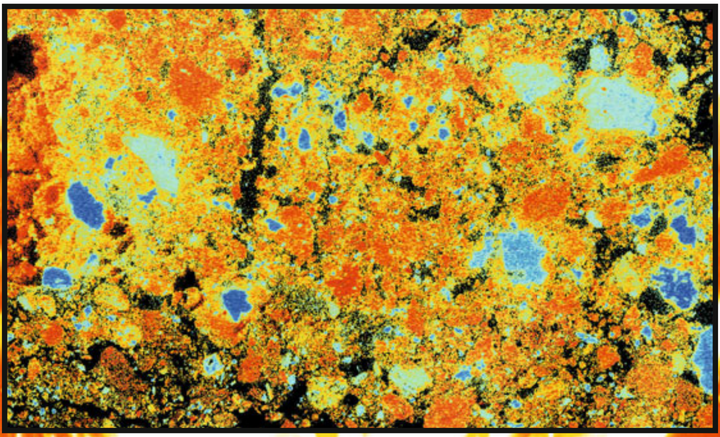
ADVANCES IN PYROMETALLURGY: DEVELOPING LOW CARBON PATHWAYS



EDITED BY
Camille Fleuriault
Joalet D. Steenkamp
Dean Gregurek
Jesse F. White
Quinn G. Reynolds
Phillip J. Mackey
Susanna A.C. Hockaday

TMS

Springer

The Minerals, Metals & Materials Series

Camille Fleuriault · Joalet D. Steenkamp ·
Dean Gregurek · Jesse F. White ·
Quinn G. Reynolds · Phillip J. Mackey ·
Susanna A.C. Hockaday
Editors

Advances in Pyrometallurgy

Developing Low Carbon Pathways

TMS

Springer

Editors
Camille Fleuriault
Eramet Norway
Sauda, Norway

Dean Gregurek
RHI Magnesita Technology Center
Leoben, Austria

Quinn G. Reynolds
Mintek
Johannesburg, South Africa

Susanna A.C. Hockaday
Curtain University
Perth, WA, Australia

Joalet D. Steenkamp
Glencore XPS
Sudbury, ON, Canada

Jesse F. White
KTH Royal Institute of Technology
Stockholm, Sweden

Phillip J. Mackey
P. J. Mackey Technology Inc.
Kirkland, QC, Canada

ISSN 2367-1181 ISSN 2367-1696 (electronic)
The Minerals, Metals & Materials Series
ISBN 978-3-031-22633-5 ISBN 978-3-031-22634-2 (eBook)
https://doi.org/10.1007/978-3-031-22634-2

Cover Illustration: From Chapter "Ferronickel Production from Nickel Laterite via Sulfide Chemistry" Caspar Stinn et al., Figure 1: Distribution of iron (**a**), silicon (**b**), aluminum (**c**), manganese (**d**), magnesium (**e**), and nickel (**f**) in the laterite feedstock. Nickel is observed to be primarily distributed between iron-rich phases at a grade of around 1 wt% and magnesium-silicon-rich phases at a grade of around 3 wt%. Some manganese-rich phases are observed with elevated nickel contents on the order of 10 wt%. Silicon-rich magnesium-poor phases exhibit the lowest nickel trades at around 0.3 wt% or less (SEM/EDS map, scale bars: 500 μm). https://doi.org/10.1007/978-3-031-22634-2_25.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

It is my pleasure to introduce the first installment of a new symposium series called "Advances in Pyrometallurgy", an exciting program sponsored by the Extraction and Processing Division and the Pyrometallurgy Committee of TMS. The theme of the first symposium is "Developing Low Carbon Pathways". Carbon intensive industries are at a crossroads: long-term manufacturing plans using pyrometallurgical processes all include decarbonization levers. We must solve the problem of fossil-based reduction and fossil-based power generation processes for metals production. As metallurgists, scientists, and engineers roll up their sleeves to face the greatest challenge of our generation, technologies enabling sustainable metals processing and its long-term vision develop at great speed.

The TMS community understands this challenge and embraces the opportunity. With this first symposium, we explore innovative and diverse strategies for the enablement of low carbon industries in the high-temperature metals and materials processing fields. In particular, the discussion highlights the potential of hydrogen as an alternative reducing agent for ironmaking, ferro, and manganese alloys smelting. It includes assessments of other alternatives to fossil carbon such as biocarbons, for the reduction of metal oxides but also manufacturing of electrodes and refractory. The symposium also covers novel energy efficiency and waste heat recovery concepts contributing to a lower footprint of production processes. In particular, renewable energies, such as solar power applied toward metallurgical practices, are systematically analyzed.

With this new symposium series, the Pyrometallurgy Committee wishes to illustrate how fundamental principles and advanced research translate to the production floor. Thus, the organizers favor a problem driven approach and the symposium will also include a keynote session focusing on the pathways taken to reduce carbon dependency within the industry, or directly for the industry.

I would like to thank the organizing committee for their contribution, invaluable input, and hard work. It has been a pleasure and a privilege to craft such an exciting program and to work with pyrometallurgy experts who are so passionate and knowledgeable about their field. I thank the authors for their excellent contributions, for the time spent writing the proceedings manuscripts, and for providing revisions throughout the peer-review process. Finally, I would like to thank the TMS staff for their support, especially Patricia Warren, Trudi Dunlap, Kelly Markel, Kelly Zappas, and Jeffrey Gnacinski. Additionally, many thanks to the TMS Programming Committee and the EPD Chair, Christina Meskers, for supporting the development of this new symposium.

Camille Fleuriault
Lead Organizer

Advances in Pyrometallurgy: Developing Low Carbon Pathways Organizing Committee

Camille Fleuriault
Joalet D. Steenkamp
Dean Gregurek
Jesse F. White
Quinn G. Reynolds
Phillip J. Mackey
Susanna A. C. Hockaday

Contents

Part I Keynote

Part II Hydrogen

Part III Biocarbon and Alternative Reduction Methods

Part IV Energy Valorization in Metallurgy

About the Editors

Camille Fleuriault is senior project manager at Eramet Norway AS in Sauda, Norway. Her work focuses on identifying and enabling zero carbon strategies for the production of manganese alloys. She previously worked on developing innovative and environmentally friendly recycling processes for the secondary metals industry. She holds a B.S. in Geological Engineering and an M.Eng. in Mineral Engineering from the National School of Geological Engineering in Nancy, France, and a M.Sc. in Metallurgical Engineering from Colorado School of Mines, USA. She is chair of the TMS Pyrometallurgy Committee and a former *JOM* advisor for the same committee.

Joalet D. Steenkamp recently joined Glencore XPS in Sudbury, Ontario, Canada as Chief Metallurgist, Pyrometallurgy and Furnace Integrity. Her research focus areas are Furnace Containment, Furnace Tapping, and Reducing the Carbon-footprint of Ferrous Alloy Production. She holds a Ph.D. in Metallurgical Engineering from the University of Pretoria and an appointment as Visiting Adjunct Professor from the University of the Witwatersrand, both based in South Africa. Dr. Steenkamp has 13 years of experience in the South African industry/private sector (secondary steelmaking, ilmenite roasting and smelting, and manganese ferroalloy production) and 13 years in the research/public sector, of which the majority were spent at Mintek.

Dr. Steenkamp has been a TMS member since 2009. At TMS, she has been serving on the Pyrometallurgy

Committee since 2017 where she currently serves as Vice-Chair (2022–2024), served on the Industrial Advisory Committee (2018–2021) for which she was the inaugural Chair (2018–2020), serves on the Extraction and Processing Division Council as a representative for the Professional Development Committee (2021–2023), chaired the Organizing Committee for Furnace Tapping 2022, and now serves as a member of the organizing committee for the 2023 symposium Advances in Pyrometallurgy: Developing Low Carbon Pathways. In South Africa, she chaired the organizing committees for Furnace Tapping 2014 and 2018, the Schools on Manganese Ferroalloys Production in 2012, 2016, and 2020, and the School on the Production of Clean Steel in 2016. All of these events were hosted by the Southern African Institute of Mining and Metallurgy (SAIMM).

Dean Gregurek is a senior mineralogist in the RHI Magnesita Technology Center in Leoben, Austria since 2001. Dr. Gregurek received his M.Sc. degree at the University of Graz in 1995, his doctorate degree from the University of Leoben in 1999, and degree of assoc. prof. in 2019. Prior to RHI Magnesita, he worked for two years for Luzenac Europe in talc business. His current research interests and technical expertise are focused on chemical and mineralogical studies related to interactions between refractories, molten metals, and slags from pyrometallurgical furnaces. Dr. Gregurek has been a TMS member since 2012, *JOM* advisor (2014–2017), chair of the Pyrometallurgy Committee (2018–2020), and a co-organizer for the 7th–12th International Symposium on High-Temperature Metallurgical Processing (TMS Annual Meetings 2016–2021) and Furnace Tapping (TMS Annual Meeting 2022).

Jesse F. White holds a Ph.D. in Materials Science and Engineering from the KTH Royal Institute of Technology, an M.Sc. in Metallurgical and Materials Engineering from the Colorado School of Mines, and a B.S. in Metallurgical Engineering from the South Dakota School of Mines and Technology. He began his career in 1996 as a Process Engineer at the Kaiser Aluminum Mead Works. In 1997, he moved to Luleå, Sweden, and began as a Research Engineer at MEFOS working mainly in strip casting of steel. In 2002, he moved to Oslo, Norway and spent 5 years at Alstom as a Project Engineer designing, building, commissioning, and troubleshooting gas treatment systems for aluminum smelters around the world. Since 2007, he has been employed by Elkem in Kristiansand, Norway, starting out at Elkem Solar as a Research Engineer specializing in silicon refining, later moving to Elkem Technology, and since 2015 at Elkem Carbon. He is currently Technology Director at Elkem Carbon, supporting the production facilities in Brazil, China, Malaysia, Norway, and South Africa. In parallel, Dr. White is also currently an Affiliated Faculty Member of the Materials Science and Engineering Department at the KTH Royal Institute of Technology in Stockholm, where he teaches thermodynamics and conducts research in the areas of high-temperature experimental thermodynamics and metallurgical reactor design.

Quinn G. Reynolds holds an undergraduate degree in Chemical Engineering from the University of Kwazulu-Natal, a Masters in Engineering from the University of the Witwatersrand, and a Ph.D. in Applied Mathematics from the University of Cape Town. He has worked in the Pyrometallurgy Division at Mintek for the past 23 years. Mintek is a research institute conducting applied research and development to serve the extensive mineral processing and metallurgical industry in South Africa and worldwide. Dr. Reynolds' expertise includes mathematical and computational modelling of complex coupled phenomena in high temperature processes and in particular the application of high-performance computing and open-source modelling software to pyrometallurgy. His current areas of research include magnetohydrodynamic modelling of electric arcs, multiphysics fluid flow problems in furnace tapping and phase separation, combustion modelling for metallurgical processing, and discrete element modelling for particle flow problems. He has also performed extensive work in the characterization of the dynamic behavior of direct-current plasma arcs using high-speed photography and electrical measurement techniques.

Phillip J. Mackey obtained his B.Sc. (Honors) and Ph.D. degrees from the School of Metallurgy at the University of New South Wales, Australia. He then moved to Montreal, Canada to join Noranda to work on a new copper smelting process. As Pilot Plant Supervisor, Dr. Mackey helped develop the Noranda Process, which was first implemented at the Horne smelter in the early 1970s. Here he first learned the art and technique of tapping a high temperature melt—blister copper, copper matte, and slag. The Noranda Process, one of the most important copper smelting technologies of the twentieth century, also achieved early success in the United States, Australia, and China. Dr. Mackey was later instrumental in developing the Noranda Converting Process, of which he is a co-inventor, and which was installed at the Horne smelter in the late 1990s providing enhanced environmental performance. At Noranda and Falconbridge, he was involved with other initiatives, including new developments for processing nickel laterites and concluding technology agreements with other nations, notably Chile. He conducted due diligence studies on a range of projects around the world. He later formed his own consulting company, and this has led to a range of projects worldwide, including work on the development of a new nickel laterite project in Brazil.

Susanna A. C. Hockaday has 18 years of pyrometallurgical research experience in the non-ferrous industry. She joined Mintek in 2002 after obtaining her B. Chem. Eng. (Minerals Processing specialization) and M.Sc. in Extractive Metallurgy at the University of Stellenbosch in South Africa. During 2002 to 2010 she worked in the commercial projects group on various projects including the recovery of precious metals in liquid iron and the smelting of ores to produce design specifications of an industrial ferrochrome DC arc furnace. From 2011 to late 2015 she took a break from work and had two delightful children, now aged 11 and 8. From 2015 till

2021, she has been involved in research of new technologies for titanium metal production, chlorination of titanium dioxides in a fluidized bed, and the application of renewable energy in minerals processing. Since 2016 she has been enrolled at the University of Stellenbosch as a part-time Ph.D. student with the working title of "Solar thermal treatment of Manganese Ores". She acted as a work package leader responsible for €2 million of research toward advancement of solar thermal process heating technology in manganese ferroalloy production for the PRÉMA project. The PRÉMA project is funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 820561 and is part of the SPIRE group of projects. Mrs. Hockaday was co-ordinator and the main author for Mintek's Roadmap for Solar Thermal Applications in Minerals Processing (STAMP). Mrs. Hockaday is a member of the South African Institute of Mining and Metallurgy (SAIMM) and part of the SAIMM technical programme committee. She was also head of the organizing committee for the SAIMM Colloquium on Renewable Energy Solutions for Energy Intensive Industry in 2020 and the Renewable Energy Solutions for Energy Intensive Industry Conference in 2021.

Mrs. Hockaday resigned from Mintek in June 2021 to move with her family to Perth, Australia. She has founded GamAesa as vehicle to continue her support of process innovation and renewable energy integrating in minerals processing.

Part I
Keynote

Roadmap for Reduction of Fossil CO_2 Emissions in Eramet Mn Alloys

B. Ravary and P. Gueudet

Abstract Eramet produces materials useful for a low-emission society, in a resource-effective way, and for manganese (Mn) alloys, with a lower climate footprint than the industry average. Such high standards give increased competitivity because most stakeholders, in particular customers and investors, are interested in environmental-friendly production. This responsible strategy will eventually lead to improving profitability. Eramet has set goals for the reduction of emission of greenhouse gases from their production in the framework of the Science Based Target. In this paper, we present the strategy and a simplified roadmap to reach the target in Eramet Mn alloys activity. The roadmap is made a reality through actions and investments for industrial implementations. The reduction initiatives can be divided into four main areas, somewhat reflecting some sequences in time with overlap, from short term (2025) to long term (2040 and beyond): improvement of existing processes in resource and energy efficiency (2025), increase or introduction of biomass-based reductants to replace fossil carbonaceous materials (2030), carbon capture and usage (CCU) or storage (CCS) (2030), and development of innovative technologies (2040). All actions are rooted in scientific and techno-economic studies. Open innovation is necessary when developing technologies outside the core competence of the companies.

Keywords Manganese alloys · Climate · Roadmap · Bio-reductants · CCUS

Introduction

The Paris agreement in 2015 targets to maintain global warming below 2 °C, compared to the pre-industrial age. Greenhouse Gas (GHG) emissions are to be

B. Ravary (✉)
Eramet Norway, Alfred Getz vei 2b, 7034 Trondheim, Norway
e-mail: benjamin.ravary@eramet.com

P. Gueudet
Eramet SA, 10 Boulevard de Grenelle, 75015 Paris, France
e-mail: pierre.gueudet@eramet.com

C. Fleuriault et al. (eds.), *Advances in Pyrometallurgy*, The Minerals, Metals
& Materials Series, https://doi.org/10.1007/978-3-031-22634-2_1

reduced and countries signatories of the Paris agreement have set some targets for these reductions. The manganese (Mn) alloys business unit in Eramet has production facilities in the USA, Gabon, France, and Norway. The three Norwegian plants account for approximately 70% of the total production of Mn alloys in the business unit and were early in working on reducing their carbon footprint, following a strategy set by the broader Norwegian industry.

In its Intended Nationally Determined Contribution (INDC) to the Paris agreement, Norway committed to a 40% GHG emissions reduction in 2030 compared to the 1990 level, as well as achieving carbon neutrality by 2050. Carbon neutrality means that the same amount of GHG is stored and emitted so that the total net emissions are zero. As part of the European Green Deal, the European Union (EU) Commission proposed in September 2020 to raise the 2030 greenhouse gas emission reduction target, including emissions and removals, to at least 55% compared to 1990 [3]. On 14 July 2021, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the EU by 2050, including the intermediate target of at least 55% net reduction in greenhouse gas emissions by 2030. The package proposes to revise several pieces of EU climate legislation, including the EU Emissions Trading System (EU ETS), Effort Sharing Regulation, transport, and land use legislation, setting out in real terms the ways in which the Commission intends to reach EU climate targets under the European Green Deal [4].

The revised EU ETS Directive, which will apply for the period 2021–2030, will enable this through a mix of interlinked measures. EU ETS limits emissions from more than 11,000 heavy energy using installations (power stations and industrial plants, including metallurgical industry) and airlines. It covers around 40% of the EU's GHG emissions. In phase IV of the EU ETS, operators of installations subject to emissions trading may, upon request, receive a free allocation of emission allowances for the periods between 2021–2025 (first allocation period) and 2026–2030 (second allocation period). Allocations for 2021–2030 will have a major impact on the EU and Norwegian ferroalloy industry.

The roadmap for the Norwegian process industry [5] proposes a global vision and scenarios of technology development to achieve the Paris agreement goals in line with the EU expectations. Four technology breakthroughs are proposed: Carbon Capture and Storage (CCS) from both fossil and biogenic sources, increased use of hydrogen, increased use of biomass, use of zero-emission technologies and electricity, and circular economy. In addition, it illustrates the effects of potential new industries for producing sustainable fuels: E-fuel for aviation, ammonia for shipping, and advanced biofuels. The expected reductions linked to those technologies are presented in Fig. 1.

Eramet's Climate Strategy

Decarbonization will soon become a "license to operate" and it is, therefore, a must for mines and alloys plants of Eramet Group. Having a low carbon footprint will be a condition to market our products, finance our projects and operations, and (retain

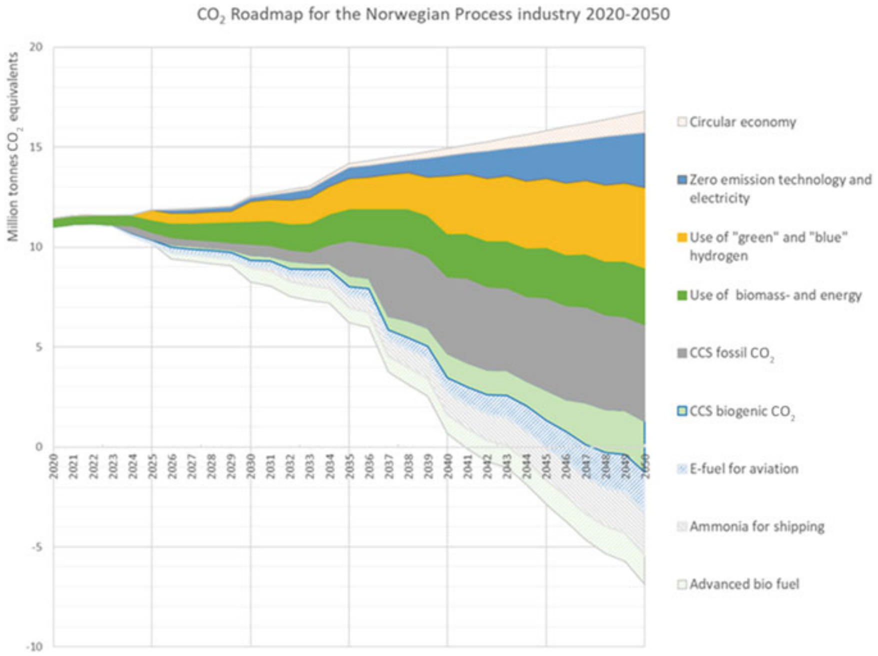


Fig. 1 Expected reductions in GHG emissions from the implementation of different technologies in the Norwegian process industry [5]

and) recruit talents and partners. The reduction of CO_2 emissions requires action in different time frames from short-term adjustments of operation to developments requiring long lead times. The governance of our efforts considers the optimization of existing assets, the development of new technologies in partnership with peers, academics, and suppliers, as well as support for decarbonizing customers.

Eramet's answer to climate change is based on the following focus points:

- The reduction of CO_2 emissions on scopes 1 (internal emissions) and scope 2 (from the production of the electricity consumed).
- Helping customers and providers (scope 3 emissions) to reduce their GHG emissions, by offering products and solutions that mainly contribute to reducing the carbon footprint. This is reflected in one of the three pillars of the Group's strategy: "to expand the portfolio of activities towards energy transition metals".
- The promotion of circular economy.

Reducing CO_2 Emissions of Scopes 1 and 2

2023: A Medium-Term Target for Reducing Specific Emissions

Eramet conducted a review to define a target for reducing scopes 1 and 2 CO_2 emissions, in 2018, based on technical and organizational levers. This led Eramet to include in its Corporate Social Responsibility (CSR), 2018–2023 roadmap, a significant reduction carbon target for the generated tons of CO_2 per ton product:

- Group Goal 2021 versus 2018: −26%, of which

- Impact of energy efficiency levers and decarbonization of energy consumed: −9.5%
- Impact of the business mix effect related to the Group's strategic choice to develop its mining activity, which is lower in emissions compared to the Group's processing activities: −16.5%

To structure all these progress initiatives, Eramet is deploying a management system for its energy and climate performance within its entities up to ISO 50001 certification for the main sites emitting CO_2.

2035: A Long-Term Objective Compatible with the Paris Agreements

Given the strong development of the mining activity, which is less carbon intensive than the pyrometallurgy activity, Eramet plans to meet its objective of reducing its specific CO_2 emissions much before 2023. The Group decided in 2020 to further accelerate the process through commitment to a Science Based Target, "well below 2 °C". Eramet is currently in "committed" approval status.

At constant perimeter, Eramet aims to reduce, in absolute value, its scope 1 and 2 CO_2 emissions by 40% in 2035 compared to 2019. This target requires activating all the levers identified, including those which are still at the R&D stage or at a pilot stage: Carbon Capture and Storage (or CCS), bio-reductants, electrification of mining activity, etc.

Eramet's carbon reduction trajectory thus depends on the Group's ability to develop multi-year, cross-functional projects on the following main axes:

- Decarbonization of purchased electricity (purchases, investments)
- Decarbonization of processes (bio-reductants and hydrogen)
- CO_2 capture and storage (CCS, in partnership)

The priority actions are:

- The development of CCS in partnership with other players: this is the most impactful action in terms of CO_2 savings and the costs are the main obstacle. We plan to develop a pilot and identify the least capital-intensive technologies.

- The use of bio-reductants in ore reduction: challenges for this level include finding biomass managed in a sustainable manner and compatible with the constraints of our processes (mechanical strength, polluting elements).
- The implementation of purchases and production of electricity from renewable sources coupled with the electrification of mines: the successful implementation of this lever is based, in parallel with the development of technical solutions, on a change of background culture (electric mining trucks for example) which requires long-term support.
- The improvement of the pre-reduction of ores and gradual introduction of hydrogen to this end.

This roadmap on scopes 1 and 2 is accompanied by a qualitative objective of reducing emissions in scope 3: Eramet is committed to encouraging its customers to reduce their own emissions.

2050: Carbon Neutrality on Scopes 1 and 2

Eramet targets carbon neutrality of its scope 1 and 2 emissions by 2050. This ambition relies on CCS and the use of bio-reductants, together with the implementation of disruptive technologies.

Most of the significant actions to reduce Eramet's carbon footprint take place over a medium to long- term horizon, the next few years being mainly devoted to confirming the potential gains through pilots.

The actions identified can only be implemented on the condition that the market reflects the investment costs in carbon and commodity prices. In this case, it would be a substantial increase in the price of carbon, and therefore, that of metals.

Eramet Mn Alloys Roadmap

Eramet Mn Alloys will be the main contributor to reach Eramet Group's targets. Its plants have already among the lowest specific CO_2 emissions in the industry as illustrated for one line of its products in Fig. 2.

Eramet Norway, the Norwegian subsidiary of Eramet in Mn Alloys, was an early mover in its efforts to curb its carbon footprint and decided in 2017 to establish its "Climate and Environment Roadmap—Towards 2030 and 2050". The process started with a mapping of carbon emission reduction technologies (Fig. 3), based on their effectiveness and implementation. A Multi-Criteria Decision Analysis (MCDA) was applied to prioritize the levers, that are currently used in the roadmap for CO_2 reduction. A steering committee, including both representatives from Mn Alloys and Group, ensures a systematic follow-up and continuous update of our project portfolio.

The manganese alloys climate roadmap targets a reduction of emissions of 70% in 2035 through actions distributed in three main time frames (Fig. 4):

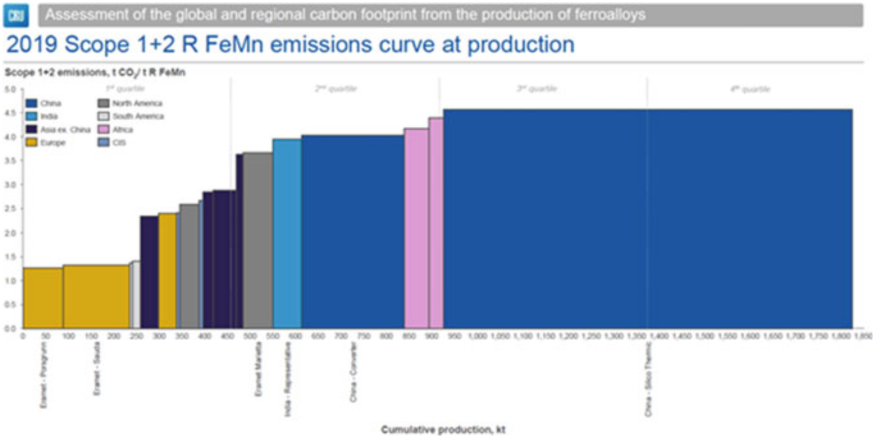


Fig. 2 Specific emissions of CO_2 in refined ferromanganese as a function of production (kt) for different producers Specific emissions Eramet Porsgrunn and Sauda—approximately 1.3 tCO_2/t R FeMn [1]

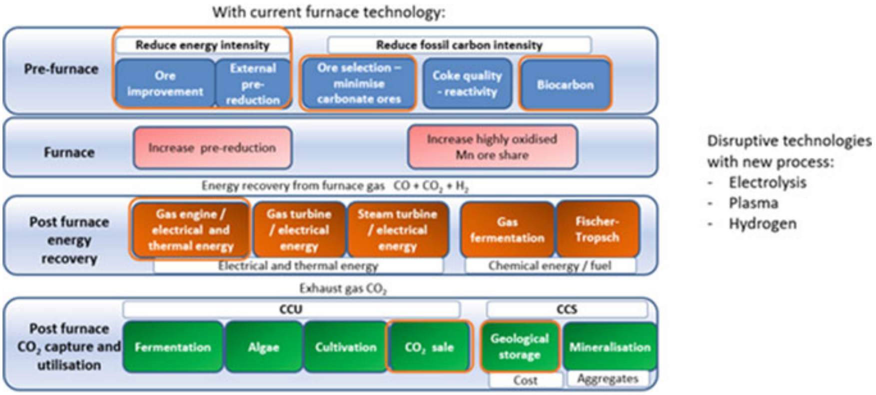


Fig. 3 Overview of main technologies with current furnace technology (left) and disruptive technologies (right). Highlighted with orange frame—technologies in the Mn alloys roadmap

- Five-year perspective: reduce carbon consumption through improvement of operation of existing processes, promoting energy-saving chemical reactions, the pre-reduction of highly oxidized ores, and limiting the amount of carbonate in the charge [2].
- Ten-year perspective:
- Introduce a significant share of bio-reductant, also called biocarbon, to replace part of the current fossil reductants, coke, and coal.
- Capture CO_2 through CCS or Carbon Capture and Utilisation (CCU).

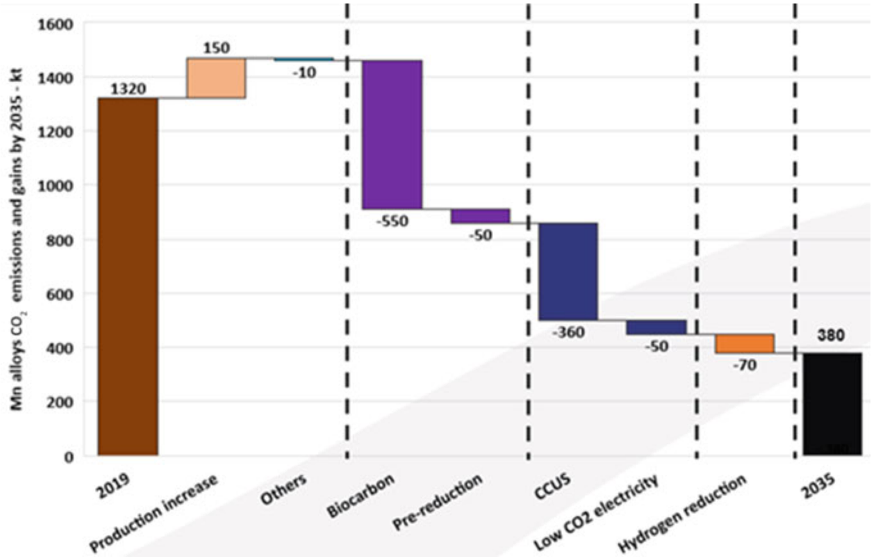


Fig. 4 Main levers towards the 2035 target for Eramet Mn alloys. Low CO_2 electricity corresponds to moving from fossil-based electricity production to renewable (hydropower, wind, solar) or nuclear electricity as input for production (in scope 2)

- Longer term: Develop ground-breaking technologies, for instance using hydrogen, which may require drastic process changes and completely new production facilities.

Some details concerning the key R&D and industrial projects supporting the roadmap are presented in [6].

Conclusion

Eramet has set objectives for the reduction of its CO_2 emissions using the Scientific Based Target framework. Eramet Mn Alloys will be the main contributor to reach these goals, following a climate roadmap, that is concretized through actions with different time frames. CCS and bio-reductants are its main levers in a 2035 perspective.

References

1. CRU (2022) Assessment of the global and regional carbon footprint from the production of ferroalloys, Final Report, 1 June 2022
2. Davidsen J (2021) Reducing the CO_2 footprint from simn production by optimization of fluxes (September 12, 2021). In: Proceedings of the 16th international ferro-alloys congress (INFACON XVI) 2021. https://ssrn.com/abstract=3926019 or https://doi.org/10.2139/ssrn.3926019
3. European Commission (2020) 2030 climate and energy framework https://ec.europa.eu/clima/policies/strategies/2030_en. Accessed Dec 2020
4. European Commission (2021) Climate Action. EU Emissions Trading Systen (EU ETS). Revision for phase 4 (2021–2030) https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en. Accessed Sept 2022
5. Prosess21 (2021) https://www.prosess21.no/
6. Ravary B, Bjelland KB, Valderhaug A, Messenlien AG (2021) Towards a climate-friendly ferroalloy industry in Norway (September 12, 2021). In: Proceedings of the 16th international ferro-alloys congress (INFACON XVI) 2021. https://ssrn.com/abstract=3926062 or https://doi.org/10.2139/ssrn.3926062

Towards Net Zero Pyrometallurgical Processing with the ISASMELT™ and ISACYCLE™

S. Nicol, T. Ryan, B. Hogg, and S. Nikolic

Abstract With the growing global focus on reducing the environmental and social impacts of modern society, many smelters and recyclers are moving rapidly to decarbonise their processes. While existing and new solutions are required to optimise for reduced emissions across all reporting greenhouse gas (GHG) emission scopes, advancement of existing solutions can hold greater emissions-reduction potential. With a 37-year operating history and 25 global installations, across both primary and secondary (recycling) applications, ISASMELT™ and ISACYCLE™ technology is a mature, modern, and efficient smelting solution. The technology is well situated as it currently stands to achieve Net Zero status. The ability to decarbonise existing and new ISASMELT™ and ISACYCLE™ operations follows an emerging 'Emissions Optimisation' approach, which builds on significant energy-saving and emissions-reduction advancements derived from traditional profit-driven innovations. Scope 1 onsite direct emissions, and Scope 2 indirect emissions associated with electricity, heating, and cooling, can be minimised through the goal of attaining a low energy-use smelting operation. This can be achieved via aspects of the smelting process itself, including proprietary refractory design, advanced temperature control, waste heat capture, feed profile modifications, and oxygen enrichment. Further, scope 1 emissions can be eliminated through improvements such as alternative fuel substitution (i.e., hydrogen and sulphides) and off-gas processing. Finally, scope 3 emissions can be minimised through reduced maintenance, reduced consumables, and reduced equipment wear—by advancements including refractory design, lance design, and furnace control (for long campaign life and consistent production of high-quality products).

Keywords Net zero · Smelting · Greenhouse gas (GHG) emissions · Green metals · Critical minerals · Circular economy · Decarbonisation · Carbon · Smelting · Extractive metallurgy

---

S. Nicol (✉) · T. Ryan · B. Hogg · S. Nikolic
Glencore Technology, Level 10, 160 Ann Street, Brisbane, QLD 4000, Australia
e-mail: stuart.nicol1@glencore.com.au; isasmelt@glencore.com.au

C. Fleuriault et al. (eds.), *Advances in Pyrometallurgy*, The Minerals, Metals & Materials Series, https://doi.org/10.1007/978-3-031-22634-2_2

Introduction

Extractive metallurgy plays a key role in mitigating environmental impacts associated with carbon dioxide and other greenhouse gas (GHG) emissions. By providing key materials to the world, metallurgists hold a great responsibility to decarbonise metallurgical systems and mineral processing operations. Specifically, the role of extractive metallurgists in providing 'critical minerals' is particularly crucial, as they are essential for the functioning of our modern lifestyles and global economy. Key minerals, such as the base metals copper, zinc, lead, and tin, are experiencing increasing global demand due to decarbonisation efforts, which involves the rapid rollout of renewable energy and electrification projects. To ensure these projects are constructed with green metals for a Net Zero future, extractive metallurgists must ensure decarbonisation efforts are made across all scopes of emission, and at all points of the critical minerals value chain.

Pyrometallurgical processes play a crucial role in unlocking metals for use in the supply chain. These processes chemically transform low-quality feeds to produce high-quality products for final refining and transport. Unlike other processing stages of the value chain, decarbonisation of pyrometallurgical processes requires more than just Scope 2 emissions reduction. Scope 2 emissions associated with purchased electricity, heating, and cooling, are comparatively simple to decarbonise. Scope 1 and 3 emissions reductions require metallurgical optimisation, due to the chemical processes involved in the smelting stage which traditionally involve the consumption and release of carbon as a fuel.

The ISASMELT™ technology is a mature, modern, and efficient smelting solution, well positioned for industry-leading emissions optimisation results, and Net Zero impact [8]. The technology was developed at Mount Isa, QLD to replace older, less efficient, and more emission-intensive technology [6]. Since its first installation, numerous developments in the technology have enabled even further reductions in gaseous emissions and fuel requirements. This progress has resulted in significantly lower smelting costs, with the Mount Isa Mines smelter becoming one of the lowest-cost operations in the world, despite its remote location in a developed country. The technology also significantly reduced the energy consumed by primary smelting, decreasing energy consumed at this stage of smelting by 93% [3]. Similar improvements have been realised at other smelters, such as the Ilo Smelter, with a 65% reduction in consumed fuel [13, 14].

Smelting operations have traditionally been optimised for profits, by maximising tonnage (revenue) and minimising costs (expenses). For 'Emissions Optimisation', existing smelting technologies must advance to also optimise their operation for reduced emissions. This is achieved by continuing to minimise energy usage, while also minimising and managing carbon consumption. The 'Traditional Optimisation' approach has driven the development of extremely efficient process outcomes. However, there remain additional areas for further advancement, development, and innovation to achieve a Net Zero smelter. These areas include feed modifications,

Table 1 Optimisation parameters—traditional versus emissions optimisation

	Manipulated variables	Measured variables	Outcomes
Traditional (cost-based) optimisation	• Furnace feed rate • Feed profile modifications to manage impurities, size, moisture • Oxygen enrichment • Steady furnace control • Advanced refractory design • Advanced lance design • Efficient ancillary equipment design (i.e., fans, blowers, conveying)	• Tonnage • Campaign life and parts integrity • Required smelting energy • Furnace temperature • Slag chemistry • Product grades • Electricity input • Recycle rates	• Increased revenue through maximised tonnage and product grade/quality • Decreased OPEX with minimised energy and consumables • Decreased CAPEX with minimised maintenance and shutdowns
Emissions optimisation[a]	• Feed profile modifications to reduce carbon	• Direct, indirect, and embodied GHG emissions	• Reduced GHG emissions across scope 1, 2, and 3
	• Alternative fuels substitution (i.e., hydrogen, pyrite concentrates)		
	• Advanced waste heat capture system design		
	• Off-gas processing		

[a] Additional to the traditional optimisation activities

materials substitution for fuels and reagents, further heat integration, and advanced gas processing (Table 1).

These 'Emissions Optimisation' activities will be explored with reference to the emission reporting scopes, to highlight the impact of emissions optimisation for an ISASMELT™ technology installation or modification. The following block flow diagram defines these emissions optimisation scope boundaries for the system (Fig. 1).

ISASMELT™ and ISACYCLE™ Technology

ISASMELT™ furnaces are modern bath-smelting processes for the smelting of non-ferrous materials from both primary and secondary materials to produce various matte, slag, and metal products. The ISACYCLE™ furnace is an adaption of the ISASMELT™ furnace, to smelt secondary materials and various waste streams, such as electronic and municipal waste streams. The technology processes these streams

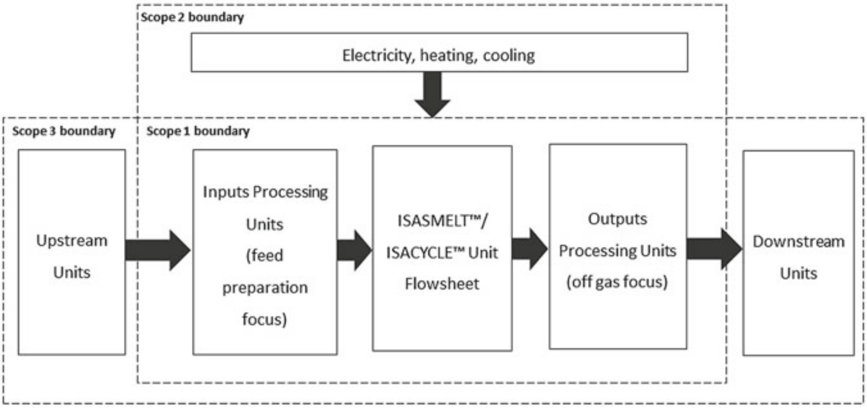


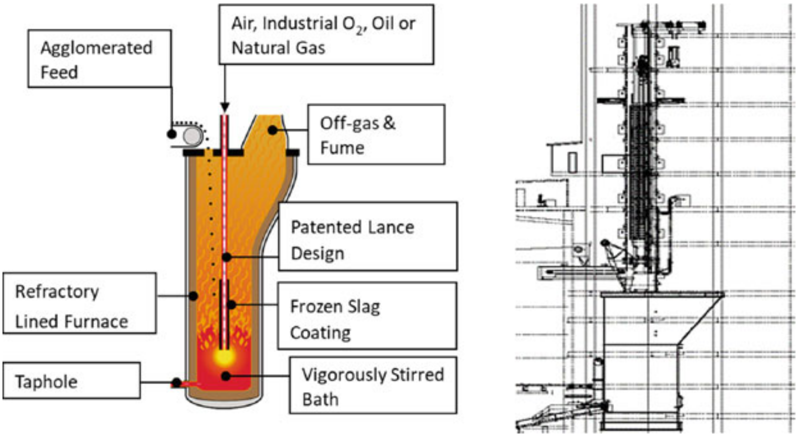
Fig. 1 'Emissions optimisation' scope 1, 2, and 3 emissions boundaries

to treat hazardous materials and circulate and recycle finite mineral stocks. Both furnaces can be constructed at any scale, to suit the required facility.

The ISASMELT™ top submerged lance (TSL) technology was developed at Mount Isa Mines (now part of Glencore) during the early 1980s [6] . It was identified that the smelter was running old technology, with new technology required to significantly reduce energy consumed in the smelter. The furnace technology was first tested in a 250 kg/h test rig in the 1980s [4]. The furnace technology was subsequently scaled-up to an operational demonstration plant, and finally a full-scale furnace. The technology resulted in 93% less energy being consumed in the primary furnace [3], and the smelter became one of the lowest-cost operations globally [3]. Due to the success of the ISASMELT™ at Mount Isa Mines, the technology has been installed at 25 sites around the world, with smelters using the technology to process nickel [5], lead [15], and copper [1, 2] concentrates and secondary materials.

The ISASMELT™ and ISACYCLE™ furnaces, depicted in Fig. 2, are cylindrical vessels with a flat roof. In an ISASMELT™ furnace, the vessel is refractory lined and regularly achieves campaign lives of 4 years of operation, without copper coolers [11]. A centrally located submerged lance injects air, oxygen, and fuel into a molten slag bath. This blast of air, oxygen, and fuel down the lance oxidises and violently agitates the liquid slag, to ensure a rapid reaction between this oxidised slag and feed materials. A frozen layer of slag forms on the outside of the lance and protects it from the aggressive environment in the furnace. The furnace products, slag, and metal or matte, can be tapped simultaneously or separately through water-cooled copper tapholes.

Table 2 presents key parameters and associated values.



a) ISASMELT™ and ISACYCLE™ major features

b) ISASMELT™ and ISACYCLE™ General Arrangement

Fig. 2 ISASMELT™ and ISACYCLE™ technology

Table 2 ISASMELT™ and ISACYCLE™ operating parameters and conditions

Parameter	Value
Facility sizes	1 kg/h–200 t/h
Lance total flowrate	10–71,000 Nm^3/h
Furnace fuel/reductant	Coal, plastic, coke, secondary scrap (e.g., e-scrap)
Furnace trim fuel supply	Natural gas, diesel, pulverised coal, waste oil, hydrogen
Lance oxygen enrichment	21 (air) to 92 vol% O_2 proven
Furnace availability	92% (including re-brick and maintenance)
Furnace lining	Fully bricked, copper staves, and intensively cooled copper panels proven
Taphole types	Combined or separate metal/matte and slag tapholes proven
Furnace campaign	4+ years proven by four separate ISASMELT™ licensees, 6+ years possible
Ramp-up to design capacity	3 months proven
Furnace operation	Batch and Continuous proven, able to change back and forth during asset life
Feed size	<100 mm proven
Feed moisture	Up to 12 wt% proven
Feed delivery system to furnace	Vibrating or belt-style for coarse and/or wet feed Pneumatic injection for fine, volatile, or low-density feed

Developments in Low Energy Smelting (Scope 1 and 2)

ISASMELT™ and ISACYCLE™ developments under the Traditional Optimisation approach, involve progress towards low-energy smelting [10]. Similarly, the Emissions Optimisation approach for the reduction and minimisation of scope 1 and scope 2 emissions, requires attaining a low-energy smelting state to minimise fuel requirements.

To attain a low-energy smelting state, and ultimately autonomous (or net positive energy) smelting, inefficiencies in the smelting process must be minimised. This involves metallurgical optimisation activities. These scope 1 and 2 emissions minimisation advancements include:

- Advanced refractory design and temperature control,
- Feed profile modifications, focusing on impurities and moisture,
- Waste heat capture; and
- Oxygen enrichment.

Recent advancements in the ISASMELT™ technology have led to a significant improvement in the energy efficiency of the furnace technology. A summary of the total energy savings available with the next generation of the technology is provided in Table 3, where the energy available from the feed is 11 MW. For other furnace technologies, 17 MW of energy from carbon-based fuels is required. Using modern ISASMELT™ Technology, there is a surplus of 7 MW available for the melting and smelting of other materials.

Advanced Refractory Design and Temperature Control

Many advancements for low-energy smelting have been made in the most recent generation of ISASMELT™ furnaces. These developments were built on the success

Table 3 Energy savings with modern ISASMELT™ designs (350 kt/a Cu from sulphide concentrates; the energy available from the feed is 11 MW)

	Energy saving (MW)
Lower dusting rates (10% to 2%[a])	5
Fully bricked furnace, with insulative lining[a]	8
Lower furnace temperature (1250 °C–1190 °C[a])	2
Advanced slag control (including 20 °C temperature decrease)	1
Pneumatic injection of dried concentrate (9.5 wt% to 0 wt% moisture)	8
Oxygen enrichment (60 vol% to 95 vol% in Lance)	2
Total energy saving	28

[a] Standard ISASMELT™ Design, comparison with alternative furnace technology shown

of its first generation, aiming to decrease capital cost, operating cost, and emissions through refractory design and temperature control. In this way, developments progressed with traditional optimisation at the forefront; but provided strong grounds for significant progress towards emissions optimisation.

Energy is lost through furnace walls in two ways. Firstly, through into the surrounding air, and secondly, to the cooling water used in water-cooled furnace components. Therefore, energy efficiency can be increased considerably by decreasing the heat lost to the surrounding air and cooling water system. For the ISASMELT™ furnace, the non-requirement for a complex and expensive water-cooling system also results in comparatively low heat losses from the furnace. Additional minor loss areas include the water-cooled splash block and water-cooled roof. The ISASMELT™ furnace is constructed with both an insulative and working lining. The working lining uses bricks resistant to slag attack, with the bricks slowly wearing over time. The insulative lining is constructed from bricks quickly corroded by the slag, but highly insulative. This layered lining approach effectively reduces heat lost from the furnace, improving the furnace's energy efficiency.

Smelting energy inefficiencies may also be a result of poor furnace temperature management. Successful furnace temperature management works to ensure that the minimum energy is used to produce a molten bath. This is achieved by minimising slag mass and temperature, through advanced process chemistry design and with chemical adjustments made online through advanced slag chemistry process modelling tools. Further, advanced furnace tapholes and advanced tapping designs are commonly installed on ISASMELT™ furnaces. This ensures molten material produced during low-energy smelting can be easily tapped from the furnace.

Advanced Waste Heat Capture

Optimised ISASMELT™ systems under the traditional optimisation approach include heat recovery, to provide steam for heating on-site, or for export to other plant areas. However, there exist several opportunities for improved emissions optimisation outcomes. Typical ISASMELT™ practice includes integration of the furnace's water-cooled components, with the off-gas waste heat boiler (e.g., boiler tube roof), enabling the waste heat from these components to be recovered as well.

Additional waste heat capture systems are possible across the broader system boundary, including units upstream and downstream of the immediate ISASMELT™/ISACYCLE™ unit. These include waste heat within output processing units (e.g., acid plant units, scrubber). Further, excess generation of saturated steam can be converted to electricity, for use within the site. If any excess electricity was sold to a wider energy grid, it may be classified as a carbon offset activity.