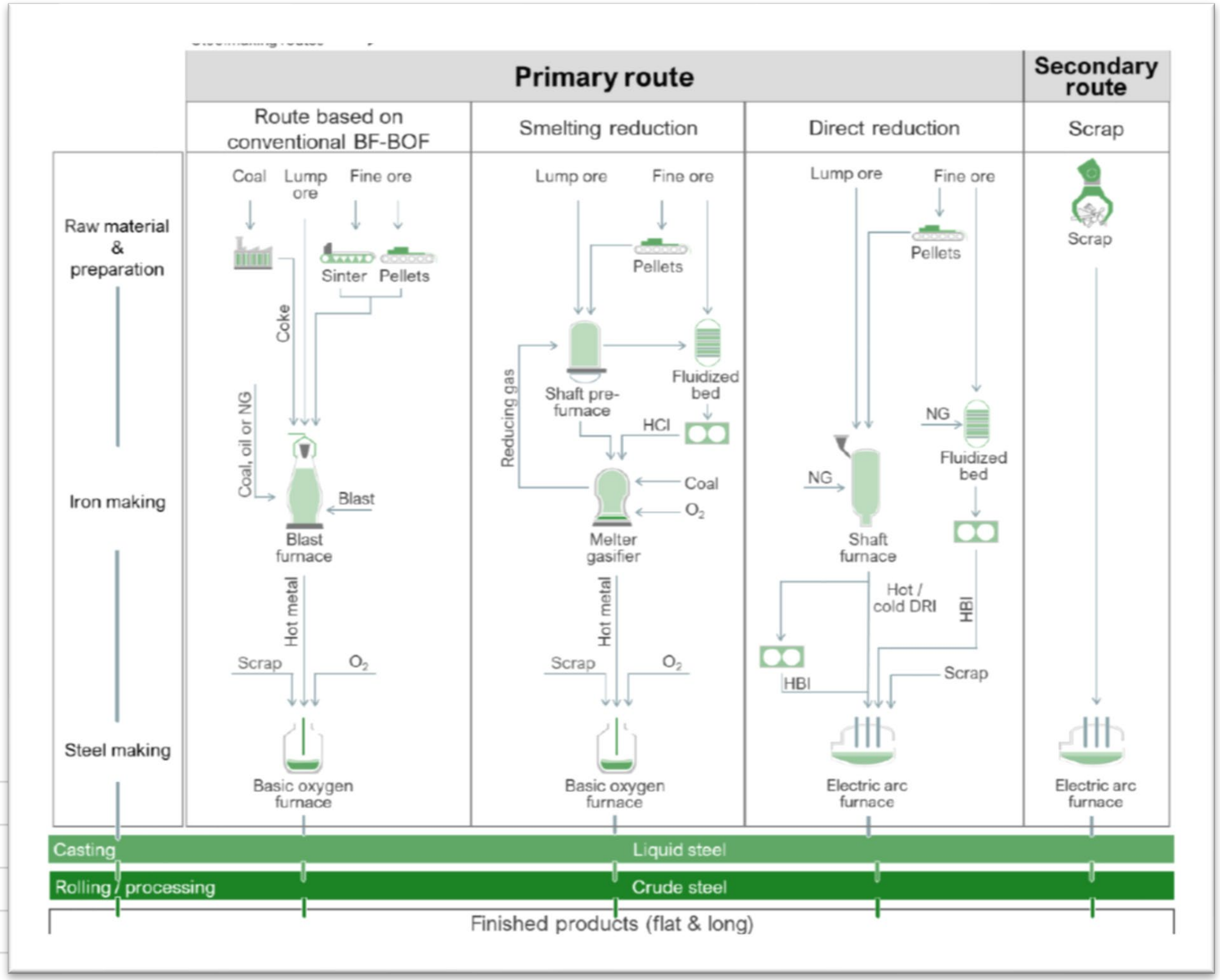
→ **Secondary route**

Iron supply (2019)

- 1 280 Mt Pig Iron (BF)
- 108 Mt DRI
- 780 Mt Scrap

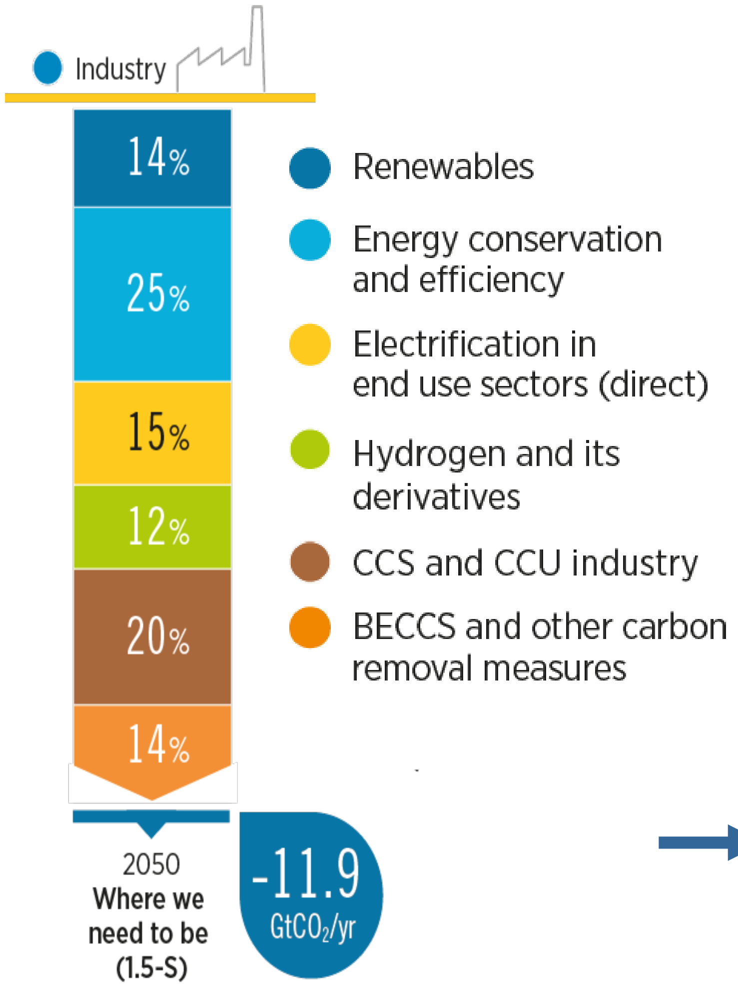


Source: WSA, MIDREX



Source: GreenSteel (2020)

Decarbonisation pathways for iron and steel



2 options compatible with reaching zero emissions

ZERO

OPTION 1: Green H_2-DRI-EAF

Hydrogen-based direct reduction of iron and electric arc furnace-based steel production

- Produce iron via the direct reduction process using clean, preferably green, hydrogen as a reducing agent.
- Produce steel using electric arc furnaces.
- Source all heat and electricity inputs from renewables.

OPTION 2: CCS or CCU

Capturing and storing process and waste emissions, and using renewables for energy

- Apply CCUS to existing iron and steel production processes.
- Source all heat and electricity inputs from renewables.

Major implications for infrastructure

power,
H_2 supply,
CO_2 transport / storage

OTHER NICHE OPTIONS

- Material use efficiency
- Recycling
- Biomass replacing coal/coke in BF-BOF

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OPTION 1: Green H2-DRI-EAF

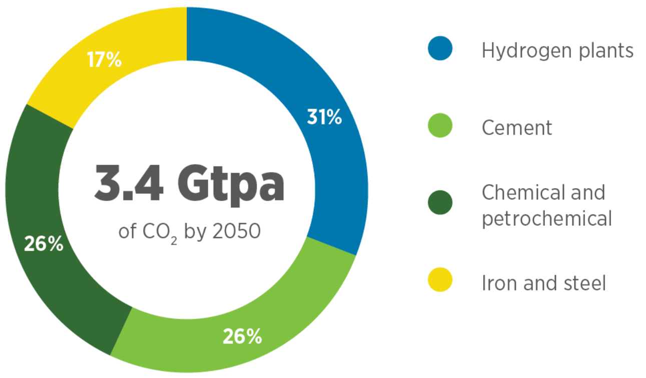
- Fossil fuel-based DRI-EAF is a mature technology (7% of total production)
- **Priority** increase development of commercial-scale **fully hydrogen-based** DRI production
- Only green H2- DRI commercial plant is HYBRIT, ArcelorMittal a big player in H2-DRI-EAF
- Several other projects →
- **Relocation** of iron-making **to areas of low-cost renewable electricity** can **reduce CO_2 emissions by nearly 1/3 ~ 0.7 Gtpa of CO_2**
- What it would entail:
  - **Investment** of USD 0.9 trillion (~ 0.7% of the total energy investment needs)
  - **7-fold increase** of **DRI production** from current DRI levels (108 Mt)
  - **5 EJ of hydrogen** needed per year (= **1%** of global primary energy supply)
- **Depends on:** energy and ore feedstock **cost**, economies of scale and **CO_2 price of more than USD 67/t**

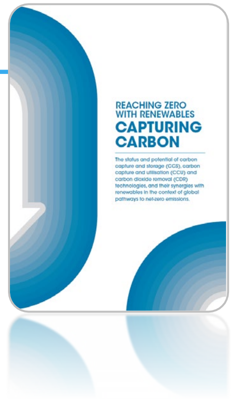
H2Hamburg (DE)	SuSteel (AT)
SALCOS (DE)	**HYBRIT (SE)**
GrInHy 2.0 (EU)	ULCOS (EU)
H2GS (SE&SP)	Paradigm Project (CN)
Green Iron Making (US)	Novel Flash Iron (US)
GREENSTEEL (AU)	POSCO & Roy Hill (AU & KR)

Projects on H2 steel making

OPTION 2: Capturing Carbon

- Putting carbon capture technology on BF-BOF / SR-BOF / DRI-EAF
- **0.6 Gtpa of CO_2 captured in 2050** in iron and steel sector according IRENA 1.5C Scenario
- **DRI-EAF: only 1 commercial project (DRI-EAF Abu Dhabi)**, there are several demonstration projects at different sages of development,
- **BF-BOF**: no plant in operation or development
- **CCS route** – requires CO_2 transport and storage infrastructure
- **CCU route** – being explored (e.g. steel and chemical companies collaborating – locating plants together)





● Pilot and demonstration
● Commercial
● Feasibility Study

Facility	Location	Capacity Mtpa/CO_2	Status: Early development	Advanced development	Under construction	Operating	Completed	Cancelled
Abu Dhabi CCS (Phase 1)	UAE	0.8				● Commercial		
ArcelorMittal Steelanol	BE	1			● Pilot and demonstration			
BHP Iron and Steel Sector CCS Project	CN	-					● Feasibility Study	
C6 Resources CCS Project United States	USA	-						● Pilot and demonstration
COURSE 50	JP	0.01				● Pilot and demonstration		
DMX demonstration in Dunkirk	FR	0.5		● Pilot and demonstration				
SEWGS-STEPWISE	SE	0.005				● Pilot and demonstration		
ULCOS Florange	FR	0.5				● Pilot and demonstration		
ULCOS HIsarna CCS	DE	0.8	● Pilot and demonstration					
White Biotech CCS	CT	-				● Pilot and demonstration		

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Ten priorities for action

Co-develop strategies & plans		Address enabling conditions		Enhance business models	
Pursue a renewables-based with an end goal of zero emissions.	Develop a shared vision and strategy and co-develop practical roadmaps.	Build confidence and knowledge among decision makers.	Plan and deploy enabling infrastructure early on.	Foster early demand for green products and services.	Develop tailored approaches to ensure access to finance.
• Requires linked sectoral strategies at the local, national and international levels • Plans built on the five technology pillars.	• Must be supported by all key actors • So co-develop with broad engagement nationally and internationally to build consensus. • International and inter-governmental bodies can assist.	• Decision makers need to better understand the risks. • Many more demonstration and lighthouse projects are needed. • Those who can must lead, showing what is possible.	• New approaches will require substantial new infrastructure. • Investment needs to come ahead of the demand. • Requires carefully co-ordinated planning & targeted incentives.	• Creating early sources of demand for green fuels, materials, products and services will help scale of production and reduce costs. • Use public procurement, corporate sourcing, regulated minimum percent requirements, etc.	• Sectors have specific needs i.e., high CAPEX, long payback periods, etc. • So tailored financial instruments along the whole innovation cycle are needed. • Co-operation between public and private financial institutions can help.

Work international			Support further innovation
Collaborate across borders.	Think globally, utilise national strengths.	Establish pathways for evolving regulation & international standards.	Support RD&D and systemic innovation.
• A global challenge, and the solutions needed are complex and expensive. • Countries working alone will not be able to explore all options in the necessary depth. • Countries can share the burden.	• Relocating industrial production to access low-cost renewable energy could reduce costs and create new trade opportunities. • Countries with large or expanding production should be supported in getting on the right (zero-carbon-compatible) track early on.	• Regulations and standards are both enablers and barriers for change • Requires careful planning to ensure that they shift at the same pace as the technological changes.	• Large gaps in capability and large cost differences still remain. • Increased investment in RD&D is needed across a range of technologies to reduce costs, improve performance and broaden applicability. • Innovation support needs to be systemic.

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Thank you!

Martina Lyons

Innovation and Technology Centre

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Canadian perspective

John Smiciklas

Interim Director, Environment
Canadian Steel Producers
Association

Canadian Steel Producers Association (CSPA) – Who we are

- The CSPA represents Canada's primary steel producers and pipe and tube manufacturers
- Canada's steel producers represent a $15B industry
- Domestic steel operations support 123,000 direct and indirect jobs
- A critical supplier to North American automotive, construction, energy and other manufacturing sectors
- Highly skilled workforce in a high-tech manufacturing environment

CSPA's Members

ALGOMA STEEL INC.

AltaSteel

ArcelorMittal DOFASCO | HAMILTON

ArcelorMittal Long Products Canada

Atlas Tube A DIVISION OF ZEKELMAN INDUSTRIES

EVRAZ

GERDAU

IVACO ROLLING MILLS

NOVA STEEL

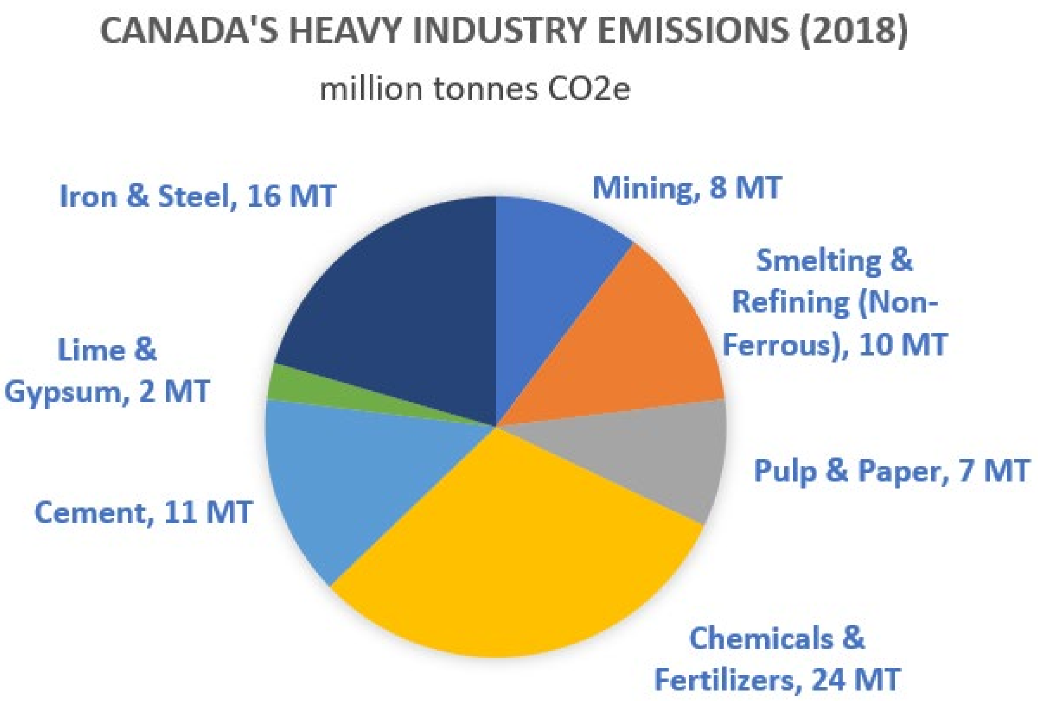
RioTinto Fer et Titane

STELCO

Tenaris

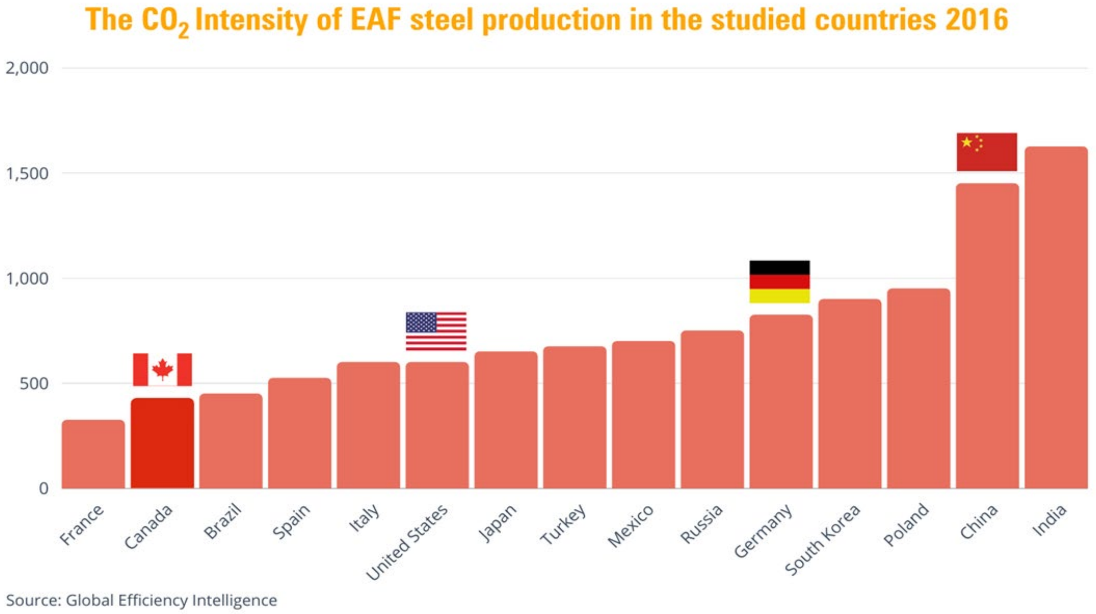
VALBRUNA ASW INC.

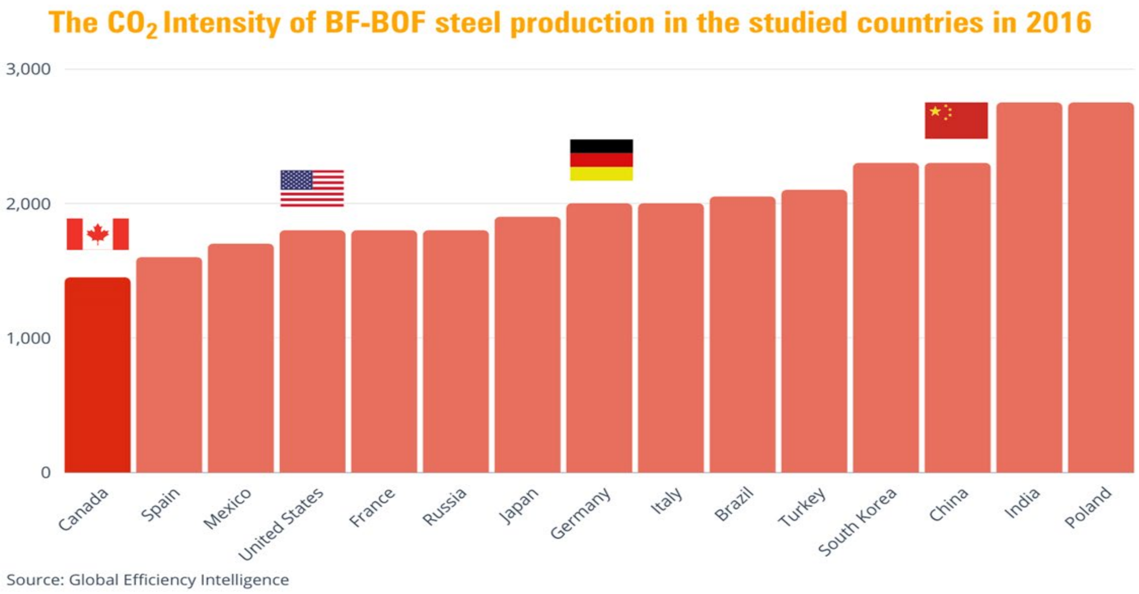
Canadian Steel Sector Emissions



- Steel sector GHG emissions ~16MT (or 2% of Canada's GHG emissions)
  - ~85% of emissions from Ontario operations
- Since 1990 to 2018:
  - 17% reductions in absolute GHG emissions
- Announced projects at ArcelorMittel Dofacso and Algoma will remove 6MT annually

Canadian Green Steel





Canadian steel is amongst the lowest CO_2 intensity steel in the world

2050

CANADA'S STEEL PRODUCERS HAVE THE AMBITION TO ACHIEVE NET-ZERO CO_2 EMISSIONS BY 2050.

Climate Call to Action released March 2020

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Thank you!

John Smiciklas
Canadian Steel Producers Association

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Canada

Session 4: Decarbonisation of Iron And Steel - PANEL

Moderator

Ted Todoschuk
Board Chairman
Canadian Carbonization
Research Association

Panellists

Chad Cathcart
Director of
Research
Stelco

Kashif Rehman
Director of Product
Development &
Technology
Algoma Steel

Ka Wing Ng
Research Scientist,
Canmet - NRCan

Tony Valeri
Vice President
Corporate Affairs
ArcelorMittal
Dofasco

Jean-Pierre Birat
CEO
IF Steelman

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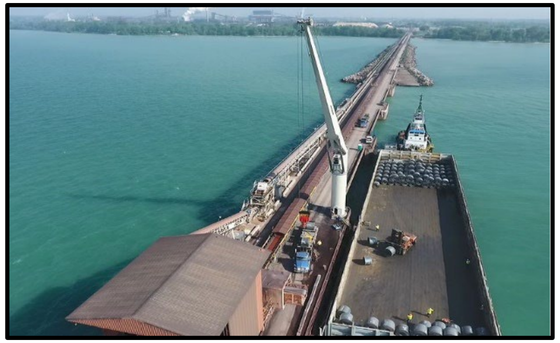
Session 4: Decarbonisation of Iron And Steel

Chad Cathcart

Director of Research
Stelco

Stelco Today – An Iconic Canadian Company



- Stelco is a leading producer of flat rolled sheet steel in North America
- Operations in both Nanticoke and Hamilton, Ontario
- Capable of producing approximately 3 million net tons of steel annually
- Since 2017, more than $700 million in strategic investments
- Publicly traded on TSX under the ticker "STLC"
- Employs 2,200 people in high-quality jobs
- Supports approximately 10,000 pensioners and their families

OUR PRODUCT RANGE

Coke

Hot-Rolled Sheet

Cold-Rolled Fully Processed

Pig Iron

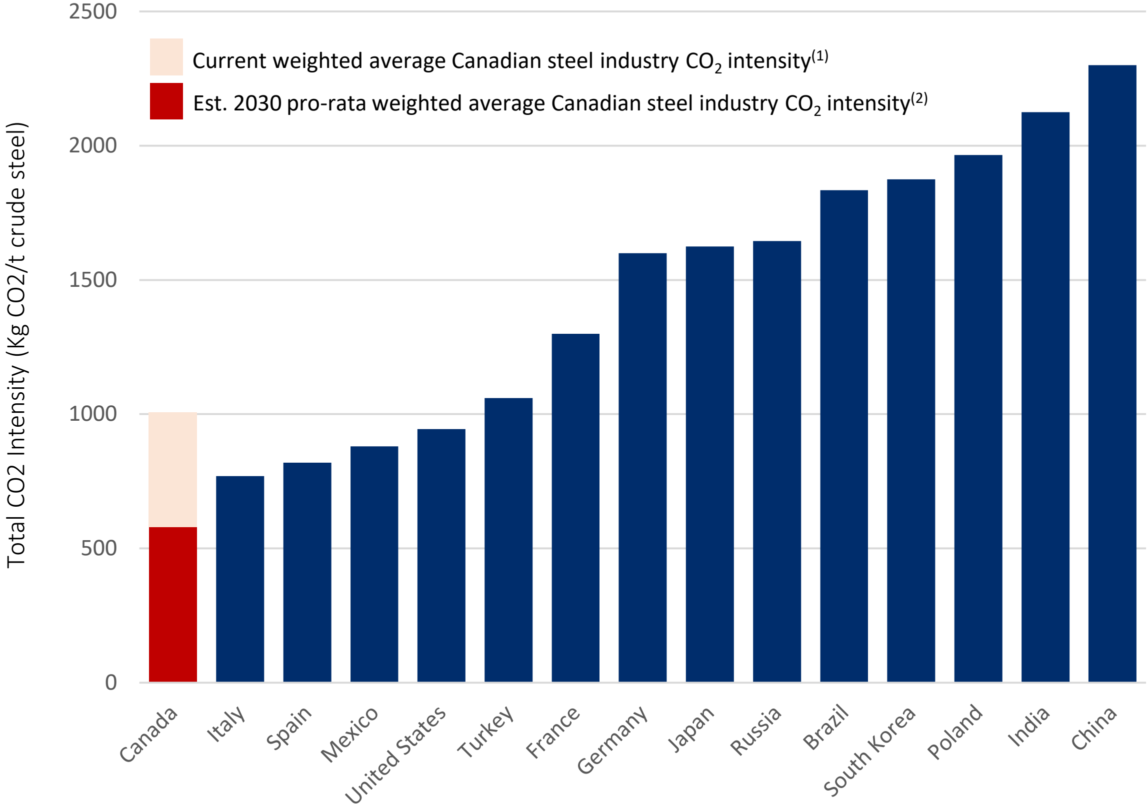
Pickled Sheet

Galvanized and Galvannealed Sheet

Slabs

Cold-Rolled Full Hard

World Class Emissions Profile – Canadian Industry Already Global Leaders



- A 2019 international benchmarking study[1] indicated Canada's steel producers have the 5th lowest total CO_2 intensity of global steel producers (blend of integrated and EAF producers). The report notes that 45% of Canada's steel production is by EAF producers
- Following the planned transition of two Canadian steelmakers from integrated to EAF steelmaking and Stelco achieving potential GHG reductions associated with currently planned projects, **the Canadian industry will improve its CO_2 intensity by more than 40%[3] and have the lowest CO_2 intensity in the world**

The Canadian steel industry on a whole is on track to reduce emissions intensity by **more than 40% by 2035**.
This is consistent with the Government of Canada's GHG reduction commitments.

(1) Global Efficiency Intelligence, How Clean is the U.S. Steel Industry?, November 2019
(2) Estimated pro-rata CO2 intensity assumes complete transition of two integrated Canadian steelmakers to EAF production per respective company disclosures and assumes Stelco's completion of currently planned objectives to eliminate accessible emissions
(3) Weighted industry intensity Based on reported WorldSteel production volumes for BOF an EAF producers in Canada and assumes Stelco will produce 3 million net tons

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Investing in Improved Production and Lower GHG Emissions

Over $700 million in strategic investments since 2017 – all funded with internally generated cash flow – to support our future as a green, integrated steelmaker

Smart Blast Furnace Upgrade
- Commenced operations at North America's only smart blast furnace in Q4 2020
- Modernization and upgrade project implemented best-in-class technologies from around the globe
- Increased production capacity by ~300k net tons of additional hot metal per year

Coke Battery Upgrades
- Full rehabilitation and upgrade of Lake Erie Works coke battery nearing completion
- Highly engineered strategic investment will increase coke production, improve environmental performance, lower costs and reduce greenhouse gas emissions

Electricity Co-Generation Project
- Currently under construction, the 65MW CoGen will reduce reliance on the provincial electricity grid
- Anticipate up to $20 million in annual electricity cost savings via improved productivity when responding to 5CP peaks
- Consumption of off-gas fuels will reduce our greenhouse gas emissions

Electric Vehicle Battery Recycling Initiative
- Licensing and option agreement with Primobius to commercialize their proprietary lithium-ion battery recycling technology
- Proposed 20,000 ton per annum integrated battery shredding and hydrometallurgical refinery.
- Provide a robust closed-loop EV recycling solution for North America

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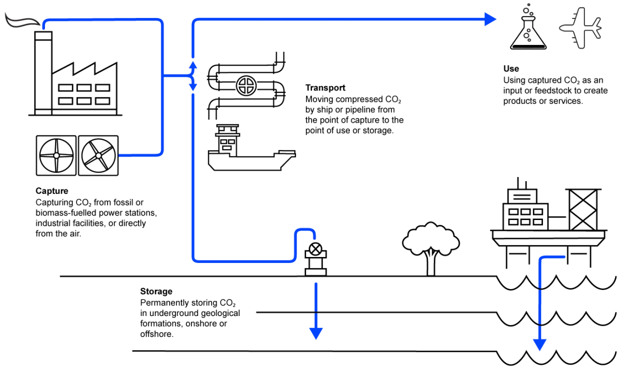
The Path Towards Net-Zero



CARBON CAPTURE, STORAGE AND UTILIZATION (CCUS)

- Stelco has been at the forefront of CCUS in the industry through partnerships and collaborations aimed at not only capturing our CO2, but finding productive uses and markets for alternative products
- Several unique opportunities are being explored in the CCUS space that could further position Canada as a global industry leader

HYDROGEN AND OTHER PRODUCTION ALTERNATIVES

- As new production technologies continue to evolve, one of the challenges we face is the production of enough green hydrogen to support our collective operations
- Substantial assistance will be required from governments to support the development of the necessary infrastructure including massive investments in renewable electricity generation and hydrogen supply chain development
- Stelco is well positioned in the Ontario context with 96% of electricity generation already coming from non-carbon emitting sources[1]

(1) Canada Energy Regulator, 2018.

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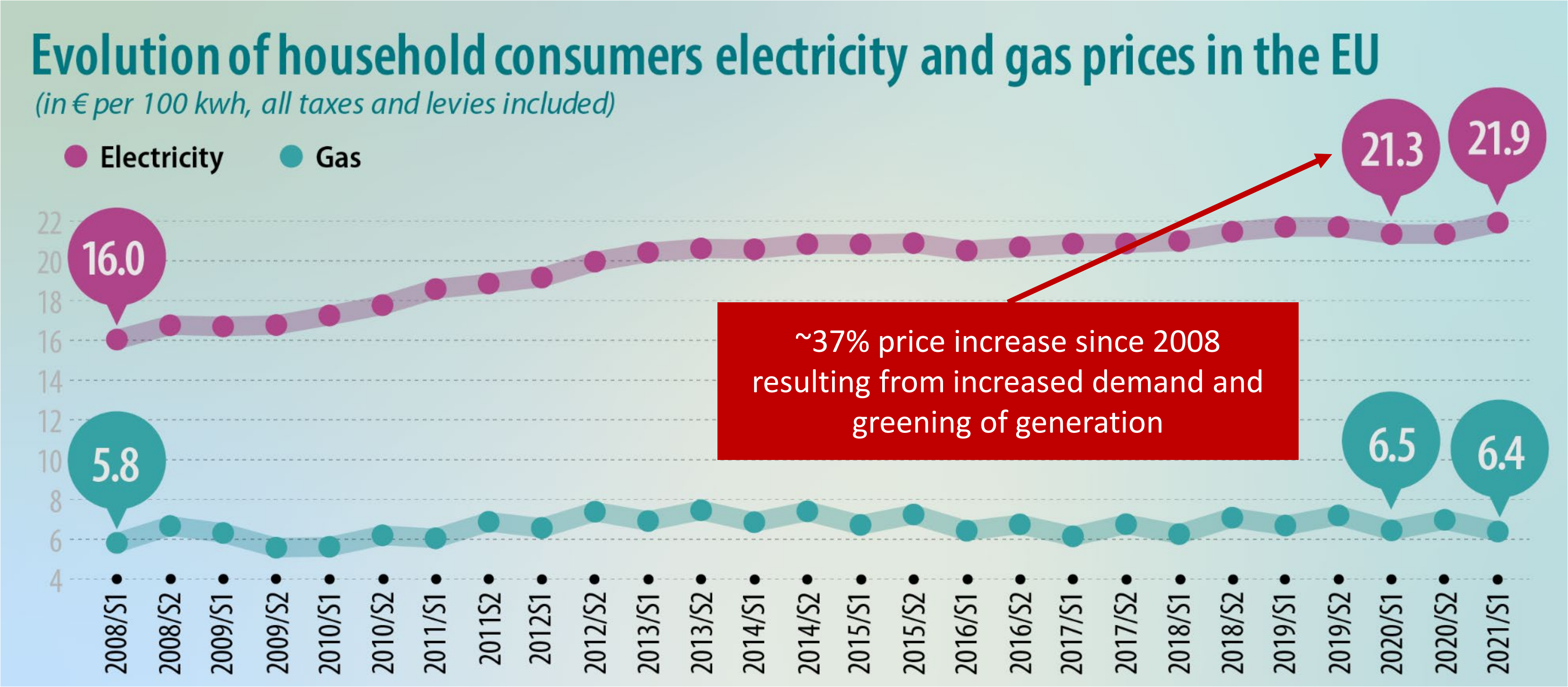
Electricity Demand Driving Higher Prices

STELCO

DEMAND FROM ALL SECTORS FOR ZERO-CARBON ELECTRICTY INCREASING

- Power demand is projected to be 1.5x 2019 levels by 2030 and more than 3x by 2050
- Transition to electric vehicles (EV) as well as the increases in demand for electric heating for buildings are major drivers of the projected increase
- The electrification of industry is also a key driver of the increase in demand, including for H2 generation
- Concern is the economic feasibility of the transformation as demand for non-carbon emitting generation is at risk of outpacing supply growth



Sources: McKinsey & Company; ec.europa.eu/Eurostat, October 2021; euronews.com

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Stelco's Pathway to Net-Zero – A Sustainable Approach

- Stelco is committed to the pursuit of transformative technology that will allow our business to remain profitable and sustainable

- Breakthrough technology must be supported by adequate infrastructure and the pursuit of net-zero emissions must balance economic feasibility and environmental sustainability

- We are engaging with leading researchers to develop these technologies and forge partnerships that will not only transform our business but also create a foundation for future growth

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Thank you!

Chad Cathcart
Stelco

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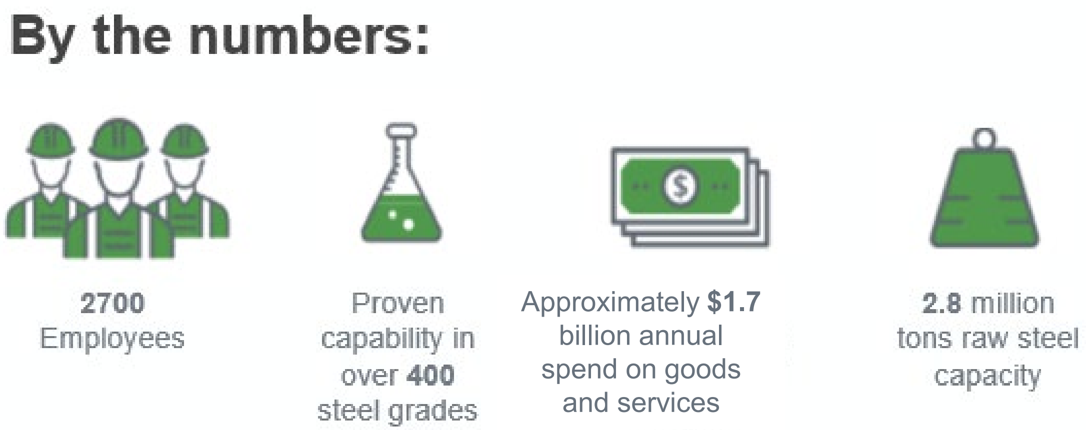
Session 4: Decarbonisation of Iron And Steel

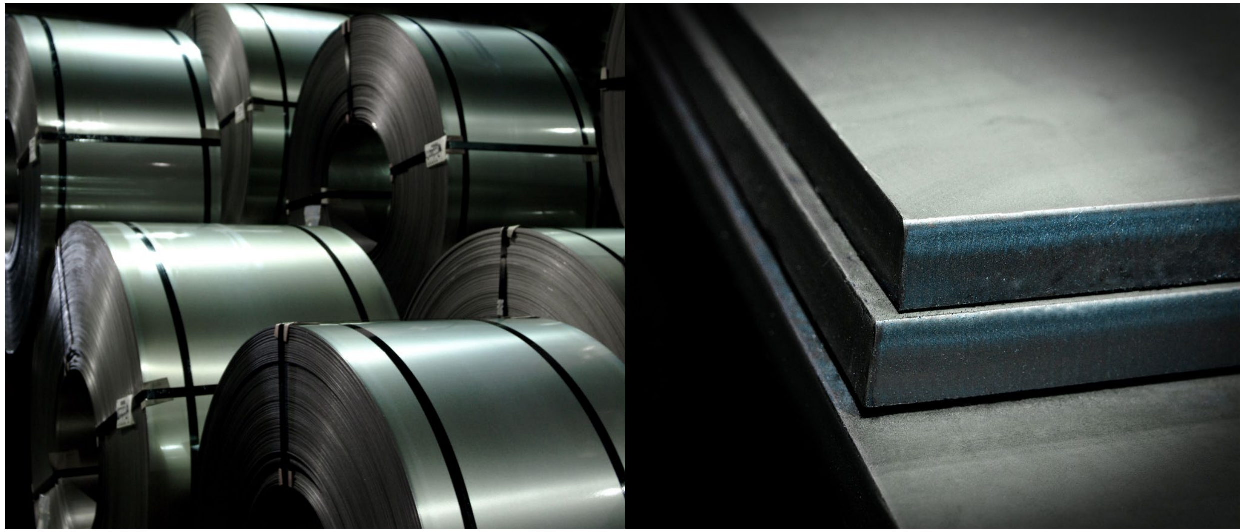
Kashif Rehman

Director of Product Development & Technology
Algoma Steel

Your Partner in Steel Since 1901

- Based in Sault Ste. Marie, Ontario, Canada, Algoma Steel is a fully integrated producer of hot and cold rolled steel products including sheet and plate
- Algoma's size and diverse capabilities enable us to deliver responsive, customer-driven product solutions straight from the ladle to direct applications in the automotive, construction, energy, defense, and manufacturing sectors
- Algoma is a key supplier of steel products to customers in Canada and Midwest USA and is the only discrete plate producer in Canada
- Today Algoma is on a transformation journey, investing in its people and processes, optimizing and modernizing to secure a sustainable future. Our customer focus, growing capability and courage to meet the industry's challenges head-on, position us firmly as your partner in steel





Algoma Invests $700M in Transition to Electric Arc Steelmaking

- In November, 2021 Algoma Steel Inc. announced its decision to invest CDN $700 million in the transition to electric arc steelmaking
- Two state-of-the-art electric arc furnaces will replace its existing basic oxygen steelmaking operations and result in the elimination of Cokemaking
- This process change is expected to:
    - shrink environmental footprint dramatically, reducing greenhouse gas emissions by up to 70% and positioning Algoma as one of the leading producers of green steel in North America
    - increase liquid steel capacity from 2.8 to 3.7 million tons
    - enhance product quality with new vacuum degassing capability to expand Algoma's offering of steel plate grades
    - create at least 500 new construction jobs in the region and provide more apprenticeships, co-op placements, and high-skill career opportunities

Algoma's Shrinking Environmental Footprint

Algoma's process change will shrink Algoma's environmental footprint dramatically, **reducing greenhouse gas emissions by up to 70%**[1] and positioning Algoma as one of the leading producers of green steel in North America.

Other benefits include:

Quieter
Fewer noise sources.

Less Waste
Fewer by-product streams.

Cleaner Water
Fewer effluent discharges.

Cleaner Air
Lower emissions from fewer sources.

		Preliminary Estimated Reduction[1]	% Reduction
GHG Emissions	$C0^2$	3.0 MM tonnes	70%
	$C0_2$ /NT production	1.33 tonnes	75%
SOx Emissions		4,060 tonnes	82%
NOx Emissions		1,604 tonnes	52%
Cokemaking Emissions		Complete elimination of Cokemaking Stack and Fugitive Emissions	100%

Note (1): Source: Company information. Expected environmental benefits from the EAF are based on projected estimates for Algoma, using published data sources for similar technologies. Estimated benefits based on current production versus forecasted production of 3.0MM tons of steel shipments produced under full, exclusive EAF configuration.

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Proposed Operational Transition to Electric Arc Steelmaking

Production Method

NOV 2021-2024	APR-2024	2025	2026	2029 LONG-TERM
CONSTRUCTION PERIOD	COMMISSION RAMP	PRODUCT CERTIFICATION	ALTERNATING HYBRID MODE ("EAF PHASE I")	INDEPENDENT MODE ("EAF PHASE II")
Coke Ovens 7,8,9	Coke Ovens 7,8,9	Coke Ovens 8, 9	Coke Ovens 8,9	
Blast Furnace 7	Blast Furnace 7	Blast Furnace 7	Blast Furnace 7	
Oxygen Steelmaking	Oxygen Steelmaking	Oxygen Steelmaking		
	EAF 1| EAF 2	EAF 1| EAF 2 *(Alternating Mode)*	EAF 1| EAF 2 *(Alternating Mode with 30% hot metal from BF)*	EAF 1| EAF 2 (With full power upgrades; no LSP power required)
				100% Cold Charge Scrap *(option for alternate iron units)*

Phase I

Operations would alternate arcing on one furnace at a time with approximate 30% hot metal charge from No. 7 Blast Furnace (input power constraint).

Phase II

Operate both electric arc furnaces simultaneously with 100% cold charge, including obsolete and prime scrap with option for addition of alternate iron units, such as HBI or pig iron as required. Fully powered by the Ontario grid.

Note: 2025 onwards, No. 7 Blast Furnace will operate at a lower rate.

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Kashif Rehman
Algoma Steel

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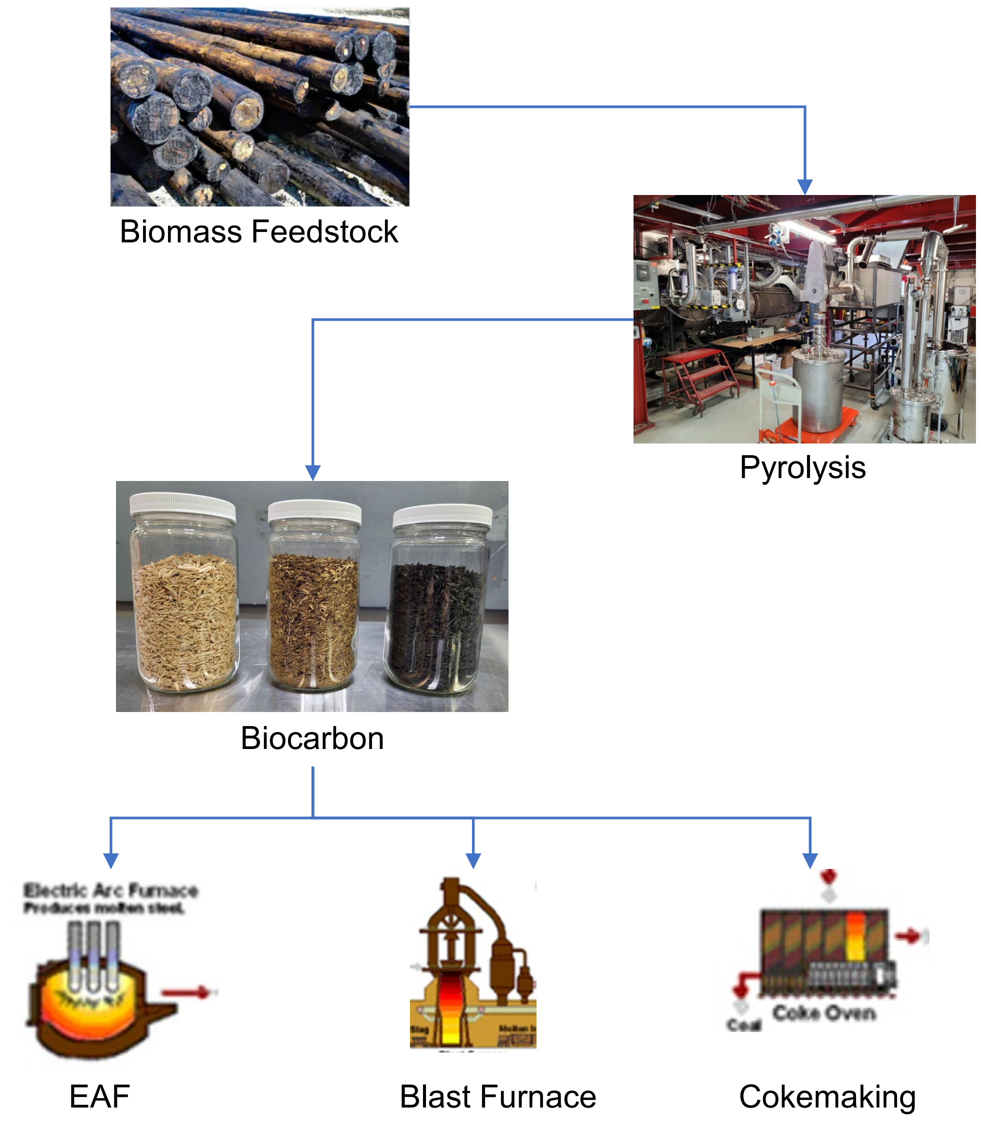
Session 4: Decarbonisation of Iron And Steel

Ka Wing Ng

Research Scientist
Canmet - NRCan

Current Efforts: Reduce GHG Emissions by Fuel Switching

- **Fuel Switching**
  - Substitution of coal by renewable solid biocarbon in existing ironmaking and steelmaking process
  - Utilization of suitable biocarbon in existing steel production instead of developing new steel production processes to enable utilization of existing biocarbon
  - Raw biomass cannot be used directly. Enhancement of biomass properties by pyrolysis is needed
  - Biocarbon is used as a reducing agent, not just an energy source
- **Limitation**
  - Not addressing the emissions arising from heat demands in the process, especially in the downstream product finishing
  - The design of existing blast furnaces in Canada does not allow complete replacement of coal by biocarbon
  - Fossil fuel is still needed



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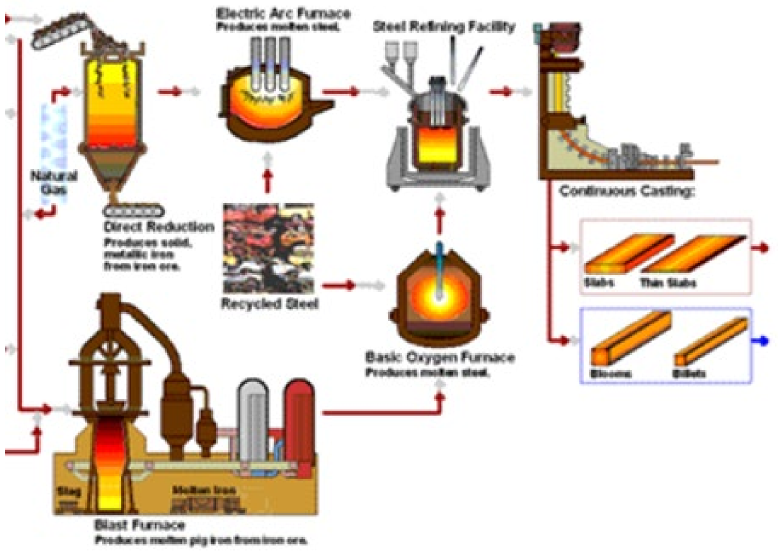
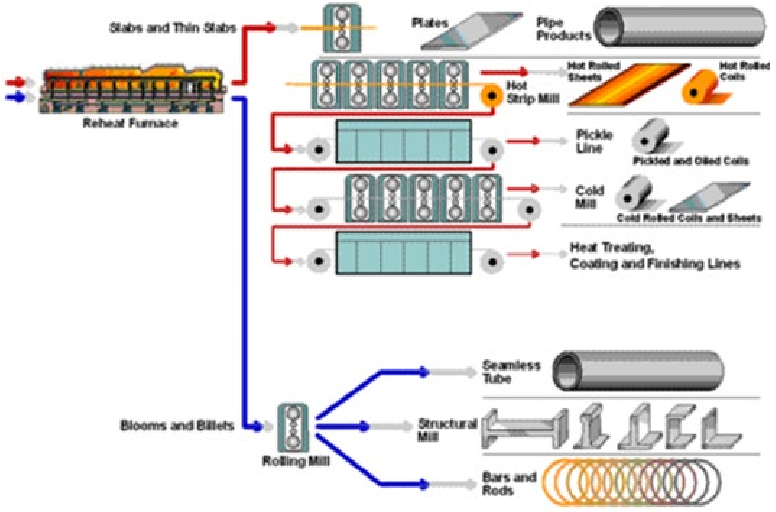
Future R&D to Achieve Near Net Zero Emissions

- **Alternate Reductant (H2, Biocarbon, Electron)**
  - Production and utilization of alternate reductants to reduce iron ore into metallic iron in existing and new steelmaking processes
- **Alternate Heating (Renewable Fuels and Non-Emitting Electricity)**
  - Replacement of fossil fuel consumption for heating by renewable fuels and/or non-emitting electricity
  - Recovery and utilization of waste heat
- **CO2 Capture, Utilization and Storage**
  - Application of CO2 capture, utilization and storage in steel production routes
- **System Integration and Optimization**
  - Integration of alternate reductant and alternate fuel productions and CCS with steel production processes
  - Impact of upstream decarbonisation strategies on downstream processes





Canmet Research Centers

- Studies a wide array of clean energy technologies R&D and Implementation
- Coordination of efforts between technology centers to assist the Canadian steel industry to achieve near net zero emissions

Devon (Alberta)

CanmetENERGY in Devon is at the forefront of technology innovation for developing energy resources, to reduce the carbon intensity of hydrocarbon products and mitigate impacts to land, water and greenhouse gas. We focus on novel technologies for extraction, upgrading, refining, bioenergy/biofuels and oil spill science.

Ottawa (Ontario)

CanmetENERGY in Ottawa conducts R&D on a wide array of clean energy technologies. We are working to improve existing technologies and methods, while pioneering novel ones, with the goal of reducing greenhouse gas emissions, improving energy efficiency, and making clean energy technologies economically competitive with traditional approaches.

Varennes (Quebec)

CanmetENERGY in Varennes leads innovative science research and activities for the industry, buildings and renewable energy sectors. Our teams of experts design and implement clean energy solutions, and build on knowledge that helps produce and use energy in ways that are more efficient, valuable and sustainable.

Hamilton (Ontario)

CanmetMATERIALS is the largest research centre in Canada dedicated to fabricating, processing and evaluating metals and materials. Scientific and technical staff in Hamilton and Calgary research and develop materials solutions for Canadian industry in the energy, transportation and metal-manufacturing sectors.

https://www.nrcan.gc.ca/science-and-data/research-centres-and-labs/22054

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Ka Wing Ng
Canmet - NRCan

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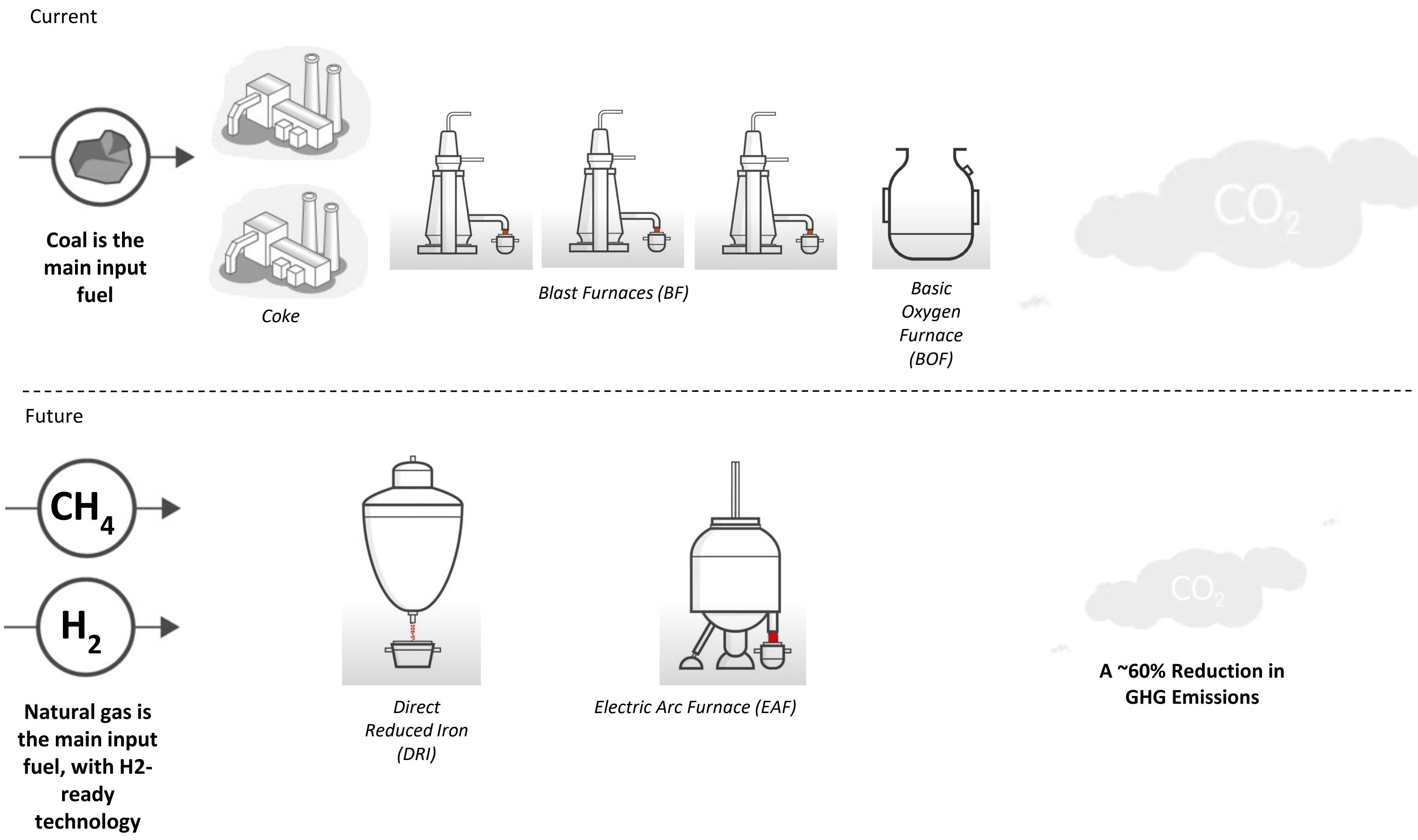
Session 4: Decarbonisation of Iron And Steel

Tony Valeri

Vice President Corporate Affairs
ArcelorMittal Dofasco

Decarbonizing our Hamilton Operations while supporting our demanding product mix



In the new DRI – EAF Stream

- Steel slabs will support the same highly demanding and innovative product mix, making Dofasco the first integrated plant in the world to make the transition.
- High DRI charge (up to 100% of the charge) ensures we will tap BOF-quality steel and meet all existing chemical capabilities, with significantly reduced CO2 impact.
- **60%** CO2 reduction

XCarb®
Towards carbon neutral steel

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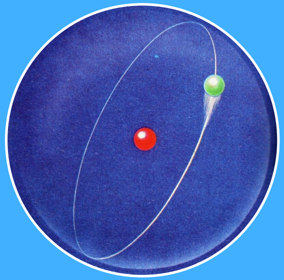
Net Zero Strategy Pillars – Complementary Pathways

Alternative Reductants (Removing Fossil Carbon) | Carbon Management

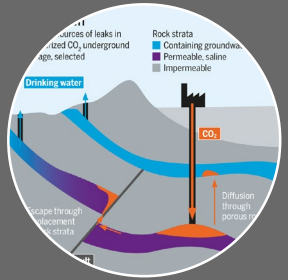


Hydrogen

Bioenergy

Electrification

CCU



CCS

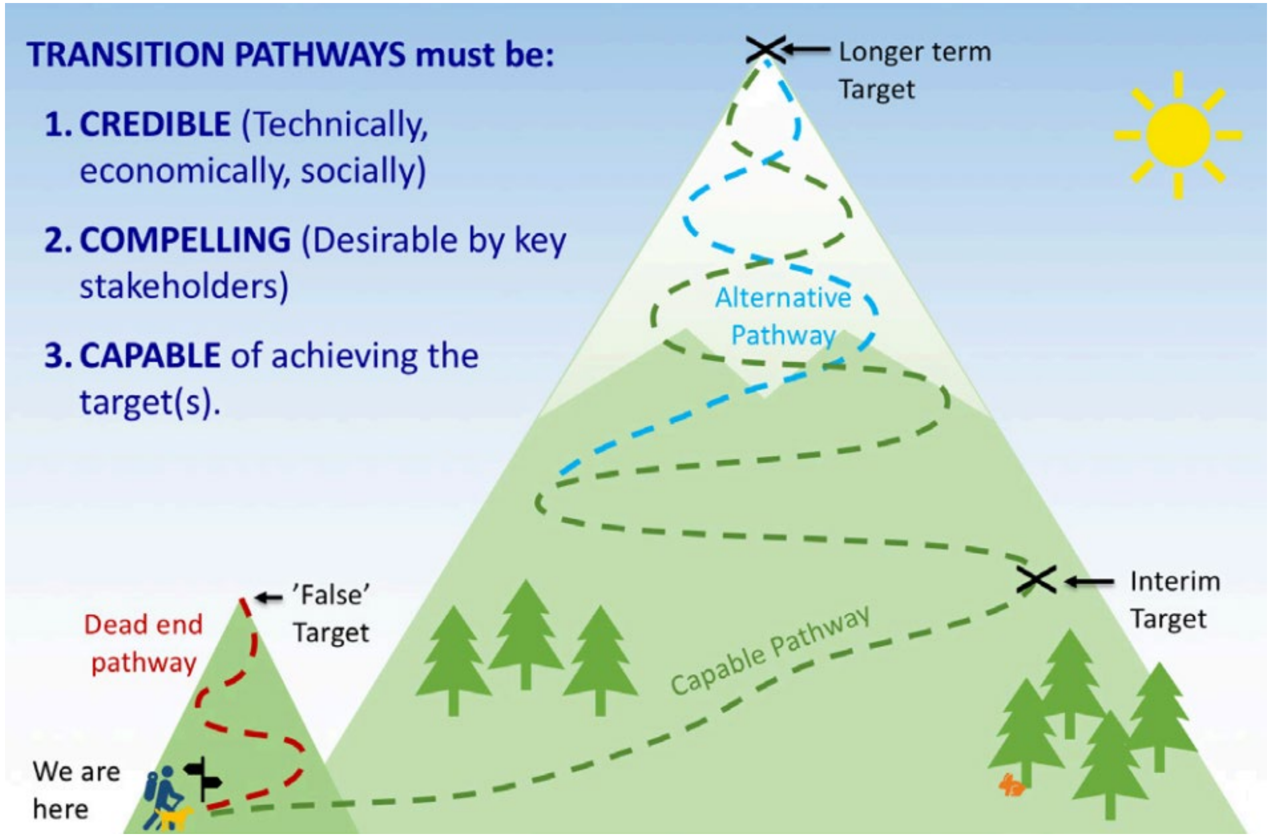
General CO_2 Reduction Opportunities & Pathway Synergies

There are several pathways to decarbonize with varying scopes and timelines

Net Zero Feedstocks for Heavy Industry & Society

What is needed for Net Zero 2050?

- Securing new forms of energy will require a demand-driven push to deliver energy that works for transforming industries.
- These pathways to change must be compelling for businesses to invest. Roadblocks can be identified along the pathway in advance of reaching them.
- Large industrials and government, in partnership with energy providers, need to find the path forward and start executing on projects.
- An inter-industrial, collaborative means of action is required to successfully achieve change.



D. Layzell & J. Lof, "The Future of Freight – Part A", (2019)

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Thank you!

Tony Valeri
ArcelorMittal Dofasco

IRENA
International Renewable Energy Agency

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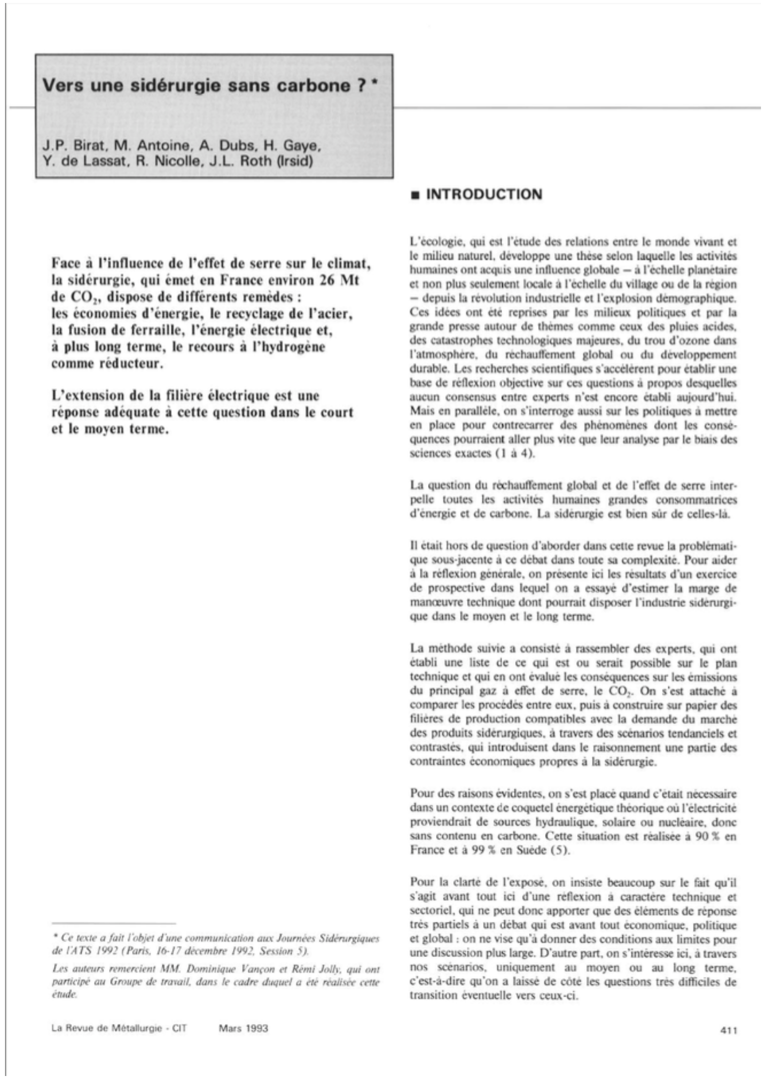
Jean-Pierre Birat

CEO
IF Steelman

First set of solutions to decarbonise iron and steel in 1992

J-P Birat, M. Antoine, A. Dubs, H. Gaye, Y. de Lassat, R. Nicolle, J-L Roth, *Vers une sidérurgie sans carbone? (towards net-zero steelmaking?)*, Journées sidérurgiques 1992, Paris, 16-17 December, **1992**, invited lecture, & Revue de Métallurgie 90 (**1993**) Mars p.411-421

- 1992 - my first paper on low-carbon steelmaking
- 1989 - aware of the issue of climate change, gathered a group of people inside **IRSID** where I worked (Institut de recherche de la sidérurgie) - the former name of a private research centre of ArcelorMittal Maizières Research SA
- We spent some time wondering how serious the problem was and analyzing what the steel sector could do about it
- We did not speak of net-zero then, but came up with **a set of over 120 solutions** that are identical to ones on the table today



Vers une sidérurgie sans carbone ? *

J.P. Birat, M. Antoine, A. Dubs, H. Gaye, Y. de Lassat, R. Nicolle, J.L. Roth (Irsid)

Face à l'influence de l'effet de serre sur le climat, la sidérurgie, qui émet en France environ 26 Mt de CO_2, dispose de différents remèdes : les économies d'énergie, le recyclage de l'acier, la fusion de ferraille, l'énergie électrique et, à plus long terme, le recours à l'hydrogène comme réducteur.

L'extension de la filière électrique est une réponse adéquate à cette question dans le court et le moyen terme.

■ INTRODUCTION

L'écologie, qui est l'étude des relations entre le monde vivant et le milieu naturel, développe une thèse selon laquelle les activités humaines ont acquis une influence globale – à l'échelle planétaire et non plus seulement locale à l'échelle du village ou de la région – depuis la révolution industrielle et l'explosion démographique. Ces idées ont été reprises par les milieux politiques et par la grande presse autour de thèmes comme ceux des pluies acides, des catastrophes technologiques majeures, du trou d'ozone dans l'atmosphère, du réchauffement global ou du développement durable. Les recherches scientifiques s'accélèrent pour établir une base de réflexion objective sur ces questions à propos desquelles aucun consensus entre experts n'est encore établi aujourd'hui. Mais en parallèle, on s'interroge aussi sur les politiques à mettre en place pour contrecarrer des phénomènes dont les conséquences pourraient aller plus vite que leur analyse par le biais des sciences exactes (1 à 4).

La question du réchauffement global et de l'effet de serre interpelle toutes les activités humaines grandes consommatrices d'énergie et de carbone. La sidérurgie est bien sûr de celles-là.

Il était hors de question d'aborder dans cette revue la problématique sous-jacente à ce débat dans toute sa complexité. Pour aider à la réflexion générale, on présente ici les résultats d'un exercice de prospective dans lequel on a essayé d'estimer la marge de manœuvre technique dont pourrait disposer l'industrie sidérurgique dans le moyen et le long terme.

La méthode suivie a consisté à rassembler des experts, qui ont établi une liste de ce qui est ou serait possible sur le plan technique et qui en ont évalué les conséquences sur les émissions du principal gaz à effet de serre, le CO_2. On s'est attaché à comparer les procédés entre eux, puis à construire sur papier des filières de production compatibles avec la demande du marché des produits sidérurgiques, à travers des scénarios tendanciels et contrastés, qui introduisent dans le raisonnement une partie des contraintes économiques propres à la sidérurgie.

Pour des raisons évidentes, on s'est placé quand c'était nécessaire dans un contexte de coquetel énergétique théorique où l'électricité proviendrait de sources hydraulique, solaire ou nucléaire, donc sans contenu en carbone. Cette situation est réalisée à 90 % en France et à 99 % en Suède (5).

Pour la clarté de l'exposé, on insiste beaucoup sur le fait qu'il s'agit avant tout ici d'une réflexion à caractère technique et sectoriel, qui ne peut donc apporter que des éléments de réponse très partiels à un débat qui est avant tout économique, politique et global : on ne vise qu'à donner des conditions aux limites pour une discussion plus large. D'autre part, on s'intéresse ici, à travers nos scénarios, uniquement au moyen ou au long terme, c'est-à-dire qu'on a laissé de côté les questions très difficiles de transition éventuelle vers ceux-ci.

** Ce texte a fait l'objet d'une communication aux Journées Sidérurgiques de l'ATS 1992 (Paris, 16-17 décembre 1992, Session 5).*

Les auteurs remercient MM. Dominique Vançon et Rémi Jolly, qui ont participé au Groupe de travail, dans le cadre duquel a été réalisée cette étude.

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First European and worldwide projects on the production of green steel

JP. Birat, JP. Lorrain, Y. de Lassat, *The "CO_2 tool": CO_2 emissions and energy consumption of existing and break-through steelmaking routes,* La Revue de Métallurgie-CIT, Sept. **2009**, 325-336

JP. Birat, JP. Lorrain, Y. de Lassat, *The "cost tool",* La Revue de Métallurgie-CIT, Sept. **2009**, 337-349

- 10 years for the topic of the previous paper to go beyond working groups (like at IISI), reports and modeling publications
- In 2004, 2 large international research projects were launched:
  1. in EUROPE called **ULCOS**, financed by the EU,
  2. Worldwide - run by the **WorldSteel** organization
- 2 papers present series of investigated and analyzed 60 process routes between then and 2050 in terms of:
  - energy needs
  - CO_2 emissions
  - cost of production
- Following the analysis - **4 major routes to focus on**

J.-P. Birat, J.-P. Lorrain (ArcelorMittal, Maizières, France)
Y. de Lassat (ArcelorMittal, Luxembourg)

The "CO_2 Tool": CO_2 emissions & energy consumption of existing & breakthrough steelmaking routes

J.-P. Birat, J.-P. Lorrain (ArcelorMittal, Maizières, France)

The "Cost Tool": operating and capital costs of existing and breakthrough routes in a future studies framework

Nous pratiquons un impérialisme qui n'est déjà plus spatial mais temporel, celui du présent qui envahit tout. Il y a une colonisation du futur qui consiste à vivre à ses dépens, un impérialisme du présent qui absorbe et parasite le futur.

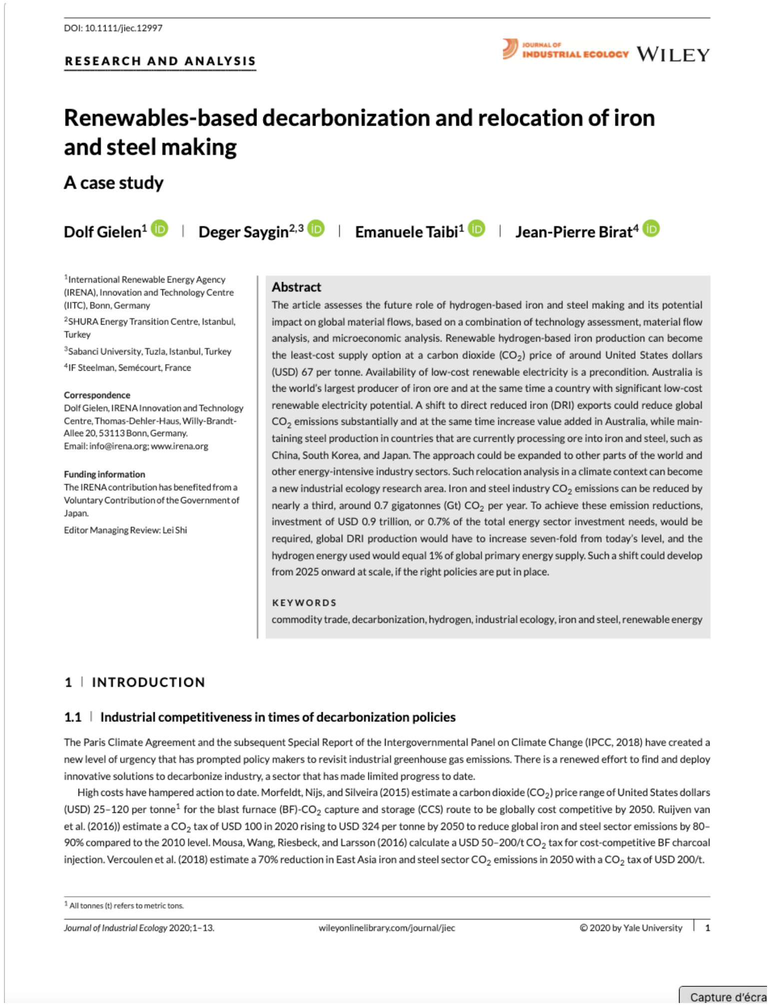
Daniel Innerarity, Le futur et ses ennemis, *Climats,* 2008

Article available at http://www.revue-metallurgie.org or http://dx.doi.org/10.1051/metal/2009061

Decoupling and relocation of iron production

Gielen D, Saygin D, Taibi E, Birat J-P. *Renewables-based decarbonization and relocation of iron and steel making: A case study.* J Ind Ecol. 2020;1–13.

- Paper co-written with IRENA tackles the matter of **hydrogen as a reducing agent** and discusses the issue of the **location of H_2-DRI production**:
  - at the iron ore mine; or
  - at the steel mill
- The **question is still open**



DOI: 10.1111/jiec.12997

RESEARCH AND ANALYSIS

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Renewables-based decarbonization and relocation of iron and steel making

A case study

Dolf Gielen[1] | Deger Saygin[2,3] | Emanuele Taibi[1] | Jean-Pierre Birat[4]

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[2]SHURA Energy Transition Centre, Istanbul, Turkey
[3]Sabanci University, Tuzla, Istanbul, Turkey
[4]IF Steelman, Semécourt, France

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Funding information
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Editor Managing Review: Lei Shi

Abstract
The article assesses the future role of hydrogen-based iron and steel making and its potential impact on global material flows, based on a combination of technology assessment, material flow analysis, and microeconomic analysis. Renewable hydrogen-based iron production can become the least-cost supply option at a carbon dioxide (CO_2) price of around United States dollars (USD) 67 per tonne. Availability of low-cost renewable electricity is a precondition. Australia is the world's largest producer of iron ore and at the same time a country with significant low-cost renewable electricity potential. A shift to direct reduced iron (DRI) exports could reduce global CO_2 emissions substantially and at the same time increase value added in Australia, while maintaining steel production in countries that are currently processing ore into iron and steel, such as China, South Korea, and Japan. The approach could be expanded to other parts of the world and other energy-intensive industry sectors. Such relocation analysis in a climate context can become a new industrial ecology research area. Iron and steel industry CO_2 emissions can be reduced by nearly a third, around 0.7 gigatonnes (Gt) CO_2 per year. To achieve these emission reductions, investment of USD 0.9 trillion, or 0.7% of the total energy sector investment needs, would be required, global DRI production would have to increase seven-fold from today's level, and the hydrogen energy used would equal 1% of global primary energy supply. Such a shift could develop from 2025 onward at scale, if the right policies are put in place.

KEYWORDS
commodity trade, decarbonization, hydrogen, industrial ecology, iron and steel, renewable energy

1 | INTRODUCTION

1.1 | Industrial competitiveness in times of decarbonization policies

The Paris Climate Agreement and the subsequent Special Report of the Intergovernmental Panel on Climate Change (IPCC, 2018) have created a new level of urgency that has prompted policy makers to revisit industrial greenhouse gas emissions. There is a renewed effort to find and deploy innovative solutions to decarbonize industry, a sector that has made limited progress to date.

High costs have hampered action to date. Morfeldt, Nijs, and Silveira (2015) estimate a carbon dioxide (CO_2) price range of United States dollars (USD) 25–120 per tonne[1] for the blast furnace (BF)-CO_2 capture and storage (CCS) route to be globally cost competitive by 2050. Ruijven van et al. (2016)) estimate a CO_2 tax of USD 100 in 2020 rising to USD 324 per tonne by 2050 to reduce global iron and steel sector emissions by 80–90% compared to the 2010 level. Mousa, Wang, Riesbeck, and Larsson (2016) calculate a USD 50–200/t CO_2 tax for cost-competitive BF charcoal injection. Vercoulen et al. (2018) estimate a 70% reduction in East Asia iron and steel sector CO_2 emissions in 2050 with a CO_2 tax of USD 200/t.

[1] All tonnes (t) refers to metric tons.

Hydrogen steelmaking

Fabrice Patisson, Olivier Mirgaux, Jean-Pierre Birat, *Hydrogen Steelmaking. Part 1: Physical Chemistry and Process Metallurgy,* Matériaux & Techniques, 109 3-4 (**2021**) 303

Jean-Pierre Birat, Fabrice Patisson, Olivier Mirgaux, *Hydrogen Steelmaking, part 2: competition with other zero-carbon steelmaking solutions and geopolitical issues,* Matériaux et Techniques,   109 (3-4 (**2021**) 307

- Climate change has become a serious issue - in the sense that business is now considering actually acting on it - and **hydrogen** has become a **very hot topic**
- To address that, 2 papers on **hydrogen reduction** covering
    - the physical chemistry and process engineering of H_2 reduction and
    - How this process will become part of a net-zero series of steelmaking processes by 2050 or before.

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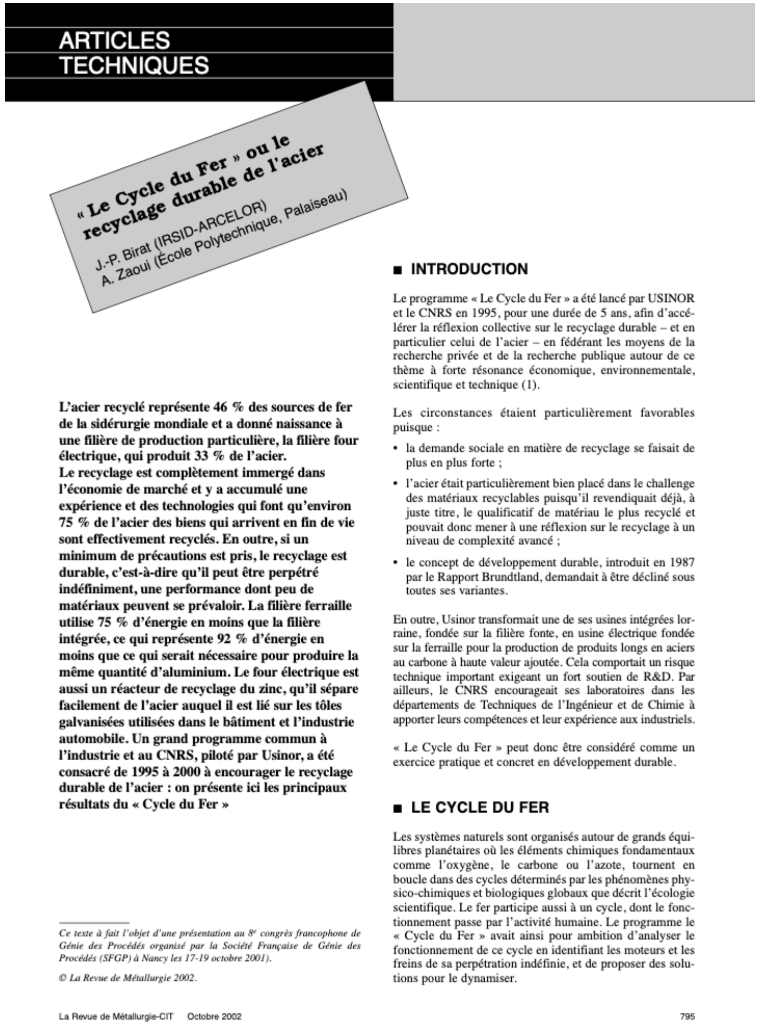
Scrap – the Iron Cycle

J.-P. Birat, A. Zaoui, *Le" Cycle du Fer" ou le recyclage durable de l'acier, (the Iron Cycle or the sustainable recycling of steel)* La Revue de Métallurgie-CIT, Octobre **2002**, 795-807

- Recycled steel – scrap - gave birth to a specific production sector: the electric arc furnace
- The scrap industry uses 75% less energy than the blast furnace
- A major joint French program **'Iron Cycle'** launched between 1995 and 2000 by USINOR and the CNRS to encourage recycling of steel



ARTICLES TECHNIQUES

« Le Cycle du Fer » ou le recyclage durable de l'acier

J.-P. Birat (IRSID-ARCELOR)
A. Zaoui (École Polytechnique, Palaiseau)

**L'acier recyclé représente 46 % des sources de fer de la sidérurgie mondiale et a donné naissance à une filière de production particulière, la filière four électrique, qui produit 33 % de l'acier.
Le recyclage est complètement immergé dans l'économie de marché et y a accumulé une expérience et des technologies qui font qu'environ 75 % de l'acier des biens qui arrivent en fin de vie sont effectivement recyclés. En outre, si un minimum de précautions est pris, le recyclage est durable, c'est-à-dire qu'il peut être perpétré indéfiniment, une performance dont peu de matériaux peuvent se prévaloir. La filière ferraille utilise 75 % d'énergie en moins que la filière intégrée, ce qui représente 92 % d'énergie en moins que ce qui serait nécessaire pour produire la même quantité d'aluminium. Le four électrique est aussi un réacteur de recyclage du zinc, qu'il sépare facilement de l'acier auquel il est lié sur les tôles galvanisées utilisées dans le bâtiment et l'industrie automobile. Un grand programme commun à l'industrie et au CNRS, piloté par Usinor, a été consacré de 1995 à 2000 à encourager le recyclage durable de l'acier : on présente ici les principaux résultats du « Cycle du Fer »**

Ce texte à fait l'objet d'une présentation au 8e congrès francophone de Génie des Procédés organisé par la Société Française de Génie des Procédés (SFGP) à Nancy les 17-19 octobre 2001).

■ **INTRODUCTION**

Le programme « Le Cycle du Fer » a été lancé par USINOR et le CNRS en 1995, pour une durée de 5 ans, afin d'accélérer la réflexion collective sur le recyclage durable – et en particulier celui de l'acier – en fédérant les moyens de la recherche privée et de la recherche publique autour de ce thème à forte résonance économique, environnementale, scientifique et technique (1).

Les circonstances étaient particulièrement favorables puisque :

- la demande sociale en matière de recyclage se faisait de plus en plus forte ;
- l'acier était particulièrement bien placé dans le challenge des matériaux recyclables puisqu'il revendiquait déjà, à juste titre, le qualificatif de matériau le plus recyclé et pouvait donc mener à une réflexion sur le recyclage à un niveau de complexité avancé ;
- le concept de développement durable, introduit en 1987 par le Rapport Brundtland, demandait à être décliné sous toutes ses variantes.

En outre, Usinor transformait une de ses usines intégrées lorraine, fondée sur la filière fonte, en usine électrique fondée sur la ferraille pour la production de produits longs en aciers au carbone à haute valeur ajoutée. Cela comportait un risque technique important exigeant un fort soutien de R&D. Par ailleurs, le CNRS encourageait ses laboratoires dans les départements de Techniques de l'Ingénieur et de Chimie à apporter leurs compétences et leur expérience aux industriels.

« Le Cycle du Fer » peut donc être considéré comme un exercice pratique et concret en développement durable.

■ **LE CYCLE DU FER**

Les systèmes naturels sont organisés autour de grands équilibres planétaires où les éléments chimiques fondamentaux comme l'oxygène, le carbone ou l'azote, tournent en boucle dans des cycles déterminés par les phénomènes physico-chimiques et biologiques globaux que décrit l'écologie scientifique. Le fer participe aussi à un cycle, dont le fonctionnement passe par l'activité humaine. Le programme le « Cycle du Fer » avait ainsi pour ambition d'analyser le fonctionnement de ce cycle en identifiant les moteurs et les freins de sa perpétration indéfinie, et de proposer des solutions pour le dynamiser.

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Back to basics - on Sustainable Materials Science

J.-P. Birat, SUSTAINABLE MATERIALS SCIENCE - ENVIRONMENTAL METALLURGY, two volumes, 960 pages, EDP sciences, **2020, 2021**

- A broad series of topics related to materials, environment and society, have been put together in this series of 2 books, meant for researchers, students and the curious general public.
  - **Volume 1 :** Origins, basics, resource and energy needs
  - **Volume 2 :** Pollution and emissions, biodiversity, toxicology and ecotoxicology, economics and social roles, foresight

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Thank you!

Jean-Pierre Birat
IF Steelman

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Wrap up of Day 2 and Closing Remarks

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Closing Remarks - Wrap up of Day 2 – IRENA

Dolf Gielen

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IRENA International Renewable Energy Agency Canada

Closing Remarks - Wrap up of Day 2 – Natural Resources Canada

Abigail Lixfeld

REED Senior Director
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