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ESTEP

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Opening Lecture

1. **The Clean Steel Partnership: working together to achieve a clean and sustainable future for competitive steelmaking**
   Speaker: Alessandra Colli, DG RTD, European Commission

The Clean Steel Partnership: working together to achieve a clean and sustainable future for competitive steelmaking

Dr. Alessandra Colli
Policy Officer at European Commission DG RTD

Since 2021 the European Commission and the European Steel Technology Platform (ESTEP) have signed a memorandum of understanding and officially established the Clean Steel Partnership (CSP), a collaboration that engaged € 700 million of EU funding and triggered a commitment of € 1 billion from the private side for a 7-year period until 2027. The CSP has the clear purpose to facilitate, through research & innovation, the transition of the steelmaking sector to climate neutrality by 2050, while first achieving the intermediate targets established for 2030 and 2040 by the EU policy guidelines.

The commitment of the partners towards the CSP is a commitment renewed daily through our work since 2021, a commitment to the sector and the entire range of its stakeholders for a better Europe tomorrow. Together, public and private sides can achieve a sustainable future for steelmaking, while maintaining the competitiveness of the sector at EU and global level, helping to close the R&I gaps and transitioning the industry to a new era based on near-zero and digital technologies. As clearly reported in the Draghi report, decarbonization presents an opportunity for Europe, but it must be pursued in a way that also supports competitiveness and growth. On this road, one of the main obstacles is that the EU faces substantially higher energy and raw material costs. The work that the Commission has started in the direction of the Clean Industrial Deal, to be achieved in the next 3 months, is focused on actions needed for the industry to succeed, including simplifying, investing, and ensuring access to cheap, sustainable and secure energy supplies and raw materials.

Nevertheless, the most important components in this process are the people of the steel community, at every level and in every role. Most importantly a big thank you is going to all those applicants that, with passion, effort and likely also some sleepless nights, take up the challenge to apply in the calls for proposals that the Commission regularly opens, propose new ideas, and bring new technologies to the next level of innovation. This huge work of each of you fully active in the context of Clean Steel is appreciated, admired and, most of all, extremely valuable.

Let's look at the numbers: as a new partnership under Horizon Europe, the CSP can count, until 2024 included, 32 projects awarded, some of them already in advanced development, some just started or on the way to kick off. The portfolio of those projects, awarded under Horizon Europe and the Research Fund for Coal and Steel, covers areas spanning from the most relevant innovative steelmaking technologies including DRI, EAF, and hydrogen plasma smelting, to hybrid heating technologies, use of secondary carbon carriers, digital techniques, models and sensorics, re-use of gases for onsite hydrogen production, use of low quality scrap, recover of chemical elements from the scrap, and at the same time deal with the impact of impurities affecting the steel production process.

The effort that will be required in the years ahead will be much more intense, pointing to not only industrial transformation, but also optimization of technologies and full digitalization of the entire system of processes in steelmaking. Making our steel industry strong and competitive will be the main purpose and the Commission is fully focused on achieving simplification to promote a dynamic industrial structure, increasing investment in R&I, and translating innovation into commercialization. Under this scenario, re-skilling an up-skilling of workers will be fundamental for the survival of the steel sector, as well as our research must improve in quality to be able to attract and retain talents.

The Commission is looking forward to a stronger engagement of the steel community in our future calls for proposals of the next few years until 2027, and beyond. Extended collaborations between industry, research centers, and universities are expected. There is still a long way ahead to fully transition the industry to climate neutrality, and it is a way paved with plenty of possibilities for research and where your disruptive ideas are of extreme value.

Session 1 - Green Steel production by hydrogen

1. **Hy4smelt - Hydrogen-based direct reduction and smelting of ultra-fine iron ores to green hot metal**
   Speaker: Hanspeter Ofner, Primetals
2. **Simulation, modelling, and monitoring of plasma and arc-based processes for green metal production**
   Speaker: Hamideh Hassanpour, K1-MET
3. **Model-based control of electric arc plasma in the HPSR process for zero-emission iron ore reduction**
   Speaker: Erwin Reichel, K1-MET
4. **Mechanism of iron ore pellets direct reduction: new insights of factors affecting the kinetic of the process with low quality materials**
   Speaker: Filippo Cirilli, RINA-CSM
5. **Decarbonization solutions for the steel industry: an update**
   Speaker: Gorkem Oztarlik, AirLiquide
6. **Growing with Green Steel, how regional funding can play an important role in the development of decarbonisation know-how**
   Speaker: Hans van der Weijde, Tata Steel

Hy4smelt - Hydrogen-based direct reduction and smelting of ultra-fine iron ores to green hot metal

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The steel industry contributes up to 9% of global CO_2 emissions, positioning it as a key player in addressing climate change. In line with the European Union's ambitious climate goals, the steel sector has committed to a 55% reduction in CO_2 emissions by 2030, compared to 1990 levels, and aims for climate neutrality by 2050 [1]. Traditional ironmaking methods, particularly the blast furnace (BF), are constrained by their dependence on fossil fuels and limited integration of hydrogen. To achieve the reduction targets, a revolutionary shift in technology is necessary.

The Hy4Smelt project introduces a breakthrough solution to decarbonize the ironmaking process. By combining green hydrogen-based direct reduction (HYFOR) with a renewable-powered electric furnace (Smelter), Hy4Smelt offers a sustainable alternative to BF ironmaking. One key innovation is its ability to process any type of ultra-fine iron ore in an innovative fluidized bed direct reduction process without the need for agglomeration, a limitation of current shaft based direct reduction (DR) technologies. Additionally, Hy4Smelt allows for the use of low and medium-grade iron ores based DRI in the Smelter, addressing concerns over the global availability of high-grade ores [2], [3].

Hy4Smelt's demonstration plant, to be integrated into voestalpine's steel plant in Linz, Austria, will validate the feasibility of producing HBI and green hot metal continuously at an industrial scale. This facility will serve as a guide model for replacing traditional BF technology, utilizing 100% green energy, hydrogen, and secondary carbon carriers. The project will also showcase the flexibility to use a wide range of ore qualities, including high gangue ores, which are traditionally unsuitable for DR-EAF plants. A critical component of Hy4Smelt's innovation is the Smelter's capability to produce metallurgical slag that can be reused in the cement industry, further promoting circular economy principles. The success of Hy4Smelt is expected to significantly reduce CO_2 emissions, making Europe a leader in climate-neutral steel production. It will also act as a digital showcase for the steel sector, addressing the critical issue of limited skilled resources to operate and maintain such new processes.

By addressing the technical challenges of current technologies, Hy4Smelt represents a transformative approach to sustainable ironmaking, paving the way for a green, CO_2-neutral future.

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Simulation, Modelling, and Monitoring of Plasma and Arc-Based Processes for Green Metal Production

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K1 MET GmbH, Austria

Project Acronym: PlasmArc4Green
Project Duration: July 1, 2024 – June 30, 2028
Total Budget: €3,750,000 **Funding:** €3,000,000 (Federal and Provincial)
Project Coordinator: K1-MET GmbH, Magdalena Schatzl (currently on maternity leave)

The transformation of the steel industry towards carbon-lean production processes requires the development of breakthrough technologies and new process routes for steelmaking. With the shift towards more sustainable production practices, the importance of arc- and plasma-based processes in reducing carbon emissions becomes increasingly evident. Such processes, recognized for their potential in lowering the environmental footprint of metal production, are at the heart of the transition to greener technologies. Electric arc furnaces (EAFs) are an existing example of arc-plasma steelmaking processes. However, other technologies such as hydrogen-plasma smelting reduction and various types of smelters are also under development.

Many phenomena underlying these processes are still not well understood, and the demand for detailed models and measurement techniques that give better insight is high. Development of process technology widely depends on a trial-and-error approach, largely due to the limited understanding of the intricate arc and magnetohydrodynamics (MHD) effects, as well as the challenges of experimental measurements within industrial environments. Over time, mathematical modelling has emerged as a more effective and reliable method for comprehending the complex physics involved in arc- and plasma-based processes. The PlasmArc4Green module at K1-MET is designed to advance these processes by developing sophisticated simulation models and monitoring techniques, enabling precise prediction and control of arc behaviour in industrial applications.

Early simulation studies, such as those by Ushio et al. [1] and Szekely et al. [2], focused on understanding the electric arc by employing computational fluid dynamics (CFD) to calculate turbulent Navier-Stokes, energy equations, and Maxwell equations with assumptions about current distribution. These studies were pivotal in predicting heat transfer mechanisms from the arc to the metal bath by integrating these regions in their models. Further advancements in modelling included the exploration of the thermophysical and electrical properties of plasma in various gases at high temperatures, which were applied in high-power DC arc simulations. Research by Qian et al. [3] and Ramirez [4] highlighted key factors affecting arc performance, such as current and arc gaps, and introduced dimensionless parameters like arc shape and magnetic flux. Ramirez's work also emphasized the importance of turbulence in both the arc and the metal bath, as well as the benefits of a slag layer in reducing refractory wear and maintaining higher temperatures in the bulk liquid metal. While most simulations were conducted in 2D, the studies demonstrated that atmospheric air was the most effective medium for heat transfer from the arc to the metal bath.

The focus is on creating comprehensive 2D and 3D simulation models that incorporate fluid dynamics, plasma chemistry, MHD, and radiation transport within plasma and arc-based processes. The effect of non-local thermal equilibrium on the 3D arc behaviour for very high current intensity will be studied. These models will simulate the complex interactions between high-current arcs and molten metal baths in metallurgical reactors. Alongside modelling, the project will utilize optical emission spectroscopy (OES) and optical absorption spectroscopy (OAS), building on previous research by [5] and [6], to monitor plasma temperature and composition. This data will be integrated into the simulation models to enable real-time adjustments.

A key component of the project is the development of in-situ measurement techniques, particularly optical and electromagnetic methods, to monitor arc behaviour in real-time. These measurements will validate the simulation models and provide critical real-time data to improve process control. Additionally, the project will delve into electrode dynamics, including erosion modelling and the impact of various gas mixtures on arc stability and longevity. By predicting electrode wear and optimizing electrode materials and configurations, the project seeks to improve the durability and efficiency of these processes.

The integration of these models and measurement techniques into a process control system represents another major goal of the project. This system will utilize real-time data to adjust operating parameters dynamically, thereby reducing energy consumption and minimizing CO_2 emissions. The technical approach includes developing multi-dimensional models using CFD combined with MHD to simulate the arc's behaviour. These models will be particularly focused on the near-electrode region, where complex phenomena such as electron emission and sheath formation occur, affecting overall process stability.

The expected outcomes of the PlasmArc4Green module include validated, high-fidelity simulation tools that can predict arc behaviour and optimize plasma-based processes. These tools are anticipated to enhance the efficiency and sustainability of metal production, leading to significant reductions in CO_2 emissions. The integration of these models into real-time control systems will allow for dynamic optimization of operations, yielding both cost savings and environmental benefits. Figure 1 shows an overview of the PlasmArc4Green module and its required scientific disciplines, i.e., simulation/modelling, metallurgy as well as validation together with the available demo plants to reach the objectives.

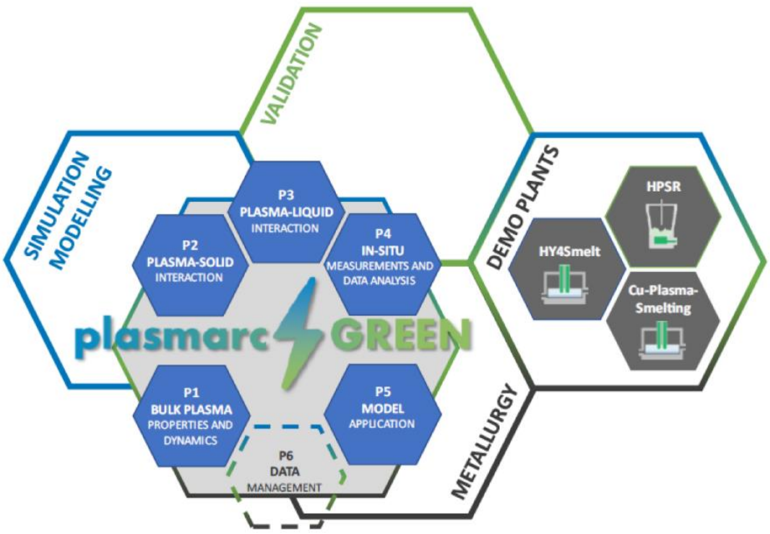

Figure 1. *Overview of PlasmArc4Green.*

The project's innovations will have a direct impact on the steel and metallurgical industries by providing advanced tools for process optimization. The real-time control systems developed will enable these industries to adapt to varying conditions, ensuring optimal performance with minimal environmental impact. PlasmArc4Green is thus poised to make a significant contribution to the industry's transition towards sustainable and CO_2-neutral metal production by 2050.

The COMET Module is funded within COMET – Competence Centers for Excellent Technologies – by BMK and BMAW as well as the co-financing federal provinces Upper Austria, Styria and Tyrol. The COMET programme is managed by FFG (www.ffg.at/comet).

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Model-Based Control of Electric Arc Plasma in the HPSR Process for Zero-Emission Iron Ore Reduction

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Motivation

The Hydrogen Plasma Smelting Reduction (HPSR) is a promising, sustainable alternative to iron ore reduction for several reasons: Fine ores can be used with minimal pre-treatment, ionized hydrogen is a highly effective carbon-free reducing agent for iron oxides, and electric current is used as the energy source. Compared to hydrogen fine-ore reduction in the solid phase, the HPSR process integrates the smelting step to obtain liquid raw steel and can use a wider range of ore qualities. At the moment, a demo-plant is operated in the voestalpine steel plant in Donawitz (Austria), and a lab-scale reactor is used at the Montanuniversität Leoben [1,2].

In this contribution, we focus on the electrical behavior of the transferred arc. Current and voltage are recorded at a much higher data rate than before. We present ways to analyze this data and point out a route to a model-based control approach by integrating various sensor data. The goal is an optimized operation to increase energy efficiency, hydrogen utilization, and reduce electrode wear.

Results

In Figure 1, the schematics of the process are shown. The voltage is measured using a PicoScope 2405A USB oscilloscope with a 1:100 voltage probe directly at the electrode contacts and a Pico TA167 Hall-effect current probe with 10 mV/A conversion. Data is continuously recorded using customized Python software. The data blocks are 8M samples at 100k samples per second.

In Figure 2, the processed data is shown as a current over voltage plot. Remarkable is the negative slope, which is characteristic for electric arcs. The parameters of the transfer function changes at certain steps, especially when the electrode is moved up and down or the gas composition is varied.

The present interpretation is as follows: A change in electrode spacing is visible by a displacement of the curve. A different gas composition changes the slope. Since the arc is ignited in pure Argon atmosphere and later changed to 40% hydrogen, both cases are visible in the graph.

The arc extinguishes when the current drops below a certain value to maintain the ionization of the gas. During normal operation this should be avoided. The control algorithm should be able to detect the probability of an extinguishing event in advance and apply countermeasures such as reducing the electrode spacing.

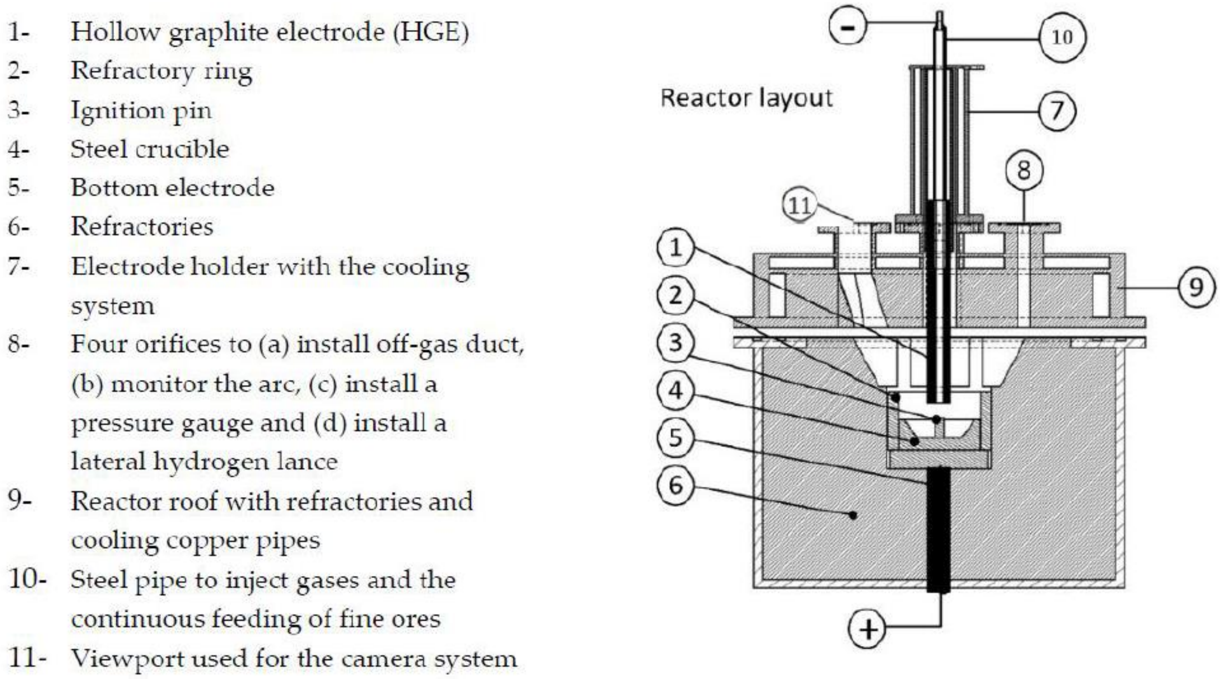

***Figure 1**. Schematic of the process (from [1] and [2])*

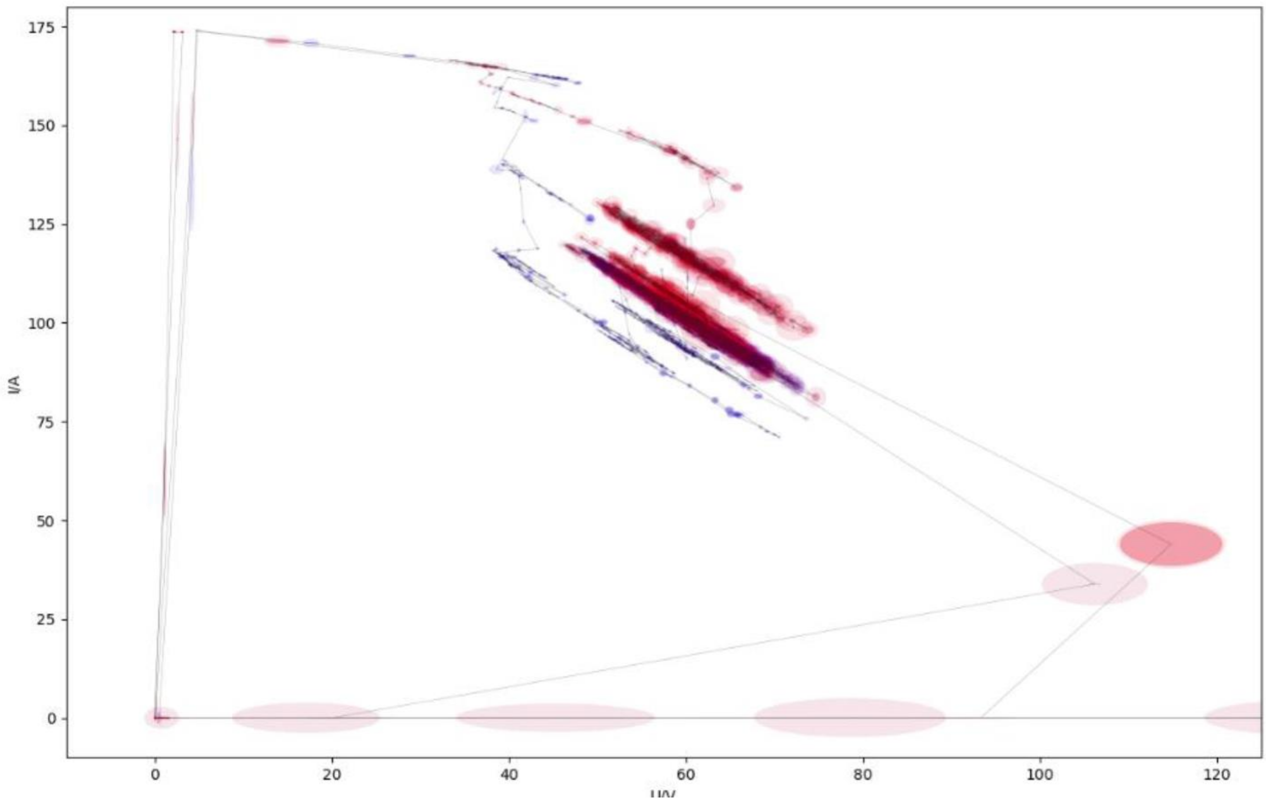

***Figure 2**. Results as a current-over-voltage plot to show different states of operation. Blue corresponds to earlier states in the process, red to later ones.*

Outlook

In the project LIGHTBOW (funded by FFG, Austria), the control algorithms will be implemented and applied to a laboratory scale transferred arc set-up in the beginning. Results of detailed numerical simulations will provide the theoretical basis for modelling. At a later stage, the method will be applied to the existing demo-plant.

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Mechanism of iron ore pellets direct reduction: new insights of factors affecting the kinetic of the process with low quality materials

Filippo Cirilli, Valentina Alemanno
RINA-CSM (Centro Sviluppo Materiali)

The production of carbon-neutral steel requires new appropriate processes and technologies. From this perspective, the use of hydrogen as a reducing agent of the iron ores has the greatest impact on CO_2 emissions in the steel production route. A serious candidate is the gas based direct reduction process, which converts pellets of iron ore into metallic iron, to be further melted to produce liquid steel. The direct reduction process, currently performed with natural gas, makes possible to use a high proportion of hydrogen, up to 100%, in the reducing gas mixture. This allows the reduction (or elimination) of CO_2 emissions. Therefore, the production cycle based on direct reduction process is expected to have a very large diffusion in the next years, passing from niche to mass production.

The consequence is lower availability and higher cost of the high-quality materials today usually used in the existing direct reduction processes, and the need to use lower quality pellets of iron ore at higher non-ferrous oxide content.

Full comprehension of the mechanism involved in the direct reduction process is fundamental to optimize the performance and energy demand of the process and to accounting the different quality of input material. The chemical physical phenomena involved in the direct reduction process include the mass transfer of gaseous species (such as reducing gases H_2 and CO), diffusion through macro- and micro-pores to the oxide interface, adsorption at the oxide interface, kinetic of chemical reactions, desorption of gaseous reaction products and mass transfer of gaseous products through the laminar layer back to the gas stream.

In this paper, a state of the art of the literature is presented, analyzing the effects of above-described factors and the identification of rate limiting steps. The rate of reduction is limited by the slowest step in the process, known as the rate-limiting step. Generally, the chemical reaction itself is highly dependent on temperature: at lower temperatures, the chemical reaction becomes the limiting factor. With increasing temperature, the rate of the chemical reaction increases exponentially.

Based on results outlined by state-of-the-art literature an experimental program has been defined, to clarify the aspects of the process with higher degree of uncertainty. First results of laboratory tests, carried out with low quality pellets in atmospheres simulating the utilization of pure methane and pure hydrogen as reducing agents, are presented and discussed.

The activities are carried out under the frame of the IPCEI project HYDRA, in which a pilot line with direct reduction plant and electric arc furnace will be realized. Hydra is financed under the frame of NextGenEU by Italian Minister MIMIT.

Decarbonization solutions for the steel industry: an update

Gorkem Oztarlik, Philippe Blostein, Jean Caudal, Mike Grant, Anna-Maria Pubill-Melsio
Air Liquide

The global steel industry faces a huge energy transition challenge. Besides the usage of electricity with a lower carbon footprint, there are basically two technology pathways to reduce carbon emissions: carbon capture (for utilization or storage), or carbon replacement by another agent performing the same function (thermal or chemical), such as hydrogen.
Air Liquide developed and proposes solutions in these two pathways:

- Capture solutions, by various technologies such as cryogenics, adsorption, absorption, permeation. If necessary, these technologies can be combined to propose the best scheme adapted to the specific steelmaker case, depending on: flowrate, pressure, purity.
- Hydrogen solutions, to replace natural gas, coke or coal, with various technologies including notably P.E.M.(Proton Exchange Membrane).

These solutions can be implemented for instance at the blast furnace or at the direct reduction plant.
Some applications can be relatively simply implemented as “quick wins”, others require more long term development. The presentation will include actual industrial references in the steel industry, but also solutions developed for other industrial sectors that may apply to the steel industry. A focus will be given to the most recent achievements and projects.

Growing with Green Steel, how regional funding can play an important role in the development of decarbonisation know how

Dr.ir.Hans van der Weijde
director Strategy, Programmes & External Collaborations TSN R&D

The dutch R&D ecosystem has always been strong in public private partnerships (PPS), for TSN this has always been an important part of the knowledge development programmes next to the European schemes like RFCS and Horizon.

These PPS collaborations have recently got a massive impulse with the presence of the so called "growtfund" , an innovation fund with several billions aimed at growth through innovation. Because the PPS structure was present already in the materials and metals world they were able to win quite a number of (large) programmes. Also the steel industry formulated a programmed in which we focus with 5 teams on knowledge creation and pilots over the entire steel (circular) supply chain. With over 100MEuro subsidy and more than 80PhD/postdocs we will focus on

-system changes in a circular metals industry
-steel production
-steel processing
-steel use
-steel recycling

(see also https://groeienmetgroenstaal.nl/en)

Next to a summary of the technical details of these themes the talk will also present how such large national programmes interact with other funding streams as discussed in ESTEP.

Session 2 - Smart, efficient and circular resource management paving the way to decarbonization

1. **Gas processing at integrated steelworks: Syngas makeup and CO valorization**
   Speaker: Balan Ramani, Tata Steel
2. **Methodologies and tools for designing a decision support system for energy management**
   Speaker: Valentina Colla, Scuola Superiore Sant'Anna
3. **Simulation and analysis of energy networks in the transition to sustainable steelmaking**
   Speaker: Christa Mühlegger, K1-MET
4. **Exploring and optimizing process off-gas management in steelworks during their transitions towards C-lean processes**
   Speaker: Lorenzo Vannini, Scuola Superiore Sant' Anna
5. **Digital transformation and sustainable innovation in steel manufacturing: the AID4GREENEST project**
   Speaker: Ilchat Sabirov, IMDEA Materials

Gas processing at integrated steelworks: Syngas makeup and CO valorization

Balan Ramani[a], Abraham Takarianto[a,b], Peter van den Broeke[a], Thijs Vlugt[b], Jan van der Stel[a]

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[b]Engineering Thermodynamics group, TU Delft, Delft, Netherlands

Introduction

During the transition to a gas-based reduction process at an integrated steelworks one of the aspects is the handling of the off-gases. During the coming years, Tata Steel Nederland will be implementing a gas-based direct reduction (DR) process and an Electric Arc Furnace (EAF.) This transition will have as a main consequence a reduction in the amount off-gas produced, and this will affect the operation of an integrated steel plant in several ways. Especially, the on-site production of electricity by the power plant will change considerably with a lower amount of off-gases being available. In the current situation the off-gas stream obtained from mixing the coke oven gas, the blast furnace (BF) gas, and the basic oxygen furnace (BOF) gas is fed to the power plant and converted to electricity. The processing of the off-gases for the future configuration of an integrated steelwork will still be required to achieve carbon neutrality, as there will be carbon-rich off-gas stream from both the BOF and the EAF.

In this work, an overview will be presented of PSA (pressure swing adsorption) for the gas treatment of the off-gases from a BF, BOF/EAF, focusing on the recovery of carbon monoxide (CO). Additionally, options for the valorization of the recovered CO through the use of syngas (mixture CO and H_2) for the makeup for the reducing gas for the gas-based DR process will be discussed. The on-site re-use of carbon monoxide as reducing gas provides an alternative to the current use as fuel for heat or power production, and can act as an enabler of hydrogen use in the ironmaking process.

Results

In order to achieving carbon-neutral iron-making, there are a few options for the processing and possible valorization of carbon-rich off-gas stream from steel mills, where in the off-gases besides CO_2 also CO is often presented in a large fraction [1 - 6]. One of the options is hydrogenation of CO_2 and CO toward C1 chemicals, such as methane or methanol. However, these so-called CCU (carbon capture and utilization) options require the development of dedicated infrastructure, covering the transport of CO_2 and CO, production of hydrogen, and a chemical plant for the chemical synthesis. On the other hand, on-site re-use of especially CO seems to be a more feasible alternative, as compared to transporting CO.

In terms of gas separation technologies, PSA (pressure swing adsorption) might be an attractive option for the separation of gas mixtures with (at least) CO_2 - CO - H_2 - N_2. Especially, efficient separation of CO from N_2 is challenging for chemical absorption processes, because of the similar properties of the two molecules.

Modeling work

The following cases will be discussed where PSA is used for the recovery of CO_2 and CO:

A. Two-step PSA process for the gas treatment of the BF gas, where first the CO_2 is removed and subsequently the CO is recovered;

B. PSA process where the CO is (directly) recovered from the BOF/EAF gas.

An overview of the typical gas composition for the off-gases and for the reducing gas is given in Table 1. A numerical model in Aspen Adsorption has been used to investigate the effect of the operating parameters, such as flow rate, adsorption and desorption pressure, rinse-to-product ratio, column length, and the addition of purge and rinse steps on the performance of the PSA separation. A parametric study has been performed based on the Ideal Adsorption Solution Theory (IAST) for multi-component equilibrium adsorption, and the results from the simulation have been validated against data published in the open literature, see Figure 1.
Results will be presented describing the performance of the PSA process for the recovery of CO_2 and CO in terms of scale (Nm^3/h), CO_2 and CO purity, CO_2 and CO recovery, and energy consumption. For the two-step PSA process for the gas treatment of a typical BF gas stream, the optimized case utilizes a four-column PSA configurations with 95% purity and 89% recovery for CO_2 and 85% purity and 95% recovery for CO.

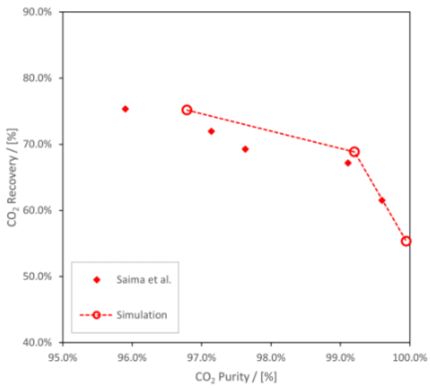
Valorization

One of the interesting options is to combine the CO with hydrogen into syngas for the gas makeup for the DR process. In addition to the recovery of the CO, options for the production of hydrogen have been evaluated. A comparison is made between green and blue hydrogen, that is blue hydrogen from methane steam reforming with CO_2 removal from the tail gas (of the PSA process for the CO_2 - H_2 separation) versus green hydrogen from water electrolysis where the electrolyzer is power with electricity from offshore wind. Different options for the hydrogen production will be compared by taking into account Intermittency of renewable electricity, carbon intensity of the power, and the available production scale of green and blue hydrogen. Additionally, for the electrolyzer case, options for process integration by using the oxygen in the BOF/EAF are considered as well.
Finally, a basic cost analysis with some key operational aspects will be discussed covering the amount of syngas that can be generated, the optimal composition of the syngas in terms of makeup gas, and amount of oxygen required for the BOF/EAF.

Table 1. *Overview of average gas composition of steel mill off-gases, including EAF [3 - 5] and for the reducing gas for the Energiron process [6].*

composition		BOF gas	BF gas	EAF off-gas	Reducing gas
H_2	vol%	2.0	3.5	0.0	66.3
CO	vol%	60.0	23.5	28.0	16.2
CO_2	vol%	18.0	22.0	7.0	5.0
CH_4	vol%	0.0	0.0	0.0	8.3
N_2	vol%	16.0	46.0	62.0	1.3
H_2O	vol%	4.0	4.0	3.0	3.0
inerts + CxHy	vol%	0.0	1.0	0.0	0.0

Figure 1. *Results for the relation between CO_2 purity and CO_2 recovery, comparing results from the Aspen simulation (this work) and data from literature (Saima et al. [7]).*



Conclusions

In this presentation an overview will be given of recovering and use of CO from a blast furnace and a basic oxygen furnace, and options for the CO as part of the makeup of the syngas as reducing gas for DR process will be discussed. The presentation will highlight the reduction potential of different reducing gas mixtures based on the use of natural gas, hydrogen, and syngas in ironmaking focusing on the recovery of CO, which can be valuable feedstock supporting the steel industry's transition toward green steel manufacturing.

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Methodologies and Tools for designing a Decision Support System for energy management

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Optimizing energy usage in large Energy Intensive Enterprises requires a plantwide viewpoint benefitting from plant managers experience, providing a global vision, and process operators that generally focus on the local operation of their specific part of the plant. However, a local energy usage optimization is not sufficient to achieve adequate global performance in terms of economic and environmental impacts, when the energy sources and networks are shared between several facilities. Processes and equipment show several mutual interactions that cannot be neglected and highly affect the operation and even the planning of single sub-plants. Traditional integrated steelworks are exemplary from this point of view. Coke Plants (CP), Blast Furnaces (BF), Converters (LD) and secondary metallurgy are characterized by highly inter-connected production scheduling and energy consumption. They produce large process off-gases quantities that can be reused for electrical and thermal energy production. However, their production is not fully stable in terms of calorific value and volume flows; thus, they must be managed through storage facilities and torches, to handle their shortage and excess.
In future steelworks, although some processes will gradually disappear being replaced by new ones, the problem will persist, also considering possible fluctuations in the provision/production of relevant energy-carriers. Moreover, the transition toward fully C-lean steel production will not be "immediate" and, during the transient, the problem of optimal handling, managing and exploiting gaseous energy carriers in related networks will play a big role in ensuring economic and environmental sustainability of the transition itself. Finally, future steelworks are foreseen to be increasingly integrated with other industrial facilities by implementing industrial symbiosis solutions which comprise the exchange and/or sharing of energy carriers in a perspective of energy efficiency.
An optimal utilization of all available valuable energy sources can be achieved only by synchronizing their production and consumption, a task that cannot be easily accomplished by industrial manager and operators with standard management tools. Decision support systems can suggest control strategies that exploit forecasting models and include a centralized data management gathering information of the scheduling of all the plants, and the main measurements depicting the current state of energy consumption. However, energy management commercial software is often unsuitable to this task, and in-house tools must be developed through existing libraries or from scratch. Existing commercial libraries can be a reliable and fast solution, but often requires costly licenses, while open-source libraries greatly decrease the development costs, but shows issues (e.g. discontinuous development, low reliability, low computational efficiency, limited support).
In this work, we present the experience and results of the RFCS project entitled "*Steam and gas networks revamping for the steelworks of the future*", during which a DSS was developed for the purpose. The presentation describes the methodologies used for developing such tools, focusing on the steps and technologies needed for the software design and deployment in a real industrial field. The work explores main available technologies and software libraries for

developing a digital twin of the integrated steelworks, an optimization framework to suggest optimal control strategies, and graphical user interfaces.

Simulation and analysis of energy networks in the transition to sustainable steelmaking

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Achieving carbon neutrality by 2050, as outlined in the European Green Deal, demands a substantial reduction in CO_2 emissions from the iron and steel industry, which has traditionally relied on the carbon-intensive blast furnace (BF) steelmaking route. To meet this challenge, worldwide steel manufacturers have initiated ambitious projects aimed at transitioning to more CO_2-lean steel production by employing electric arc furnaces (EAF) and direct reduction (DR) plants utilizing hydrogen. This transition results in the coexistence of traditional and innovative processes within integrated steel plants, profoundly impacting their energy networks.
To address these complex changes, this study, conducted as part of the SMARTER project (Steam and gas networks revamping for the steelworks of the future), analyses the gas and energy streams of the steel mill Linz using the simulation tool gPROMS (General PROcess Modeling System). This advanced process modelling software enables a detailed examination of how integrating new technologies and processes affects energy management during the transition phase. Various transformation scenarios of the steel plant are simulated to assess their impact on energy streams and CO_2 emissions.
Initially, the integrated steel mill in Linz, which consists of 3 BFs, is modelled in gPROMS using measurement data from 2019 and compared with the environmental report of voestalpine Stahl GmbH 0. The simulation results closely match voestalpine's reported values for crude steel production, CO_2 emissions, and external energy demand, confirming the model's accuracy for exploring decarbonization scenarios. The current energy streams (gas, steam, electricity) of the steel plant in Linz are illustrated in Figure 1.
To theoretically reduce CO_2 emissions at the steel mill in Linz, five hypothetical decarbonization scenarios are simulated in gPROMS:

- Replacement of 1 BF with 1 EAF.
- Replacement of 2 BFs with 2 EAFs.
- Replacement of 2 BFs with 2 EAFs + DR using natural gas.
- Replacement of 2 BFs with 2 EAFs + DR using hydrogen.
- Replacement of 3 BFs with 3 EAFs + DR using hydrogen + submerged arc furnace (SAF).

While each transformation scenario reduces direct CO_2 emissions, the demand for electricity and natural gas or hydrogen rises significantly. Notably, if hydrogen is produced onsite, the electricity demand increases accordingly. To enhance energy efficiency and sustainability, the sensible heat from the EAF and DR off gas is utilized for steam generation, allowing the steel mill to meet its steam and electricity demand through waste heat recovery in the more advanced scenarios.
In the final scenario, some CO_2 emissions are inevitable due to the specific carbon content required in steel, which necessitates the use of natural gas in hydrogen-based direct reduction. Consequently, carbon capture and utilization (CCU) technologies, such as amine scrubber and catalytic methanation, are implemented into the gPROMS simulation to close the carbon cycle. This integration reveals further significant changes in the energy networks.

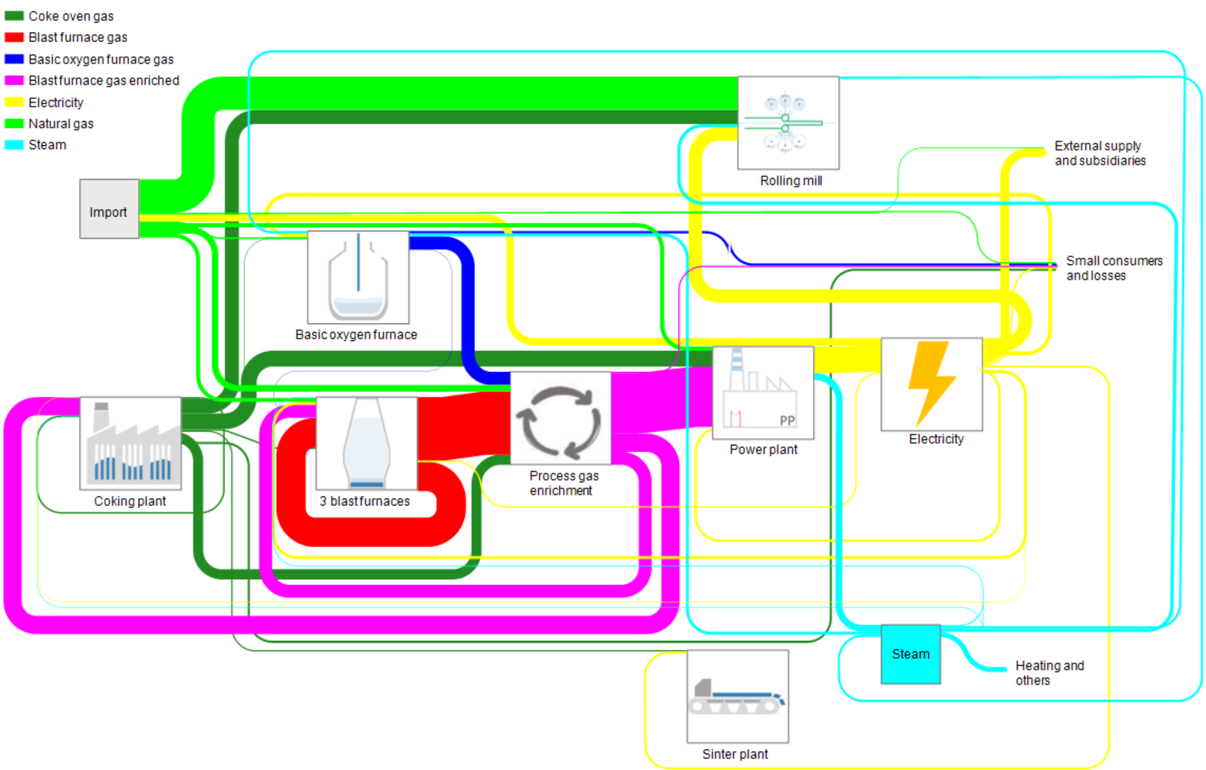

Figure 1. Energy streams base case 2019

The developed gPROMS scenarios provide valuable insights into the energy requirements and distribution in a future steel mill. Additionally, the simulation models can be adapted for its usage in other steel plants or industries, particularly regarding the application of CCU technologies.

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Exploring and Optimizing Process Off-Gas Management in Steelworks During Their Transitions Towards C-Lean Processes

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The iron and steel industry is one of the major contributors to global CO_2 emissions, largely due to its dependence on fossil fuels. Traditional processes, such as the blast furnace (BF) and basic oxygen furnace (BOF) steelmaking route, are both energy-intensive and result in considerable CO_2 emissions. Achieving carbon neutrality by 2050, as outlined in the European Green Deal, poses a significant challenge to the industry. Steel manufacturers are now tasked with integrating innovative, low-carbon technologies while managing the complex energy and gas networks within integrated steelworks. The coexistence of traditional and modern processes adds layers of complexity, especially in optimizing energy flows and minimizing emissions.
A key difficulty in this transition lies in the forecasting and management of process off-gases (POGs) generated during steel production, both in standard and novel processes. In current integrated steelworks configurations, these gases are produced in highly variable and discontinuous quantities, making their effective utilization and valorization challenging. The fluctuating nature of POGs complicates the task of maintaining stable energy and gas networks, as plant operators must synchronize processes in real time while adhering to strict operational constraints. Balancing energy production and consumption, ensuring optimal gas recovery, and minimizing flaring requires advanced forecasting tools and optimization techniques.
In this work, the primary focus is on analyzing different scenarios to assess the environmental, energetic, and economic impacts of transition from the BF route to direct reduction and electric arc furnace (EAF) based processes, and optimizing the management of POGs. Through scenario analysis, the study explores how various system configurations and operational strategies influence energetic performance. Machine learning-based predictive models were employed to forecast POGs generation and demand patterns more accurately, enabling strategies for optimizing gas use while minimizing energy waste. Mixed-integer linear optimization techniques were also incorporated to solve the energy distribution problem, considering constraints such as gas storage limits, calorific values, and process synchronization. Among the dynamic scenarios analyzed, this study presents novel approaches for methanation and methanol production from POGs. These by-products can either be sold to generate new revenue streams or reintegrated into the steelmaking process, reducing reliance on external energy sources.
The transition from traditional BF-BOF steelmaking to EAF and direct reduction processes offers a path for significant reductions in CO_2 emissions, but requires careful integration into existing energy systems to maintain operational efficiency.
The simulation results provide essential insights for integrating low-carbon technologies, optimizing POGs management and valorization, and enhancing energy recovery. This work highlights the importance of scenario analysis in evaluating the energetic and environmental impacts of rerouting POGs and transitioning steelmaking processes, emphasizing the role of advanced optimization techniques and predictive models in shaping the future of decarbonized steel production.

Digital transformation and sustainable innovation in steel manufacturing: The AID4GREENEST project

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Traditionally, steel metallurgical processes have been developed using a 'trial and error' approach, where chemistry and processing parameters (e.g., hot rolling temperature, cooling rates) are tested to achieve the desired microstructure and properties. While effective, this method is time-consuming, labour-intensive, and generates high material waste and emissions. It can also lead to high rejection rates of up to 10% in manufacturing, with design flaws often identified too late in the process, resulting in costly remedial actions. The integration of AI- and simulation-driven design holds promise for reducing this inefficiency. By improving interaction between part and process design, potential flaws can be addressed earlier, avoiding unnecessary costs and delays.

Another challenge in the steel sector is the time-consuming nature of experiments for steel characterization. For example, advanced steels often require Electron Backscatter Diffraction (EBSD) analysis, which can take more than an hour. Multiple characterizations are needed at various stages of thermo-mechanical processing (e.g., hot rolling, cold rolling) to ensure quality. Similarly, high temperature standard creep tests, which assess steel performance in high-temperature applications, can take thousands of hours, significantly slowing the development of new steel grades. Data collection in the manufacturing environment also presents challenges. Unlike private user data, industrial data is often gathered from sensors monitoring various processes. Ensuring accurate data classification, storage, and auditing is critical but lacks standardized approaches. This inconsistency can lead to difficulties in reproducing results between laboratories. Moreover, differing terminologies used by IT experts, engineers, and metallurgists hinder collaboration across disciplines.

All these challenges are tackled in the EU HORIZON project AID4GREENEST (GA 101091912), which focuses on the development of novel tools to support digital transformation of steel sector. The scope of the tools developed through the AID4GREENEST project includes the steel design (chemistry and microstructure), process design (processing parameters), product design (processing and heat treatments), and product performance stages. A consortium of 10 partners composed of leading European universities, research centres, steel companies, and a small enterprise steer the project. This presentation will cover various related aspects, with an emphasis on the following:

- How AI-based tools and advanced models will contribute to the reduction or even complete elimination of material waste during steel development and product manufacturing (for example, forging and heat treatment of meter-scale steel products).
- How novel methodologies for rapid steel characterization will significantly reduce energy consumption and carbon emissions during steel development, manufacturing, and product quality control.

How online platforms for knowledge transfer, sharing non-confidential data, and standardizing characterization methods and advanced modelling tools, along with ontologies, will contribute to effective workflows on an industrial scale.

Session 3 - Resource efficiency and industrial symbiosis

1. **TransZeroWaste – Upgrading of low-quality iron ores and mill scale with low carbon technologies**
   Speaker: Martin Hubrich, BFI
2. **Decarbonization through industrial symbiosis: The use of recycled carbon raw materials in the steelmaking**
   Speaker: Elia Gosparini, I.Blu
3. **Utilization of recovered refractory material as slag additive and experimental determination of liquid slag properties**
   Speaker: Irmtraud Marschall, K1-MET
4. **EUROSLAG – Core activities and challenges for the slag value chain**
   Speaker: Thomas Reiche, FEhS
5. **Valorisation of zinc containing residues : Zincval project**
   Speakers: Damiano Capobianco, Esin Iplik, Marianne Magnelöv & Yanping Xiao, RINA-CSM, Linde, Swerim & Tata Steel
6. **Decarbonization in the steel industry and future production routes (e.g., SuSteel) and future utilization paths for the by-products generated (e.g., slags and dusts)**
   Speaker: Christoph Thaler & Wolfgang Reiter, voestalpine & K1-MET

TransZeroWaste – Upgrading of low-quality iron ores and mill scale with low carbon technologies

Martin Hubrich[a], Sébastien Zinck[b]
[a] *BFI*
[b] *LIST*

Iron ore and scrap as raw materials are forming the base of iron and steel production. Due to the transition from carbon-based iron and steel production to green steel production with H_2, most current production units such as sinter plant, blast furnace and basic oxygen furnace will be replaced by the direct reduction (DR) process followed by the electric arc furnace (EAF). As a result, the current recycling routes for mill scale will be cut off and the demand for high quality DR pellets and high-quality scrap will rise. New by-products from the gas treatment of the DR process and iron pellets sieving will emerge. Because of this, technologies for an upgrade and use of low-quality iron ores and scrap are necessary to avoid lack of raw materials.

Therefore, the ongoing Horizon Europe project TransZeroWaste focuses on e.g. i) upgrading low-grade iron ore by combining it with iron-rich by-products, ii) the development of innovative techniques to produce high-quality pre-material for decarbonised future production routes, and iii) the separation of disturbing components from by-products to replace scrap, thus supporting the transition towards zero waste in the European steel industry. Related technologies are investigated and first promising results are available for presentation.

One approach is the investigation of cold pelletisation and briquetting of low-quality iron ores for direct use in existing and future steel production process. Different materials and mixtures of low-quality iron ores for direct reuse were investigated in lab trials in combination with new binders. First suitable combinations of binders and materials were determined, thus allowing a fulfilment of the relevant parameters (e.g. cold strength of an operational handling) of the produced pellets or briquettes.

A further approach, using a breakthrough technology for a low CO_2 material treatment, is the hot pelletisation - with microwaves for upgrading low-quality iron ores to increase the iron grade - and technologies for the valorisation of low-quality materials. Materials and their combinations have been selected and their dielectric properties were determined. Microwave trials showed - depending on the material property - a combined reduction and a dezincing effect, which will be further investigated.

Besides this, the removal of impurities - such as oil, fat or grease - from low-quality iron ores equivalents (as oily fine scale) is investigated as a mandatory step allowing an internal metallurgical reuse and making this resource usable within the material supply of the production units. The chosen approach is the hydrometallurgical treatment, including the cleaning agent recovery via i) a modified magnetic separator allowing a combined selective removal of iron containing material and ii) a spray de-oiling, followed by a cleaning agent recovery using ceramic flat sheet membranes. This treatment aims at reaching oil contents below 0.1- 0.2 wt.-% for an internal reuse. Representative cleaning agents (alkaline, tenside, solvents) have been selected and investigated under different conditions e.g. different treatment temperatures. Conditions for the cleaning agent recovery of solid- and oil-loaded cleaning agent solutions with ceramic flat sheet membranes were determined. Based on the final results, field trials regarding the hydrometallurgical treatment with a metallurgical reuse are planned for 2025.

Decarbonization through industrial symbiosis: the use of recycled carbon raw materials in steelmaking

Elia Gosparini
I.Blu

Thanks to the fruitful collaboration of companies ranging from plastic recyclers to technology providers and steel producers, the use of reducing/foaming agents deriving from the recycling of mixed plastic waste in substitution of virgin fossil resources has become a consolidated best practice in Europe, both in EAF and BF processes. In this presentation, the state-of-the-art of iron and steel production using polymeric recycled carbon materials is described, including the technical results obtained by several industry stakeholders active in the value chain, and namely:

- **I.Blu (Iren Group)**, one of the major plastic sorters and recyclers in Europe, focusing on the recycling of mixed plastic waste and producing BLUAIR®, largely used in Europe both in EAFs and BFs.
- **Feralpi**, the first EAF steelwork to substitute 100% of the injected coal with polymeric secondary reducing agents (SRA/BLUAIR®);
- **Tenova**, an innovative technology provider that designed highly performing systems to inject recycled polymers into EAF processes;
- **voestalpine**, a globally leading steel and technology group based in Linz/Austria acting as the main European Blast Furnace to uptake the injection of recycled polymers in substitution of PCI, collaborating closely also with the R&D Competence centre K1-MET;
- **K1-MET,** an Austrian metallurgical competence centre of sustainable and digitalized metallurgy for a climate neutral and resource efficient planet, highly experienced in research about the use and reactivity of alternative reducing agents for ironmaking (e.g. from waste plastics), providing support to the steel industry, including voestalpine.

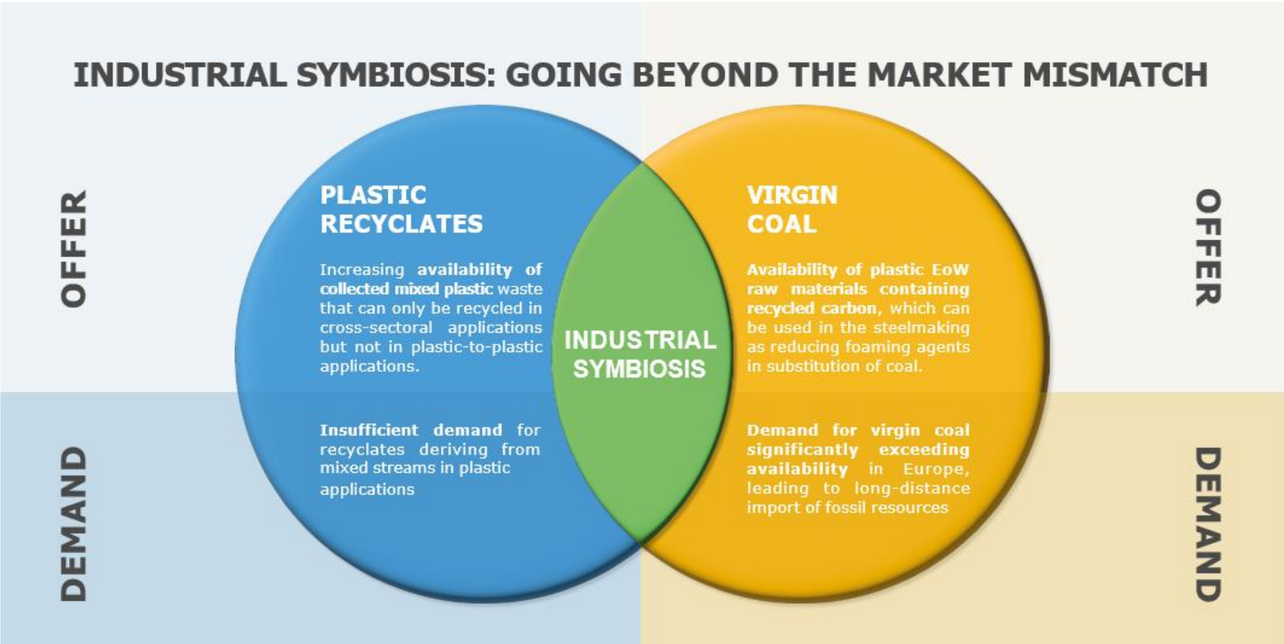
The presentation also illustrates the results on an LCA study conducted by Rina CSM within the OnlyPlastic project, which confirmed that the use of recycled carbon raw materials, in this case BLUAIR®, in EAF steelmaking is beneficial in most environmental impact categories.

Thanks to the know-how and the experience of the partners involved, highly technological recycling and utilization processes were developed, enabling the use of customized plastic recyclates deriving from post-consumer mixed plastics as reducing/foaming agents, in virtue of their recycled carbon and hydrogen content. **The use of recycled polymers in substitution of coal in steelmaking leads to significant CO_2 emission savings as well as the preservation of natural resources and, therefore, of carbon storages in the ground.**

In order to reduce the EU dependence from the import of coal and anthracite, the current mismatch in the EU market of carbon-bearing materials that can be used as reducing/foaming agents, where the demand for virgin coal significantly exceeds its resources in the European Union, needs to be counterbalanced by the uptake of recycled carbon-bearing materials deriving from plastic waste that can be sourced locally.

According to the JRC document entitled B*est Available Techniques (BAT) Reference Document for Iron and Steel Production,* injecting recycled polymers in substitution of traditional fossil reducing agents prevents the emissions associated with coke production and consumption, and can generally improve the productivity and performance of the steelmaking process. The substitution of virgin coal, normally imported from extra EU countries, reduces the EU dependency from long-distance imports, while also reducing the extraction, transportation and refinement of natural carbon storages.

In order to promote the further development of a sustainable economic model, **appropriate mechanisms should be introduced to incentivize the substitution of virgin fossil resources with the *recycled carbon* contained in secondary raw materials**. The upcoming revision of the ETS Directive as well as the revision/implementation of other ETS implementing acts, are a great opportunity for the industry stakeholders to initiate a dialogue with the European Institutions in this sense, advocating for a zero-rated emission factor for recycled carbon and a prioritization of recycled carbon raw materials over virgin fossil ones.



Utilization of recovered refractory material as slag additive and experimental determination of liquid slag properties

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To meet the European Commission's Green Deal climate target of climate neutrality by 2050 and thus counteract climate change, intensive research into new low-carbon technologies is currently conducted in the iron and steel industry. The iron and steel industry is responsible for 7-9% of CO_2 emissions from the global use of fossil fuels [1]–[3]. However, until a complete transformation of technologies has taken place, existing processes need to be optimized to reduce greenhouse gas emissions. Slag metallurgy is a key factor, as slags have a significant influence on process efficiency. The addition of usually CaO- and MgO-containing slag additives allows adjustment of the slag composition for optimum process operation. Efforts are currently being made to use recovered refractory material as slag additives to save resources and reduce CO_2 emissions. This contribution deals with the use of secondary metallurgical additives (recycled refractories) and with the determination of electrochemical properties, thermodynamic and viscosity data of primary and secondary metallurgical slags as part of an Austrian-funded project within the K1-MET competence center program in a consortium of scientific and industrial partners, such as RHI Magnesita, voestalpine Stahl Linz and Primetals Technology.

The life cycle of refractory materials can be closed by recovery and utilization using the fraction > 80 mm of refractory materials dismantled from furnaces to produce new refractory materials and processing the fine fraction (< 80 mm) into slag additives. As the carbon footprint of this fine fraction can be < 10% of the commonly available slag formers, the use of these materials would help to meet the sustainability targets of a steel plant [4],[5]. Besides to new technologies and recycling strategies, the sustainable production of metals also requires thermodynamic and kinetic simulations of metallurgical processes. Knowledge of thermodynamic data is essential for the implementation of digital tools for process simulation. Diffusion coefficient and activity of dissolved species in slags are two crucial variables for modeling of dissolution processes of additives and thermodynamic equilibria [6]. To describe the dissolution behavior of particles in slags and the foaming behavior of slags, viscosity data are also required [7],[8]. Diffusion coefficient and thermodynamic activity of CaO and MgO in slags from primary and secondary metallurgy were determined experimentally using the rotating cylinder method and Knudsen effusion mass spectrometry, respectively. The comparison of the results of both methods with literature data confirms their suitability [9]. Dissolution tests are currently carried out within the aforementioned Austrian funded project in various metallurgical slags (e.g., BOF slag, slag from an electric DRI smelting furnace) to evaluate the utilization of recycled refractory material as a slag additive. The results of these experiments are compared with the dissolution rates of currently used slag additives. In addition, the viscosity of slags is measured as a function of composition and temperature using a rheometer, paying particular attention to the influence of solid particles. The current research also employs potentiostatic experiments to determine activities and activity ratios, as well as species transport parameters in slags. A further key area of investigation is the discrimination of conduction phenomena (ionic and electronic conduction) which are causing measurable current flow through liquid slag.

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EUROSLAG – Core activities and challenges for the slag value chain

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EUROSLAG (www.euroslag.com), the European Association of ferrous slag producers and processors, is based in Duisburg and brings together 26 organizations and companies from 17 countries, including the FEhS – Building Materials Institute (www.fehs.de). As a European network for the production, use and development of ferrous slags and slag-based products, EUROSLAG's activities focus on research and technology, European standardization, and internal and external communication. Every two years, EUROSLAG organizes together with national partners the slag conference of the same name. In 2024, the 12th EUROSLAG Conference will be held in Bilbao, Spain, October 23rd – 25th. The title of the conference, which is jointly organized by UNESID, SIDEREX, PLAREA and EUROSLAG, is “Slag for the future - the future of Slags” (https://euroslag2024.eu/).

The presentation will introduce EUROSLAG and its core activities. This includes the work on dedicated important political framework issues for the slag value chain. These are for example:

1. The new work program of the European Commission with focus on circular economy and the preservation of natural resources
2. The CO_2-allocation between main and co-product of the steel production
3. The European Fertilizer Product Regulation and the corresponding claim of EUROSLAG and its partner organizations against the European Commission.

Additionally, the presentation will highlight some of the outcomes of the 12th EUROSLAG Conference, which will take place the week before ESTEPs Annual Event. For example, a summary on the main slag related transformation research projects will be given. Some background on this:

The main challenge of the steel industry for the next decade is the transformation of the steel production to fossil free processes. The CO_2 intensive route via blast furnace will be substituted by a combination of a direct reduction plant (DRP), based on natural gas and – at a later stage - on "green" hydrogen, with an Electric Arc Furnace (EAF) or a Smelter, heated with renewable energy. Thus, the well-known latent-hydraulic granulated blast furnace slag (GBS) being successfully used in cement and concrete for more than 140 years will vanish step by step. GBS is used as a supplementary cementitious material not only, but in particular due to its CO_2 reduction potential in the cement/concrete production.

Whereas the DRP itself does not generate any slag, EAF and Smelter will do. Both EAF and smelter slags will be very different. The reasons are e.g., the different oxidizing and reducing atmospheres and different shares of scrap input. Moreover, the new EAF slags will be also different compared to today's scrap based EAF slag. However, specific slag/metal ratios, slag volumes, chemical and mineralogical compositions and physical properties of the new slags are yet unknown. Thus, also their cementitious and environmental properties are still unknown! Further developments for those slags will also affect the scrap based EAF slags

In addition to its use in cement, its use in road construction cannot simply be regarded as a plan B. Depending on the ores, EAF slag will face new challenges, for which new markets and applications might have to be developed.

To gain further insight and experience regarding the composition of these slags, several national and international research projects have been initiated with the objective of investigating the effects of DRI on established applications. Frequently, the emphasis is on its utilization in cement and concrete. However, the leaching process in accordance with road construction regulations is also a significant aspect that could be influenced by metallurgical treatment.

Valorisation of Zn containing residues

Damiano Capobianco, Loredana Di Sante[a], Esin Iplik[b], Yanping Xiao[c], Johannes Hage[c], Benoît Mignon[d], Alessandro Vecchio[e], Marianne Magnelöv[f]

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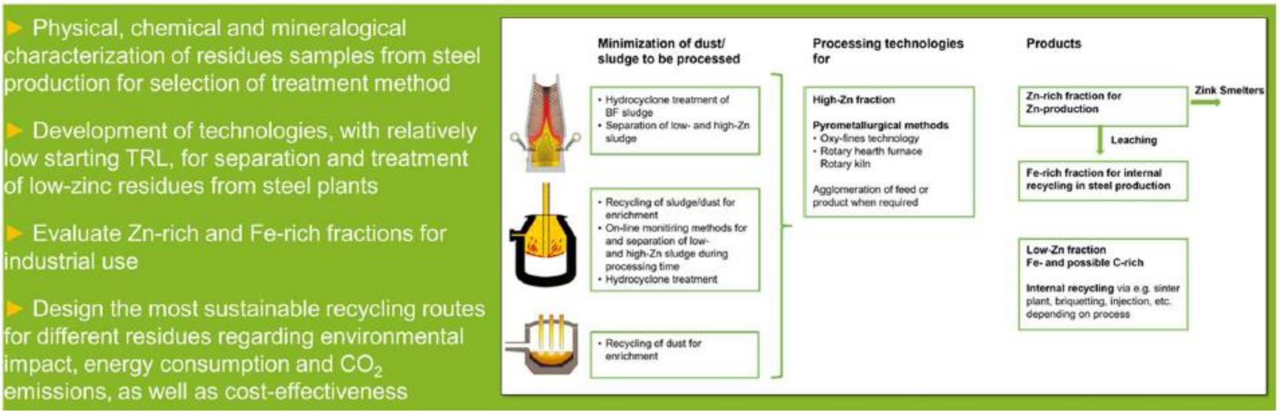
[d] *CRMGroup*

[e] *Acciaierie d'Italia*

[f] *Swerim*

The steel industry is a major contributor to the global economy, but at the same time generates significant amounts of emissions and residues. Most are valorised by internal recycling or external use, but there are still significant values in terms of carbon and iron units that cannot be recycled because the zinc content in the dust and sludge is too high, but too low and full of impurities to be sent to zinc producers. For the recycling of these residues in steelmaking processes, the removal of zinc is important since this element creates various problems in steel plants.
Dust and sludge that are not recycled, cause both raw materials losses and additional costs for preparing safe deposits and conducting landfilling. Among steel producers in EU, about 900 kt of blast furnace (BF) dust and sludge along with 1,300 kt of basic oxygen furnace (BOF) dust and sludge are generated each year, of which approximately 50% are recycled. In EAF steelmaking, about 30% of the dust cannot be recycled due to the low zinc content. It is anticipated that the zinc content of EAF dust will be lower in the future as DRI/HBI partly or fully will replace steel scrap when the transition towards green steel production is realized. Although the objectives of residue treatment are common to all steel plants, an efficient and economically feasible method for the removal of zinc and the generation of an iron-rich residue for recycling within the production cycle is not yet available.
The European project ZincVal (RFCS-02-2022-RPJ, 10111263) aims to develop technologies integrated with the steel production that enable recovery of iron, carbon and zinc from dust and sludge and avoid landfilling. The approach of using different technological routes, at relatively low starting TRL and with synergies between some of the approaches represents a significant and credible due diligence approach to both increasing the valorisation of low zinc-containing residues in current steelmaking practices and preparing for a significant increase in the availability of these in future steelmaking. Based on the properties of dusts and sludges, determined via physical, chemical and mineralogical characterization, the project will design the most sustainable recycling routes for different residues regarding environmental impact, energy consumption and CO_2 emissions, as well as cost-effectiveness.

Overall project concept of RFCS ZincVal



This project has received funding from the Research Fund for Coal and steel (RFCS) under project No. 101112631

Future production routes for a decarbonization of the Steel Industry and future utilization paths for the by-products generated

Christoph Thaler[a], Wolfgang Reiter[b]
[a] *voestalpine*
[b] *K1-MET*

Due to changing regulatory frameworks and increasing sustainability awareness towards reaching climate neutrality by 2050, the steel industry is currently undergoing a transformation process. The traditional crude steel production route (blast furnace and LD converter) causes CO_2 emissions of around 2,300 kg/t of steel. New technologies use carbon as an energy carrier, foaming and reducing agent only to a limited extent, thereby drastically reducing CO_2 emissions. Through steel production via hydrogen-based direct reduction, DRI melting in the Smelter, and hot metal refining in the LD converter, CO_2 emissions can be reduced to below 900 kg/t of steel. Similar values are also delivered by the single-stage Hydrogen Plasma Smelting Reduction (HPSR) process, where the majority of CO_2 emissions are attributed to "Scope 2".
In addition to changing production routes, the utilization of by-products originating from future production routes is also a currently relevant research focus. For the Smelter slag, a basicity of around 1.1 [-] is aimed to enable its utilization in the cement industry similar to blast furnace slag. For the utilization of zinc-rich steel mill dusts, one ongoing research work is focused on the pyrometallurgical RecoDust process. Within this, the dust is converted into a zinc-rich dust fraction (Crude Zinc Oxide) with a zinc oxide content of around 80% and a slag fraction (RecoDust slag) with an iron content of around 50% and zinc content < 0.5%. The zinc-enriched dust can be sold to the zinc industry, and the slag can be utilized internally as secondary iron carrier.
The technologies for a successful transformation of the steel industry are already known and have been tested at least on a demo scale. The implementation on a large industrial scale will certainly occupy metallurgical research for the next few decades.

Session 4 - Circularity in the European steel sector

1. **Challenges and solution for steelmaking dust valorization in the green steel transition**
   Speaker: Bernhard Voraberger, Primetals
2. **Development of a pyrometallurgical approach for iron and zinc recovery: design and modeling of a plasma reactor within the ReMFRa project**
   Speaker: Loredana Di Sante, RINA-CSM
3. **Improved analysis of post-consumer scrap to further push a circular steel industry**
   Speaker: Johannes Rieger, K1-MET
4. **Valorization and characterization of hydrochar for coke replacement in steelmaking: a circular economy approach**
   Speaker: Filippo Cirilli, RINA-CSM
5. **Green solutions for by-product utilization from process gas cleaning plants**
   Speaker: Paul Trunner, Primetals
6. **DRASTIC: Demonstrating real & affordable sustainable building solutions with top-level whole life cycle performance and improved circularity**
   Speaker: Barbara Fernandez, CELSA
7. **COACH - Cold-bonded agglomerates for blast furnace ironmaking with chemically engineered binders**
   Speaker: Frederic Van Loo, CRM Group
8. **Gaining value with Ecolbriq : Two possible applications of Ecolbriq®: Reducing CO_2 emissions and/or recycling of byproducts minimizing landfill**
   Speaker: Nella Janakova, Progress Ekotech
9. **Steel: from main to co-product in a circular economy?**
   Speaker: Harmen Oterdoom, Butterbridge

Challenges and Solution for Steelmaking Dust Valorization in the Green Steel Transition

Bernhard Voraberger*, Christoph Prietl, Krzysztof Pastucha, Gerald Wimmer, Thomas Steinparzer
Primetals Technology Austria GmbH, Austria
**Bernhard.voraberger@primetals.com*

The transition of the steel industry towards lower CO_2 emissions and increased circularity necessitates radical changes in current production methods. Key strategies include replacing blast furnaces with hydrogen-based direct reduction and electric arc furnaces (EAFs) or Smelters depending on the iron ore used, while in parallel increasing the use of secondary raw materials like steel scrap over virgin iron ores. Utilizing steelmaking byproducts such as slags and dust in primary steelmaking processes is crucial for achieving a green and circular steel industry. [1]

Future green steel production will rely on scrap-based EAFs and DRI-based EAF or smelter plants, generating significant amounts of new byproducts such as zinc and iron containing dusts with various zinc content. On the other side with the shutdown of blast furnaces less sinter plants will be in operation which leads to a limitation of internal recycling options for iron rich residues such as scales. Various technologies, including hydrometallurgy and pyrometallurgy, have been explored for valorizing zinc and iron-containing dust. However, hydrometallurgy is less effective in removing zinc from complex mineralogical phases like franklinite (ZnFe2O4) [2], which can contain 40 – 60 % of the zinc in EAF dust or BOF sludges. Currently, high-zinc dust from scrap-based EAF operations is mainly recycled via the Waelz process in rotary kilns. While energy-efficient, the Waelz process has high CO_2 emissions and produces iron-rich slag that requires landfilling. Furthermore, the (crude) zinc oxide product generate by the Waelz process requires further treatment (e.g., washing or clinkering) and even than cannot fully used in primary zinc industry which underline the necessity for new greener and circular dust recycling solutions [3].

Primetals Technologies has developed the ZEP technology [4], [5], [6] to valorize iron rich and zinc-containing steelmaking dust through a fully circular approach with minimum CO_2 emissions. This process recovers the full metal fraction (iron and zinc) and converts the mineral fraction into a sellable product for the cement industry. For high zinc containing dusts, especially those from scrap EAF, a pre-calcination step generates a clean and high-quality zinc oxide product without the need of further treatment to remove halogens (F, Cl) and heavy metals (Pb), before reuse in primary zinc industry. Utilizing renewable energy and secondary carbon carriers, the ZEP technology can reduce CO_2 emissions to near zero.

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Development of a Pyrometallurgical Approach for Iron and Zinc Recovery: Design and Modeling of a Plasma Reactor within the ReMFRa Project

Loredana Di Sante[a], Filippo Cirilli[a], Elena Carrara[b], Fabio Praolini[b], Marta Guzzon[c], Enrico Malfa[c]

[a] Rina CSM

[b] Tenaris

[c] Tenova

A **pyrometallurgical** approach based on the use of a plasma reactor and RecoDust technology for the recovery of Fe and Zn, respectively, could be the key to achieve this goal being part of the ReMFra research project funded within the Horizon Europe framework program (Clean Steel Partnership).
The present work outlines the preliminary steps required for the successful application of the ReMFra technologies at pilot scale, implying modelling and design of the Plasma Reactor unit.
The modelling started by the elaboration of historical data of the industrial streams provided by Tenaris Dalmine. The industrial streams considered were: EAF slag, LF slag, Scale, Rolling Mill Sludge, Pickling sludge and EAF dust. Some briquettes recipes were defined, produced, tested for mechanical properties and melted to define the melting behavior.
The adaptation of Tenaris Dalmine Ladle Furnace to enable the smelting reduction process was designed. This included comprehensive design work for the ladle furnace equipment and its auxiliaries, making the process feasible and efficient. The Plasma Reactor design was supported by a detailed thermodynamic modeling, assessing the influence of different materials mixes on melting behavior, including slag, metal, and gaseous phases.
The thermodynamic calculations provide the expected melting temperatures and metal yield, essential for ladle sizing. CFD analyses using ANSYS Fluent to evaluate the gas flow field, temperature, and heat flux distribution within the reactor and flue gas extraction system was conducted.

Experimental

The basic phenomenon occurring during the process are the heating of the briquettes/pellets (up to process temperature – 1600 °C) and the reduction of metal oxides MexOy to Me and melting of inert. To define the operating condition ranges, mass and energy balance has been performed by thermodynamic calculation. This permits also to evaluate the pre-defined quality of metal and slag, and to calculate the amount of reducing agent and the energy demand of the process (Figure 1***Figure***).
The basic design of the new dedicated ladle is based on two main constraints:

- The maximum electrode length, because the LF is an existing equipment the maximum ran of the electrodes column is fixed. This length determines the minimum level of the steel inside the ladle.
- The max volume of foaming slag. Based on the minim level of the steel determined by the electrodes length and based on the volume of metal bath and foaming slag, the nominal flow rate of the briquettes was determine.

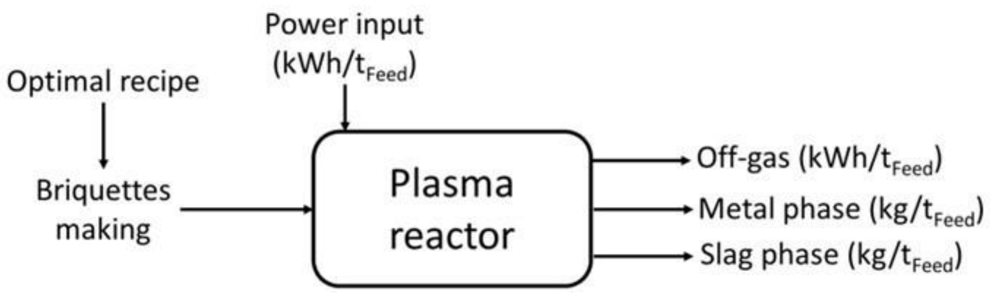

Figure 1. *Scheme reporting the input and output regarding the Plasma Reactor*

The detailed design phase focused on translating the basic design into comprehensive technical specifications and detailed engineering drawings. This phase included:

- Engineering Drawings: Created detailed engineering drawings and schematics for the modifications.
- Material Specifications: Defined material specifications and requirements for the modified components. Specifications generated from the detail engineering will be used by DALMINE for the purchasing phase.

Conclusion

This work has outlined the preliminary steps for the successful implementation of ReMFra technologies at pilot scale, focusing on the design and modelling of the Plasma Reactor and the adaptation of the ladle furnace. Thermodynamic modelling provided critical insights into expected melting temperatures and metal yield, allowing for precise definition of operating conditions and design parameters to optimize the metal reduction and recovery process.
Additionally, CFD analyses enabled a thorough understanding of the gas flow field and heat flux distribution, ensuring the efficiency of the plasma reactor and the overall process. This comprehensive approach paves the way for future experimental validation and industrial application.

Acknowledgements

The ReMFra project receives funding by the European Union (Grant Agreement no. 101058362).

Improved analysis of post-consumer scrap to further push a circular steel industry

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** corresponding author*

Forecasts reveal that the crude steel demand will be 30% higher in 2050 than it is today. Furthermore, the contribution of scrap in the total steel charge will likely grow to 40% in 2050 from 30% than it is today (see Figure 1 [1]).

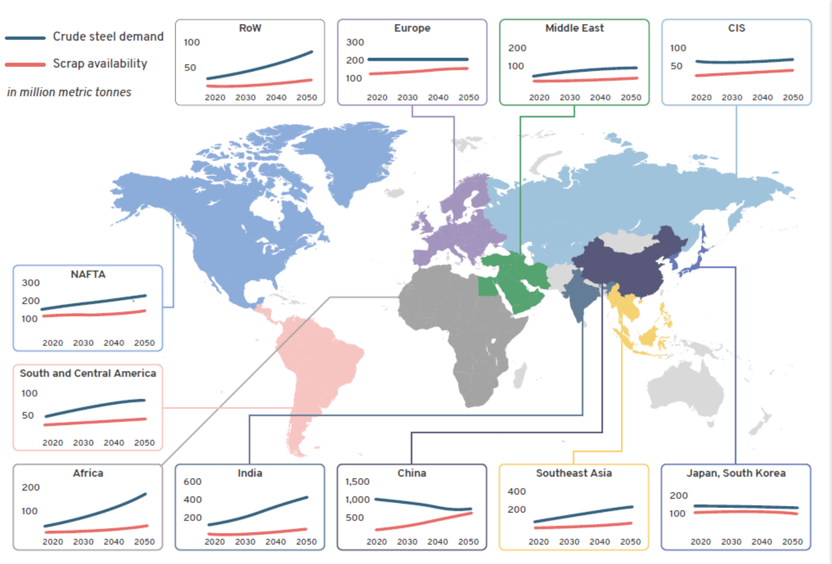

Figure 1*. Expected global demand for crude steel and availability by region [1].*

An increasing share of post-consumer scrap is also predicted (see Figure 2), which will not allow 100% recycling for all high-quality steel grades.

For some steel grades, tramp elements, such as copper, tin, chromium, nickel or molybdenum prevent the reuse of post-consumer scrap. This surplus of low-quality scrap within the EU generates enormous scrap exports. In 2022, these amounted to ~18 Mt [2]. On the contrary, scrap of higher quality is imported to the EU to fulfill the scrap demand for steel production.

Regarding scrap characterization, optical scrap inspection is state-of-the-art. Especially at the scrap yard entrance (for both, the scrap supplier, and the steelmaker) cameras record the incoming scrap on a truck or a wagon. Furthermore, 3D radars (mounted on crane grabbers) are used together with integrated weighing systems to create a 3D profile of the scrap yard and to ensure a certain sorting of the different scrap qualities. However, scrap characterization and quality monitoring are often done manually. This subjective assessment depending on the experience of the operators is a sub-optimal way for a proper scrap classification.

Compared to the state of the art, the PURESCRAP project funded within the Clean Steel Partnership of Horizon Europe is taking an ambitious, major step toward reducing impurities in post-consumer scrap prior to melting by applying highly efficient sensor stations in conjunction with improved scrap sorting (see Figure 3).

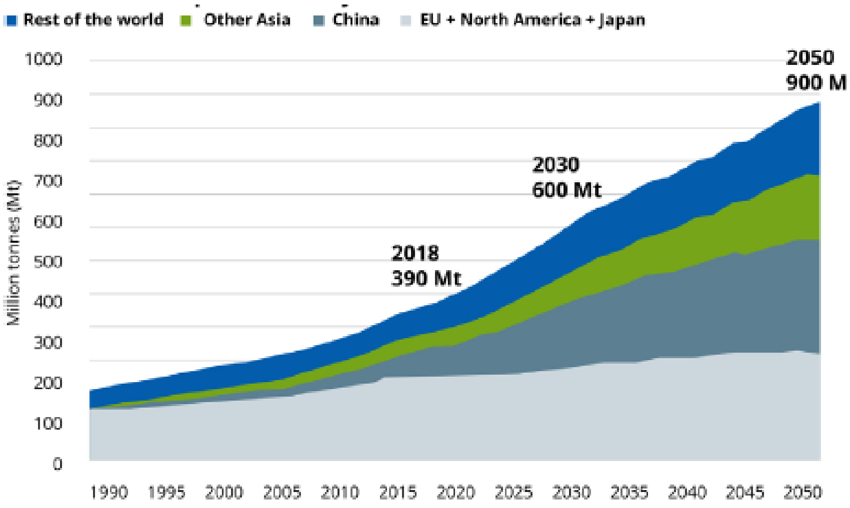

Figure 2. Expected global availability of post-consumer (end-of-life) scrap [3]

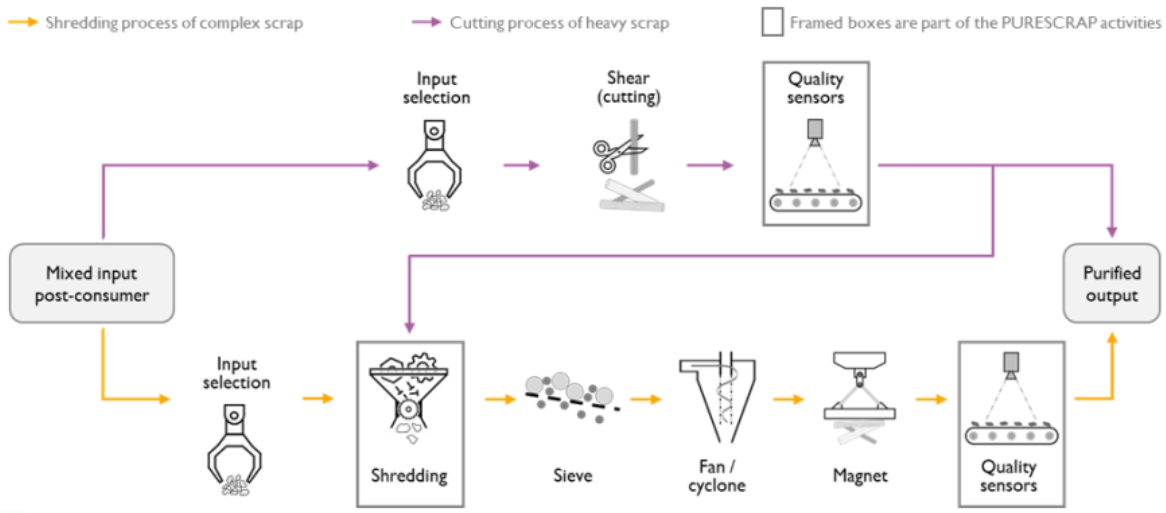

Figure 3. Foreseen concept of the PURESCRAP sensor stations for post-consumer heavy and shredded scrap.

Therefore, the current contribution focuses on the overall goals together with an insight into the current status of the research work:

- Concepts of a combined spectroscopic and vision system to characterize heavy and shredded scrap installed at a scrap supplier site
- Improving the scrap characterisation through image detection and processing models using Deep Learning solutions
- Use of the sorted scrap to demonstrate its ability to produce standard steel grades at least in semi-industrial scale

This project receives funding by the European Union (Grant Agreement no. 101092168).

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Valorization and characterization of hydrochar for coke replacement in steelmaking: a circular economy approach

Valentina Alemanno, Filippo Cirilli
RINA-CSM (Centro Sviluppo Materiali)

The replacement of fossil coal with alternative materials derived from renewable resources represents a significant challenge for the steel industry, in view of the transition to more sustainable production processes. In this context, the BioReSteel project (Grant Agreement n. 101112383) is focused on the the production and utilization of hydrochar as a replacement for coal (typically petroleum coke or antracyte) in the electric arc furnace (EAF). The hydrochar is a char derived from biomass residues treated in a hydrothermal carbonization process (HTC). This technology consists in a thermochemical process for the pretreatment of high moisture content biomass under hot compressed water; in general the process temperature is about 200°C and pressure ranegs from 2 to 6 MPa.
The HTC enables the utilization of residual raw materials from wet biomass, thereby rendering hydrochar a more economically competitive substitute for carbon from fossil materials in the production of green steel. The starting biomasses are generated in the agro-food industry, such as fruit peels and vegetable residues (leaves, stems, etc.).
The hydrochar, provided by the partner INGELIA, was subjected to a series of chemical and physical analyses in order to define range of variability of fundamental parameters necessary for its utilization in the steel industry. In particular, the elemental composition, the granulometry, the presence of selected heavy metals, and the calorific power have been defined. Further treatment s can be also carried out on hydrochar, as thermal pyrolysis or torrefaction, and densification into pellets or briquettes. In the mix of briquettes other materials (iron rolling mill scale) can be added, for further materials recovery. Drop tests were conducted to determine the material's behavior when subjected to drops (such as drops during the furnace charge) and check the mechanical stability of the material (drop test is used to verify the stability of the materials during handling operations). Thermogravimetric analyses were done to evaluate the performance of the material during changes in temperature. The study has been carried out for the different types of physical state of the hydrochar (in the form of powder, pellets, or briquettes). Finally, an experimental activity has been conducted to evaluate the material's performance. In a first serie of tests, carried out in a lab induction furnace with capacity of 20 kg of steel, the hydrochar (as powder, pellets and briquette) have been put in contact with molten steel bath. In a second series of test, a single briquette composed by hydrochar has been in a furnace up to melting (controlled by temperature measurement and visual inspection) and the reducing capability of the hydrochar has been quantified
The performed tests permitted to measure the capability of the hydrocar to provide carbon to the steel bath and to ac as reducing agent (carbon neutral) of iron oxide.
The carbureting capacity of the metallic bath, and other pertinent parameters. The preliminary obtained results suggest that hydrochar has the potential to contribute to metal carburization, offering an alternative to the total use of carbon form fossils. This could have significant benefits in terms of environmental sustainability and the valorization of waste materials. The present study represents a further contribution to the implementation of the circular economy of the steel industry, with the objective of reducing dependence on fossil fuels and valorizing organic waste.

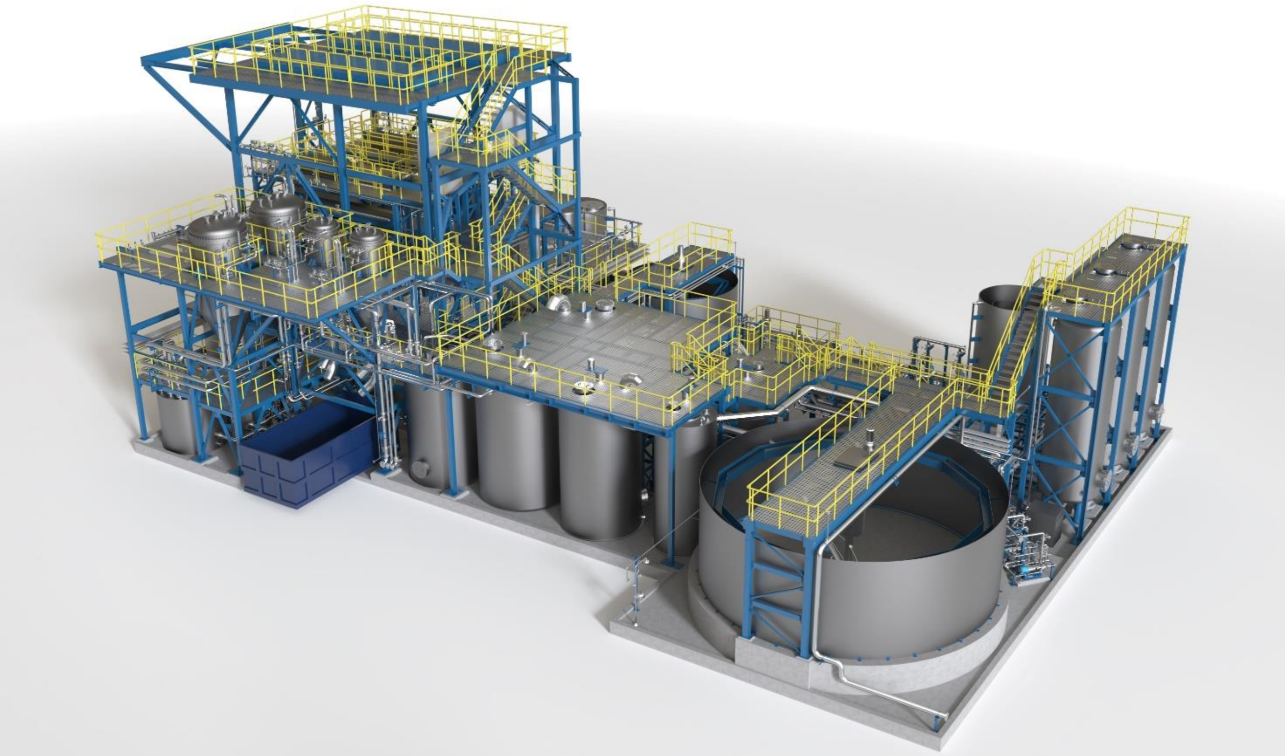
Green solutions for by-product utilization from process gas cleaning plants

T.Plattner, R.Neuhold, P.Trunner, T.Steinparzer
Primetals Technologies

Environmental standards are becoming increasingly stringent. Governmental regulations now demand minimal emission levels and the effective use of by-products in both existing and new iron and steelmaking facilities. To reduce emissions such as dust, SOx, NOx, heavy metals and dioxins from e.g. agglomeration plants, below the required levels, dry off-gas cleaning processes such as the MEROS systems are used. These systems are characterized by a multi-component additive injection system in combination with a highly efficient fabric filter system, to remove by-products, resulting out of the chemical and adsorptive reaction between the specific pollutants and the injected additives.

By-products resulting from such gas treatment plants are often disposed, leading to consumption of valuable landfilling volume and high cost as such material must be stored under special conditions to avoid uncontrolled leaching of salts and heavy metals. The innovative by-product leaching process can be closely linked to the gas cleaning plants (such as MEROS) to minimizes the residue volume already on site. After the leaching step, the suspended solid like iron oxide or carbon will be recovered for the primary process. The brine will be treated in a series of wastewater treatments steps which are designed as a modular system. These treatments steps ensure the compliance with the most stringent discharge emission limits prior to the release of the clean brine into the existing water treatment plant or directly to the sea. As an alternative for plants which are not located close to the sea a desalinization step can be installed and product (salt) can be gained by crystallization.

How the Leaching technology can fulfill the environmental targets for a green steel production, shall be illustrated based on the latest results achieved with the by-product leaching plant, realized downstream a MEROS plant in Japan.



DRASTIC: Demonstrating Real & Affordable Sustainable Building Solutions with Top-level whole life cycle performance and Improved Circularity

Bárbara Fernández
EU Digitalisation Project Manager, CELSA Group

In the rapidly evolving landscape of the steel industry, CELSA Group, a prominent steel recycler encompassing the entire value chain, is poised to revolutionize the sector through digitalization acting as an enabler to circular economy. Recognizing the pivotal role of circularity in meeting the future needs of the construction and automotive sectors.

This presentation delves into an innovative strategy, emphasizing collaborative efforts across the entire value chain. **DRASTIC (Demonstrating Real & Affordable Sustainable Building Solutions with Top-level Whole Life-cycle Performance and Improved Circularity)** is a European project funded under the European Union via the Built4people partnership. It brings together 23 partners from 8 European countries, with VITO serving as both the project and technical coordinator [1]1.

The project aims to significantly reduce the whole life-cycle environmental impact of new construction and deep-energy retrofit by demonstrating affordable innovative circular solutions tackling all layers of constructions.

This session will showcase real-world applications, deep diving into the Spanish demonstrator which the company is leading. In which two main challenges are being addresses: unlocking the potential for reuse of structural elements and reincorporating them into new constructions, and overcoming the challenge of incorporating white slag into the cement mix.

By presenting a tangible use case, CELSA aims to inspire industry stakeholders to embrace innovation, foster partnerships, and collectively drive the transformation towards a more circular and sustainable future.

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COACH - Cold-bonded agglomerates for blast furnace ironmaking with chemically engineered binders RFCS funded project – 899318

Frédéric van Loo, Yanping Xiao, José Luis García Cimadevilla, Noelia Vega Aguirre, José Barros Lorenzo, Hans Hage, Olaf Stock

In the ironmaking context, cold-bonded agglomeration could complement high-temperature sintering and pelletizing for the production of the Blast Furnace (BF) burden. It does not require a costly and highly CO_2 emitting firing/induration and, in the recycling context, could be applied to a larger range of by-products, wastes and other secondary materials.

COACH project aimed at demonstrating the use of cold-bonded agglomerates:

- Cement-free to be used in the many European blast-furnaces that do not tolerate further slag addition;
- Made of by-products to improve internal recycling.

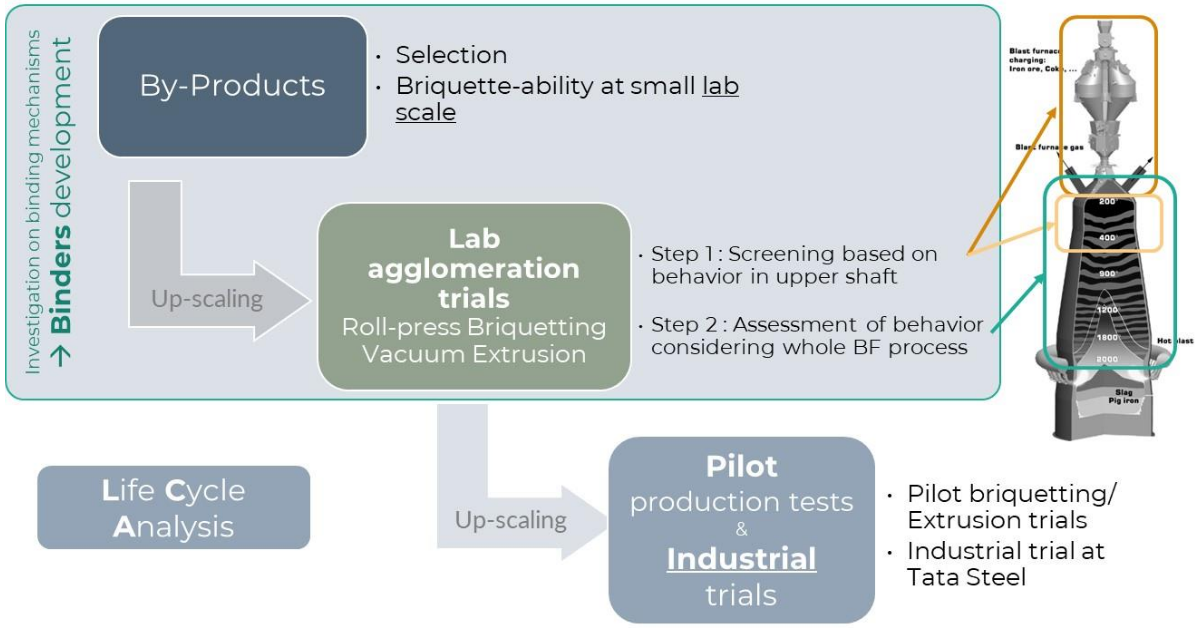
Two paths were investigated to achieve this result : firstly the use of novel polymeric binders (existing or developed on purpose), secondly the selection of the optimal agglomeration technology. Both vacuum extrusion and roll-press briquetting have been assessed resulting in a slight advantage for vacuum extrusion in terms of a better-quality agglomerate.

The suitability of the samples for Blast Furnace application was tested according to metallurgical standards, in particular the mechanical strength (ISO Tumble test) and reduction strength (RDI) but also through more complex and learn full trials for a deeper understanding of the impact on the whole BF process.

A stepwise approach was applied : starting with lab trials (some briquets) for assessment of selected materials briquetability and definition of the recipe to be assessed at bigger lab scale (about 10 kg), then pilot scale (up to 2 tons of briquets) and finally through an industrial trial at Tata Steel IJmuiden where 150 tons of extruded briquettes were produced and charged in the BF6 after 3 weeks of curing. During 18 h the extruded pellets were consumed as partial replacement of the iron burden and no negative issues were detected in BF process conditions so that the industrial trial was considered successful.

So, it was demonstrated that the selected polymeric binder (in an amount of 1 to 2%) combined with extrusion or roll-press briquetting can produce cold-bonded agglomerates adapted to Blast Furnace charging for the selected recipes (2 iron based, 1 carbon based).

Finally, the calculations based on the final recipes show a beneficial effect of consuming these agglomerates on the BF where the simulations estimate a potential for coke savings in the range of 110 to 220 kg coke/t extruded pellets for the iron rich briquettes and up to 500 kg coke/t extruded pellets for the carbon rich briquettes. In parallel, it can be expected a reduction of CO_2 emissions through these coke savings, the replacement of raw materials and its associated emissions. The cold-agglomerates are also able to replace an amount of sinter or pellets slightly higher than the agglomerates rate itself (over 1100 kg/t extruded pellets).


Investigation on binding mechanisms
→ Binders development
By-Products
Selection
Briquette-ability at small lab scale
Up-scaling
Lab agglomeration trials
Roll-press Briquetting
Vacuum Extrusion
Step 1 : Screening based on behavior in upper shaft
Step 2 : Assessment of behavior considering whole BF process
Life Cycle Analysis
Up-scaling
Pilot production tests
&
Industrial trials
Pilot briquetting/ Extrusion trials
Industrial trial at Tata Steel

GAINING VALUE WITH ECOLBRIQ®: Two possible applications of Ecolbriq®: Reducing CO_2 emissions and/or recycling of byproducts minimizing landfill

Nella Janáková
M.Sc., Strategy & Innovation, Progres Ekotech, s.r.o.

Reducing CO_2 Emissions: Industrialization of the hydrogen reduction technology will take some years and further time will pass by until all blast furnaces worldwide will be substituted by hydrogen technology. A bridging technology EcolBriq® offers tremendous value by reducing CO_2 emissions on the regular BF production route partially substituting the iron ore sinter process.

Recycling of by-products: Recapturing the valuable elements of by products and reducing landfill quantities is another EcolBriq® application creating a cost advantage.
The paper presents a cold technology to produce a low-carbon BF feedstock which can be used to supplement the sintering process of iron ore as it is currently known. The implementation of this production process of BF feedstock results in lower energy consumption compared to the high-temperature process of sintering. Thus, there is a significantly lower carbon footprint.
In addition, the technology contributes to efficient re-utilization of by-products from metallurgical processes like scale and fractions of dust and slag. A single production line can be utilized for a wide variety of materials as feedstock with different structures, eg: from powder to lumps, minerals like oxide or metal ships with sizes 0-200 mm.
the variety of advantages will be discussed:
i. Reduction of CO_2 emissions for production of the EcolBriq® feedstock compared to sinter
iii. Dust reduction for EcolBriq® compared to sinter plant
iv. Maximizing the efficiency of the circular economy in BF operations
v. Reducing energy intensity
Two case studies will show the results of briquetting two materials which cannot be recycled in sintering plant. First study is focused on briquetting of fine fraction of desulfurization slag and the second one will discuss recycling of oily scales.

Steel: from main to co-product in a circular economy?

Harmen Oterdoom
Butterbridge

The probability that steel will only become a byproduct is negligible. However, steel may become more and more a co-product considering the potential role steel can play in a circular economy. On the front end, biomass and urban residuals can be converted to syngas and coke, useful in prereduction and final reduction of iron-oxides. Furnaces themselves can play an important role in the reuse of CaO or even production of CaO from CaO containing materials. Slag from blast furnaces has been used in the cement industry for a long time, and only now is it realized that this role must either be taken over by primary cement producers or incorporated in green steel production. Processes exist already to upgrade EAF slag into cement ready slag or insulation wool. Unfortunately, these appear to be absent from any of the many EAF projects in Europe which may prove to be a lost opportunity to save vast amounts of energy and primary raw materials.

More elaborate:
Steels' current main production route is BF – BOF
Slag from the BF is already used in cement
The main foreseen route to replace the BF in Europe is the DRI / scrap-EAF route. This will:

- Reduce availability of Portland clinker for cement
- Require vast amounts of not yet affordable nor available H_2 and electricity
- Requires large amounts of natural gas while waiting for H_2
- Result in scrap that is already being recycled to be rerouted to the EU
- Requires DR-grade ore, while 1.2 billion tpy steel is made with BF grade ore
- Provide a slag that is of little better use than roadfill and may even be harmful

Meanwhile, increasingly effort is put into making BFs greener by charging DRI, injection of biochar, recirculating gas, injecting syngas or H_2. This only leads to a few to tens of percents of CO_2 reduction.

It can be different, it can go faster, and it can be in EUrope:
1: biomass can be used to do prereduction

- ➔ Testresults DOPS/Butter Bridge batch tests with gasified biomass on pellets and lump ore labscale tests in a continuous shaft reactor
- ➔ Ferrosilva is setting up a 50 ktpy facility on Sweden, probably fluidised bed based

From here onwards:
Route A:
A1: DR grade ore can be pre-reduced and made to steel in an EAF
A2: the liquid slag is reduced in a second step to recover a maximal amount of Fe and produce BF quality slag or reactive glass by adjusting the slag using biochar and selected additions
Route B:
B1: BF grade ore can be pre-reduced and made to hot metal or steel in an ESF (Smelter)
B2: Liquid slag is already slag Portland clinker cement if hot metal is made, or
B3: can be processed while liquid into a high quality CaO product if steel is produced.

Butter Bridge demonstrated small scale production of DRI using biomass in cooperation with DOPS, followed by making hot metal or steel using own biochar.

- ➔ Show of fotos

Ascem has demonstrated how EAF slag can be used to make a reactive glass for high quality cement, and is looking for an industrial partner to develop

- ➔ Show of fotos and the layout of a plant layout (to be confirmed if allowed)
- ➔ Preferred is liquid slag!

Being aware this know how is already available raises following questions:
1:→ Image of a Flowsheet future DRI-plant including biomass gasification
Similar to "small step decarbonisation" of BFs, why not inject biomass-based syngas into DRI units to already reduce dependency on natural gas while simultaneously reduce GHG emissions by not allowing biomass to rot?
Why not invest more money into the use of urban waste based syngas and its potential for replacing natural gas in DRI production?
2: → Image of a flowsheet of a 2 stage smelting operation allowing liquid EAF slag treatment into cementitious material
Why is CaO not considered an SRM and is more consideration taken to not let this material be used in a wasteful manner like roadfill, landfill, or Direct Air Capture?
Why not insist that any BF replacement by an EAF in the EU must be accompanied by installation of an EAF slag processing plant to secure maximal usage of CaO, thus preventing displacement of CO_2 emissions, increase recovery of Fe, and minimisation of an even hazardous material
3: → Table of impact of different technologies
Why not allow more financial support for companies that do more than buying "off-the-shelf" technology to NOT solve the BF grade ore problem, or even only achieve relocation of CO_2 emissions by using scrap that is already being recycled anyway

Session 5 - Clustering special session on Hydrogen in heating technologies

A. Projects

1. **HyInHeat**
   Speaker: Thomas Echterhof & Nico Schmitz, RWTH Aachen
2. **HyDreams**
   Speaker: Martin Demuth, Messer Austria
3. **H2AL - Full-scale demonstration of replicable technologies for hydrogen combustion in Hard-to-Abate Industries: The aluminium use-case**
   Speaker: Marco Lubrano Lavadera, The Université libre de Bruxelles
4. **H2GLASS**
   Speaker: Antonio Tuzio, Stam Tech
5. **HyTecHeat**
   Speaker: Filippo Cirilli, RINA-CSM
6. **TWINGHY**
   Speaker: Hassan Mohanna, CELSA
7. **GreenHeatEAF – Demonstration and Digital tools to investigate hydrogen exploitation in EAF burners**
   Speaker: Oliver Hatzfeld & Marianne Magnelöv, BFI & SWERIM
8. **H_2Reuse**
   Speaker: Salvatore Nardi, Tenova

B. Technical Presentations

1. **Development and testing of low-NOx roof burner SMS-RADFlame HY2 for the steel industry**
   Speakers: Tommaso Bortolussi & Irene Luzzo, SMS Group & RINA-CSM

2. **Results from the experimental campaign with H2 oxyfuel burner for electric arc furnaces (EAF)**
   Speaker: Irene Luzzo, RINA-CSM
3. **CFD modelling of flameless combustion: from natural gas to hydrogen**
   Mattia Bissoli, TENOVA
4. **Scenario analyses to evaluate the effects of hydrogen exploitation in EAF burners**
   Speaker: Ismael Matino, Scuola Superiore Sant'Anna
5. **Fuel flexible self-recuperative burners for radiant tube heating systems**
   Speaker: ***Christian Wupperman,*** *RWTH Aachen*

Hydrogen technologies for decarbonisation of industrial heating processes - HyInHeat

Thomas Echterhof, Nico Schmitz
RWTH Aachen

Hydrogen combustion for decarbonisation of melting and heating processes in energy-intensive industries requires the adaption and redesign of technical equipment and infrastructure. In this context, the EU-funded HyInHeat project aims to integrate hydrogen as a fuel for high-temperature industrial heating processes through efficient hydrogen combustion systems in the aluminium and steel sectors. The project will redesign and modify the heating process itself, supported by simulation methods enhancing digitalisation along the value chain to increase energy efficiency and reduce the future hydrogen demand of the processes. HyInHeat will implement the developed technology in eight demonstrations in technical centres and industrial plants and perform test trials complemented by industrial case studies.

Clean Hydrogen and Digital tools for REheating And heat treatMent for Steel - HyDreams

Martin Demuth
Messer Austria

HYDREAMS is a European flagship that aims at total CO_2 emissions reductions of 4.5 $MtCO_2$/year by partners by 2032. HYDREAMS will demonstrate clean H2 oxycombustion at TRL7 with minimal NOx emissions. Partners include 3 steel producers; 1 clean H2 electrolyser manufacturer; 2 burner manufacturers; 1 gas producer/distributer; 1 refractories manufacturer; plus public research organisations with expertise in modelling and materials for combustion, burners and furnaces. The steel annealing furnace demonstrator will be supplied with the most OPEX-competitive and energy-efficient H_2, which will use waste heat from the steel factory to produce CO_2-free clean hydrogen, at a target cost lower than 2 €/kg H2. The clean hydrogen for the demonstration will be provided free of cost for HYDREAMS, as its production is funded elsewhere. The solutions' competitive OPEX and CAPEX enable H_2/O_2 combustion to be cheaper than business as usual natural gas/air combustion at electricity prices below 56.5€/MWh, for a typical use-case for a carbon tax of 150€/tCO_2 and natural gas price of 30€/MWh. We will demonstrate an increase in combustion energy-efficiency by 10 to 47% with no loss in steel properties. Modelling and demonstration will enable to elucidate stable combustion conditions, identify hot spots, and limit NO_x. Partners will contribute to emerging ISO and CEN norms. To ensure broad replication, they aim to obtain investment decisions by the end of the project for industrial-scale deployment in 5 steel plants and commitments from 8 brand-owners to adopt green steel in their products. Further replication is planned to reach the maximum possible market size with clean H2 combustion via solid exploitation plans and clear paths to clean hydrogen.

H2AL - Full-scale demonstration of replicable technologies for hydrogen combustion in Hard-to-Abate Industries: The aluminium use-case

M. Lubrano Lavadera[a], A. Parente[a], consortium[b]

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[b] Université Libre de Bruxelles (Belgium), 2A SpA (Italy), Nippon Gases Industrial SRL (Italy), Fraunhofer (Germany), Tecnalia Research & Innovation (Spain), GHI Hornos Industriales SLR (Spain), Gas- und Wärme-Institut Essen e.V. (Germany), BlueEnergy Revolution (Italy), EKW Refractories GmbH (Germany), European Aluminium (Belgium)

The project aims to address the challenges of adopting hydrogen (H2) in hard-to-abate industries (HTAIs) through a hybrid approach using digital tools and state-of-the-art experimental techniques. The consortium will develop an integrated O2-CH4-H2 burner and support system for a heating furnace in an HTAI, specifically the aluminium scrap recycling industry. The project will investigate the impact of H2 combustion on the furnace structure and product quality while minimizing emissions.

Oxy-fuel of H2 will be applied as combustion technology, combined with low-NOx combustion techniques, such as the flameless/MILD combustion mode. This approach will allow us to benefit from the main advantages of oxy-fuel combustion while minimizing its emissions, particularly NOx. The impact of H2 combustion on currently used commercially refractory materials, overall furnace structure and product quality (aluminium) will also be investigated, and measures to minimize its impacts will be implemented.

To ensure widespread replication and exploitation of the technology, the consortium will perform techno-economic modeling, develop guidelines for technology integration, analyze geographic information, and develop new business models. The consortium comprises ten partners from four countries: four research organizations, an industry association representing the aluminium sector in Europe, and five industrial partners, including an end-user. The project seeks to achieve TRL7 by running a full-scale demonstration for more than six months, with at least one trial of 100h at 100% H2 and a total thermal output of 2.25 MWth.

H2GLASS

Antonio Tuzio
Stam Tech

The glass industry will have to be completely decarbonized in the next 30 years. The lifetime of a glass furnace is about. 12-15 years. So, it is urgent to start innovating because the year 2050 is only 2 furnaces away. H2GLASS aims to create the technology stack that glass manufacturers need to:

a) realize 100% H2 combustion in their production facilities,
b) ensure the required product quality,
c) manage this safely.

H2GLASS will address the challenges related to NOx emissions and high flame propagation speed, process efficiency, and supply of H2 for on-site demonstrations. Digital Twin techniques will be critical for risk-based predictive maintenance, optimized production control, and combustion system control. Hydrogen will be supplied by a portable electrolyser co-funded by the industrial demonstrators, and the oxygen produced will be reused in the process. The H2GLASS technologies and design solutions will be validated up to TRL 7 on 5 industrial demonstrators from 3 segments (container glass, flat glass and glass fibre), which together represent 98% of the current glass production in the EU.

A demonstrator for the aluminum industry will prove the transferability of the basic solutions and underlying models to energy-intensive industries that have similarities with the glass manufacturing process, thus strengthening the impact of the project.

The innovations generated by H2GLASS will potentially create 10.000 new jobs and unlock 1 - 5B€ revenues for glass technology deployment, >17B investments and 200.000 new jobs for green H2, and cut emissions by ca.80%.

HYbrid TEChnologies for sustainable steel reheating - HyTecHeat

Filippo Cirilli
RINA-CSM

The project HyTecHeat (HYbrid TEChnologies for sustainable steel reheating, GA 101092087, started on the 1st December 2022, duration 42 months) is focused on utilization of hybrid heating in steelmaking downstream processes (reheating furnaces and refractory preheating). With hybrid heating is intended utilization of natural gas and hydrogen. Three *democases* are envisioned: (1) a hybrid by-design burner designed and tested in a combustion chamber, directly fed by Hydrogen produced by purposely installed electrolyser; (2) a burner currently fully-NG fed will be adapted to evaluate the limit up to which the current systems can be pushed to work in hybrid heating gas atmospheres; (3) ladle preheating burners will be fed by a blend NG/Hydrogen. Moreover, lab oxidation and descaling tests will be carried out on a large variety of steel grades.
Composed by multinational collaboration among research centers, industrial operators and technology providers:

- RINA CONSULTING - CENTRO SVILUPPO MATERIALI SPA
- TENOVA SPA
- NUNKI STEEL
- TATA STEEL NEDERLAND BV
- SWERIM AB
- SSAB EMEA AB
- LINDE SVERIGE AB (AGA)
- ARCELORMITTAL MAIZIERES RESEARCH SA
- SNAM S.P.A.
- INDUSTRIE DE NORA SPA-IDN
- DALMINE SPA

TENOVA will work on the multifuel burner development, realization of **DEMO case 1**, with RES installation (realized with own resources), 1 MW electrolyser installation and burner testing; modelling supported by CFD analysis; **TATA** and **NUNKI** will realize the **Demo case 2** and **Demo case 3**, to study the limit of current combustion systems used with blends of H2/NG (Tata Steel will tests the burners for reheating furnace, while Nunki Steel the ladle preheating burners). The quality assessment will be carried out by different partners following their expertise: **RINA-CSM** will perform thermogravimetric tests in different thermal conditions and oxidising atmosphere; **SWERIM** will perform pilot plant trials with hydrogen combustion and the effect on hydraulic descaling for the final surface quality and steel losses. **SSAB** will provide reference conditions for the reheating and descaling trials at **SWERIM** together will specimens of selected steel alloys of industrial importance and **LINDE** will provide expertise in the industrial supply and use of hydrogen and experience using oxyfuel technology. **AMMR** will test steel samples from as-cast steels (slabs, thin slabs) and plates for the measurements of the oxidation kinetic. Industrial samples will be heated in a furnace designed to reproduce the industrial heating curves. **Tenaris Dalmine** will provide the working condition of industrial furnaces and will collect steel samples with different composition. **SNAM** and **DENORA** will provide all the competencies for hydrogen management, electrolyser installation, and will be strongly involved in the specification of electrolyser unit and installation at Tenova premises.

TWINGHY

Hassan Mohanna
CELSA

TWINGHY aims to introduce hydrogen as a fuel to replace natural gas in the reheating furnaces of the steel sector. The main objective of the project is the demonstration of an advanced heat transfer process in the reheating furnaces of the steel sector. New hybrid burners are developed in order to gradually increase the introduction of hydrogen with natural gas for direct combustion. Another development is the utilization of new oxyfuel burners to increase the efficiency of the process using oxycombustion. The impact of introducing hydrogen and oxygen to the process, refractory and product will be thoroughly studied at lab scale and on industrial reheating furnace. The project will develop a Digital Twin to control the behavior of the furnace and optimize the operations. The Digital Twin can be applied to other furnaces after being trained on the pilot furnace.

GreenHeatEAF – Demonstration and Digital tools to investigate hydrogen exploitation in EAF burners

Oliver Hatzfeld[a], Marianne Magnelöv[b], Joel Orre[b],Pascal Kwaschny[c], Ismael Matino[d], OrlandoToscanelli[d], Valentina Colla[d]
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[d]*Scuola Superiore Sant'Anna –TeCIP -ICT-COISP, Pisa, Italy*

Electric Arc Furnace (EAF) are increasingly relevant for the transformation towards a Green Steel production. Various measures like hydrogen exploitation have to be taken and investigations need to be done to allow a fully carbon-neutral steelmaking process in the EAF. In the EU-funded Horizon Europe project "Gradual Integration of Renewable carbon and alternative non-carbon Energy sources and modular Heating technologies in EAF for progressive CO_2decrease –GreenHeatEAF", several of these measures are investigated, developed and tested in pilot and industrial scale. These experimantal developments are accompanied by application of different kinds of process models which are newly developedfor simulation and optimization.

Within this project the H2exploitation is experimantally investigated in hydrogen oxyfuel combustion for EAF heatingandtheoretically investigated in EAF heating with hydrogen enhanced combustion (HEC).The impact of H_2 exploitation is additionally investigated regarding the impact on the EAF process itself and the impact on avoiding fossil carbon in the steelmaking process.

Experimental invetisgations focus on EAF heating with EAF-burnersfrom Linde for 100% hydrogen and pure oxygen combustionat demonstration level.The investigations focus on the demonstration of hydrogen enhanced oxyfuel combustion with an existing EAF burner. The results are the basis for the CFD-simulation of EAF heating with HEC in combination with electric heating for the melting process. Results are neede as well to analysethe technical, economical and ecological impact of hydrogen combustion in the EAF process. In this contribution the status of tests and test bed development in the project are presented.

H_2Reuse

Salvatore Nardi
Tenova

Supported by the European Union's LIFE fund, the *H_2Reuse* project aims to introduce a market-ready solution that improves the bright annealing process's carbon footprint and energy efficiency. Bright annealing typically requires a 100% H_2 process atmosphere, which is then flared after use, leading to resource waste and environmental impact. *H_2Reuse* aims to recover the process H_2 and reuse it in specialized burners that will partially replace the currently employed electrical heaters, thereby decarbonizing the process and improving its circularity.

Development and testing of Low-NOx Roof Burner SMS RADFlame HY2 for the Steel Industry

Tommaso Bortolussi[a], Jimmy Fabro[a], Umberto Zanusso[a], Irene Luzzo[b], Andrea Provesi [b], Michele di Cataldo [b]
[a] SMS Group S.p.a., Via Udine 103, Tarcento (Italy)
[b] Centro Sviluppo Materiali, Piazza Caduti 6 luglio 1944, Dalmine (Italy)

The reheating furnace is responsible for the majority of energy consumptions and carbon emissions of an entire rolling mill. An optimized control of the combustion process and the possibility to use green hydrogen with low nitrogen oxide (NOx) emissions are consequently in the steel makers focus. The big interest is not just for new installations, but also for the modernization of existing furnaces. While for new installations, side and frontal burners are nowadays often preferred, a vast number of existing installations are equipped with radiant roof burners.
For the aforementioned reasons, SMS group S.p.A. focused on the development and characterization of a new generation of radiant roof burner, able to be installed in existing furnace without substantial modifications when no change of throughput or fuel is expected, that requires low air pressure value and are optimized for low NOx emissions with natural gas (NG) and NG/hydrogen (H2) mixtures ranging from 0 to 75%vol. of hydrogen. The development has been carried out with the support of CFD analysis and tested at the RINA-CSM Combustion Station in Dalmine.
Several different configurations of SMS RADFlame HY2 radiant burner were identified and investigated by CFD simulations. The most promising ones were then experimentally tested.
The experimental trials conducted on the 750 kW SMS RADFlame HY2 roof burner confirmed its capability to operate with natural gas (NG), NG/H_2 blends up to 75%vol. H2 with low NOx emissions. The burner was characterized by varying the fuel's chemical composition, the furnace and air preheating temperature, the burner's rating, and oxygen concentration in the flue gas. Figure 1 reports the experimental rig and the images of burner during the test at furnace temperature of 1150 °C with NG and H2 (100%vol.).
During the experimental campaign, the optimized configuration of the burner reached NOx emissions performance in the range of 90-121 mg/Nm^3 @3% O_2 DFG at furnace temperature of 1150 °C, preheat air temperature of 450 °C, 1% O_2 excess in the flue gas and 0-75%vol. H_2 presence in the fuel blend. NOx emissions' performance of SMS RADFlame HY2 working with different NG-H2 blends, are presented in Figure 2. No soot and CO emissions were detected during the experimental campaign. In general, the variation of fuel compositions does not change significantly the thermal profile trend below the burner (along the longitudinal axis of the furnace). The results obtained with the experimental campaign of the burner, suggest how the SMS RADFlame HY2 burner represents a valid solutions for applying hydrogen usage over a wide range of NG-H_2 blend composition, in steelmaking industry, both for novel reheating furnaces and revamping projects.

Figure 1. *(a) Experimental setup at RINA-CSM Combustion Station, Dalmine (Italy); (b) SMS-RADFlame HY2 burner working at furnace temperature 1150 °C with 100%vol. NG, and (c) with 100%vol.* H_2

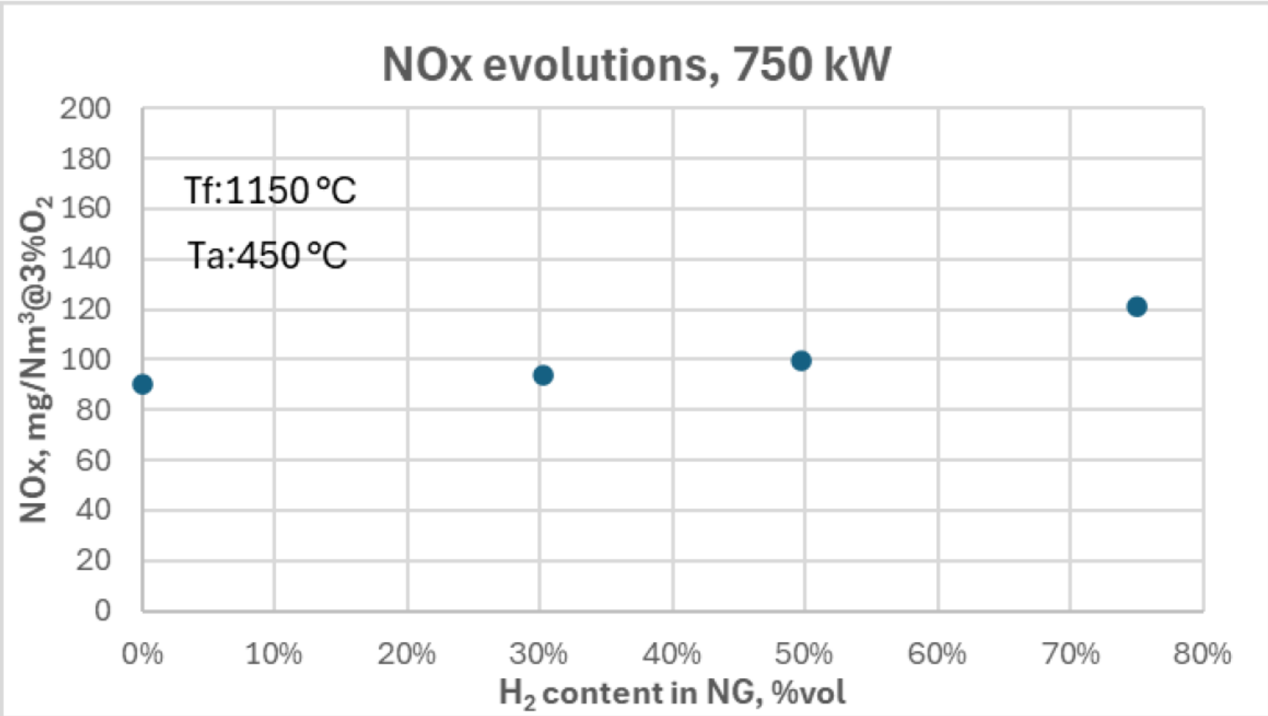

Figure 2. *NOx emissions performance of the SMS RADFlame HY2 at furnace temperature of 1150 °C, preheat air temperature of 450 °C, 1%* O_2 *excess in the flue gas and 0-75%vol.* H_2 *presence in the fuel blend*

Results from the Experimental Campaign with H_2 Oxyfuel Burner for Electric Arc Furnaces (EAF)

***Enzo Faraci*[a], *<u>Irene Luzzo</u>*[a], *Andrea Provesi*[a], *Jacopo Greguoldo*[b], *Fabio Vecchiet*[b], *Giulio Rinaldi*[c], *Fabiano Ferrari*[c], *Federico Nastro*[c]**

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The steel production through electric arc furnaces (EAF) plays an increasingly important role in modern steelworks concepts. Today the electric arc furnace steel of the overall steel production in the EU-28 is 41.5 % (69 Mtons/year).

In the modern EAF, the contribution of chemical energy for the scrap melting and refining is the range of 25-45% of the total energy required. The Natural Gas (NG) burners provide in the range of 40-80 kWh/t of energy. It means that the production of 100 tons of steel requires the combustion of 370-750 Nm^3 of NG with CO_2 emission of 0.75-1.5 tons. The substitution of NG with hydrogen in the EAF steel production will bring a remarkable reduction of CO_2 emission.

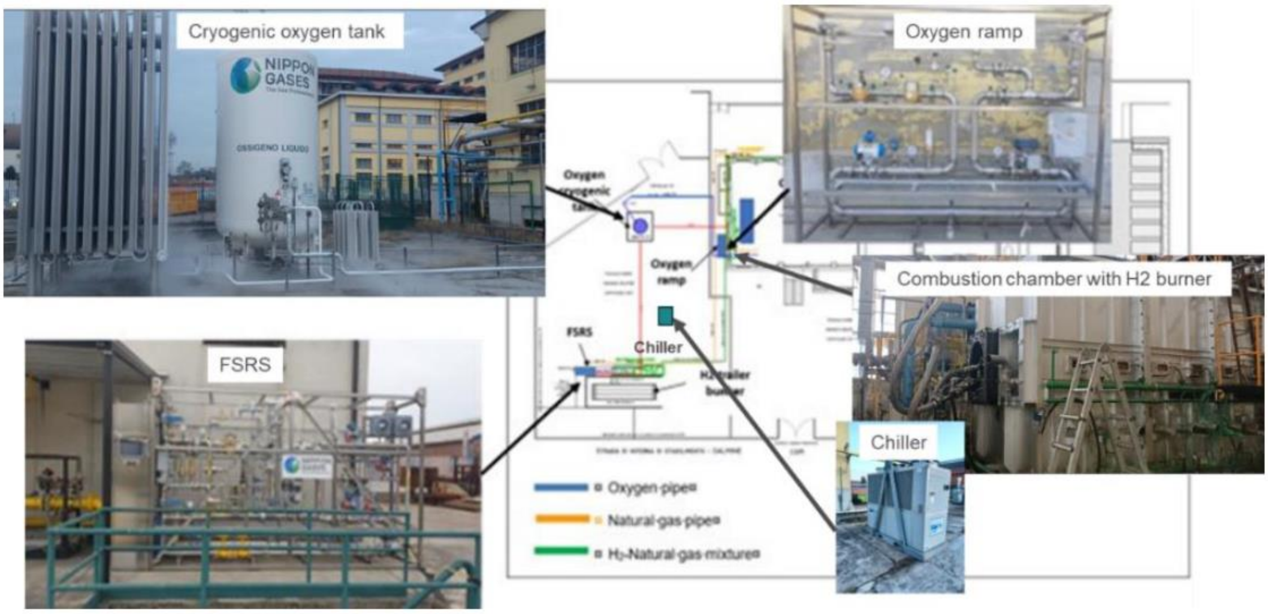
In this frame the RFCS project "Developing and enabling H2 burner utilization to produce liquid steel in EAF"(DevH2forEAF) is in line with the European roadmap toward achieving zero greenhouse gas emissions. The project focuses on the design and realization of burners, able to work with NG/H_2 mixture, up to 100% hydrogen. The burners has been designed and manufactured to work in severe environment, thus ensuring mechanical and thermal resistance in respect of EAF operative conditions

The experimental campaign with an Oxyfuel burner was conducted, at the RINA-CSM combustion laboratory in Dalmine, to evaluate performance and feasibility of the burner with different fuels supplies: from 100% NG to 100% Hydrogen, including mixed configuration of NG-H_2. The fuel mixing was performed by a dedicated mixing regulation system developed by Nippon Gases.

These experimental trials represent a preliminary step to verify the functionality of the H_2 burner and to identify the optimal operating conditions for future industrial-scale tests at Ferriere Nord and Celsa production plants.

The H_2 Oxyfuel Burner was designed and built by SMS. The burner was tested in the modular furnace pilot plant at RINA-CSM with a maximum thermal load capacity of 3 MW. The burner has been installed in the modular furnace and connected to the hydrogen line. For the experimental tests the following equipment have been installed and set up:

1) Cryogenic oxygen tank with the capacity of 10.000 Liters.
2) FSRS (Fuel Supply and Regulation System) to provide NG and H_2 mixture at proper flow rate composition, and pressure.
3) Oxygen ramp to provide Oxygen at the target flow rate and pressure.
4) Dedicated water-cooling circuit (comprising chiller) to cool the burner (of the same type to water cooling circuits installed in EAFs).



The cryogenic oxygen tank, the FSRS and the Oxygen ramp was provided by Nippon Gases with a tailor-made solution for RINA-CSM combustion station.

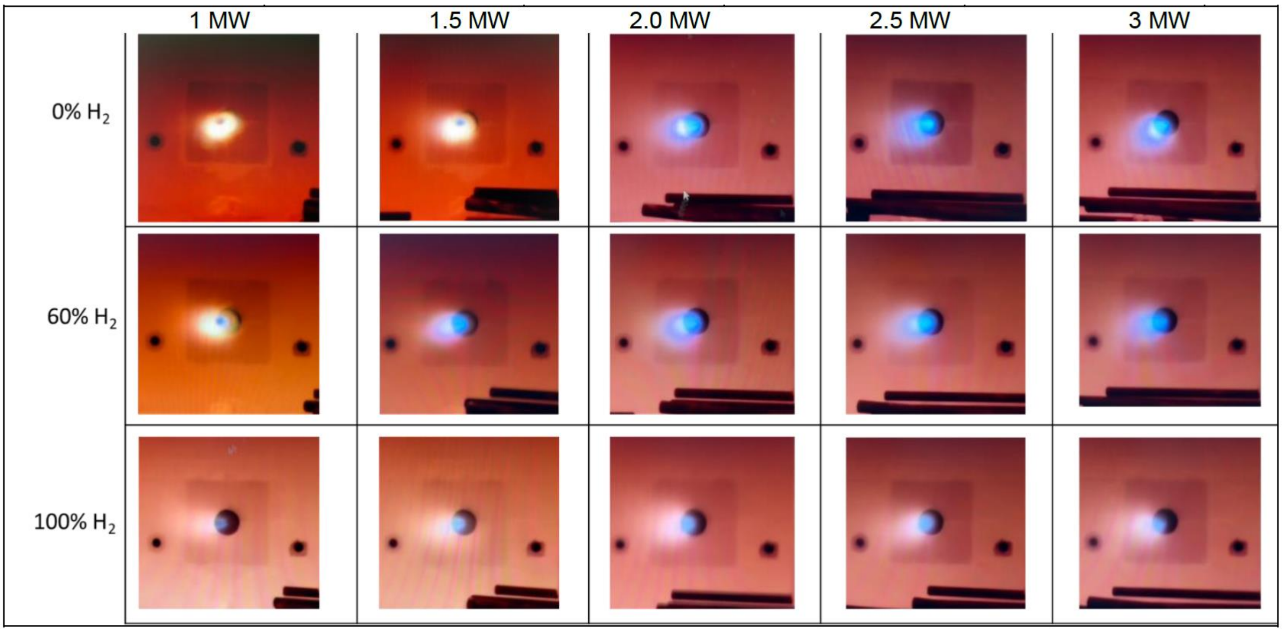
The modular furnace has been equipped with thermocouples, flow rate, and pressure sensors for the H_2, NG, and O_2 inlet lines, along with off-gas analysers. Flue gas analysis has been conducted intermittently for O_2, CO, NO_x, and CO_2 to ensure accurate monitoring of the combustion process.

The experimental campaign has been carried out, with the objective to verify performance of the H2 - burner in preparation for the industrial trials.

Based on the results of the experimental campaign, several key conclusions can be drawn:

1) The H_2/NG flow rate remained stable, even at 3 MW and high hydrogen concentrations. Stable operating conditions were achieved within minutes for each tested point. The flame straightened as power increased, a result of the higher impulse due to greater flow rate and velocity. With higher hydrogen content, the flame's luminosity decreased, disappearing entirely when the hydrogen concentration exceeded 60%. The flame became obscured by infrared emission from the wall but was more visible with a frontal view camera.

2) An increase in hydrogen content led to a rise in temperature at the first thermocouple, indicating that hydrogen is more reactive and initiates ignition closer to the burner tip. At 1 MW, temperatures decreased along the furnace, while at 3 MW, they increased, suggesting complete combustion in the first part of the chamber at 1 MW, whereas at 3 MW, combustion continued throughout the entire chamber.



3) The average heat transferred to the water of the cooling lances (which can be considered as scrap in the EAF) was 61% at 1 MW and 74% at 3 MW, attributed to the longer cooling lances necessary to maintain furnace temperatures below 1250°C.

4) NOx measurements for all operating points exceeded the instrument's full-scale range (2000 ppm), with no soot or CO production observed. The high NO_x emissions are likely due to air inside the furnace, simulating the slagging door opening. Working with no air inside the furnace (i.e. simulating closed slag door) the NO_x emission would be greatly reduced. To reduce the CO_2 percentage in the off gas to 50%, approximately 80% hydrogen is needed in the fuel mixture.

CFD modelling of flameless combustion: from NG to H_2

M. Bissoli, S. Nardi
Tenova S.p.A.

The massive usage of hydrogen in steel industry is envisioned in the Carbon Direct Avoidance pathway of the ESTEP and EUROFER masterplans. Today, hydrogen use is limited to annealing processes on a small scale, therefore a complete transformation of the steelmaking production route from liquid steel process (Upstream) up to the rolling and finishing line (Downstream) requires the development and the validation of new technologies.

To achieve the complete substitution of fossil fuels with hydrogen in Downstream processes, it is necessary to overcome the higher NOx production experienced using traditional flame burners. This allows to match both targets of the Green Deal at the same time: carbon neutrality and zero-pollution.

Tenova has a long tradition in leading edge combustion technology thanks to a joint design between Computation Fluid Dynamic (CFD) modeling, industrial scale test and industrial applications. This paper presents the upgrade of a Computational Fluid Dynamic (CFD) model for the simulation of the full spectrum of CH_4/H_2 mixtures (up to 100% H_2) done in the framework of the HyTecHeat HORIZON EU project.

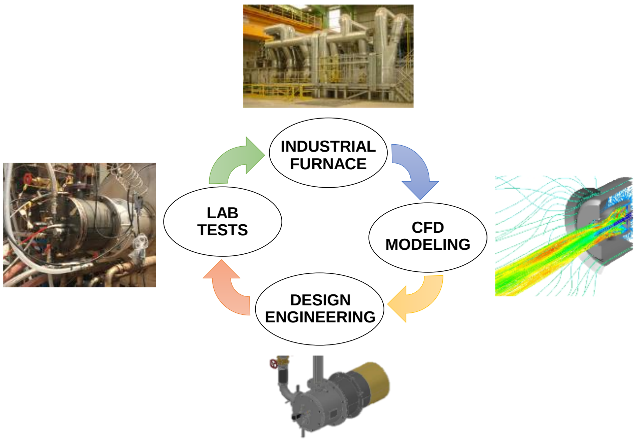


Figure1. *Tenova workflow adopted for burner development*

The main goal is the development of a digital twin able to describe the complex series of experiments, and to guide the final pilot burner design, working both in flame and flameless regime. The activity starts from the well-assessed experience in the NG modeling, already validated in previous projects. Then, the whole CFD model was critically revised by means of the scientific literature to evaluate its applicability at the whole range of NG/H2 mixtures, up to 100% H2. Particular attention is given to the turbulence-chemistry interaction (a.k.a. the combustion model), the kinetic mechanism, and the radiation model. The new tool is then used to assess the performances of the preliminary design of the 320 kW multi-fuel TLX burner.

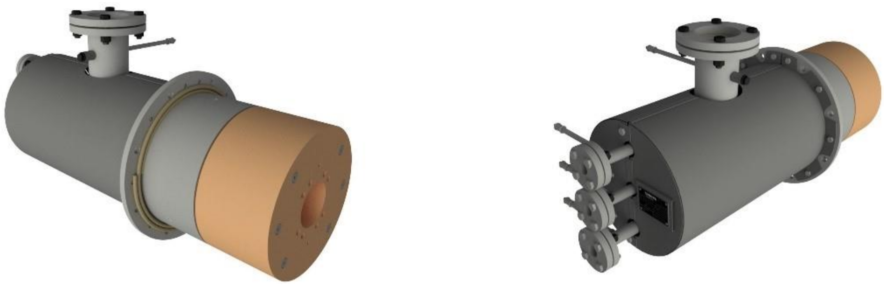


Figure2. *Bottom-lateral external view of TLX (left) and frontal-lateral external view of TLX (right).*

The analysis highlights a stable behavior of the burner under flame and flameless conditions, with NO_x emissions aligned with Tenova "Hydrogen Ready" combustion system technology with all the representative mixtures investigated. The analysis also shows the impact of the different combustion atmospheres on of the radiation heat fluxes the system.

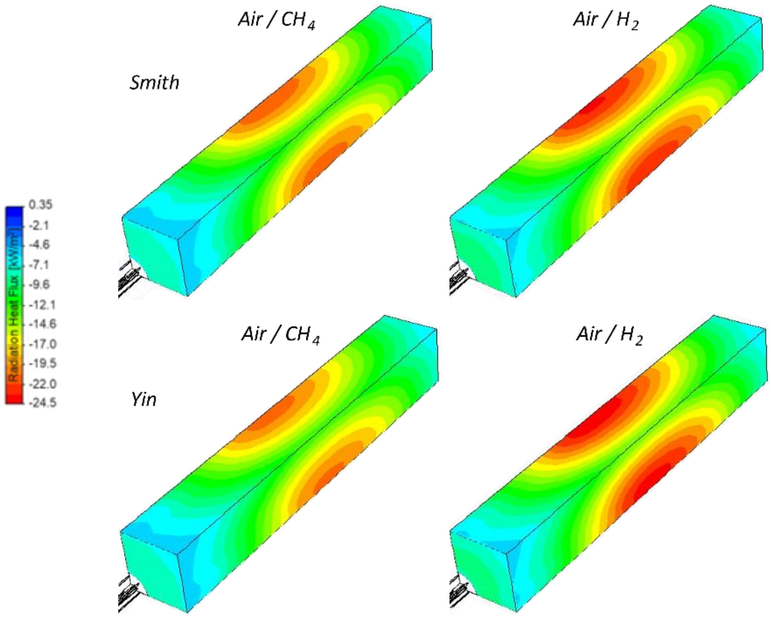


Figure 3. *Radiation heat transfer to furnace walls for the TLX burner under flameless conditions for different mixtures. Comparison between two models: upper row for Smith et al. (Smith, Shen, & Friedman, 1982), lower row for Yin (Yin, 2013).*

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Scenario analyses to evaluate the effects of hydrogen exploitation in EAF burners

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Steelmaking sector is strongly committed to reach the European Green Deal objectives of achieving the climate neutrality by 2050. Several solutions are under investigations, such as transition from BF-BOF to DRI-EAF route, substitution of fossil sources and fuels with renewables and alternative fuels, improvement of resource and energy efficiencies. In this context, the EAF-based steelmaking route is acquiring a higher role compared to the past, and efforts are spent to improve the sustainability of processes that already intrinsically fit the concept of circular economy. Among the different analysed possibilities, the replacement of natural gas used in EAF burners to provide part of the chemical energy required in EAF with green hydrogen has increasingly been considered. However, effects on the process and product have to be investigated to avoid unexpected issues. The project entitled "*Gradual Integration of Renewable non-fossil energy sources and modular heating technologies in EAF for progressive CO2 decrease – GreenHeatEAF*, which is funded by the EU through the Horizon Europe programme based on a Clean Steel Partnership call, develops trials with conventional and innovative burners as well as with pilot EAF, and these trials are complemented by scenario analyses carried out with ad-hoc simulation studies. To this aim, a flowsheet model was adopted, which has been updated through the years within different research initiatives [1-3] and represents the whole EAF production route until the beginning of the continuous casting. In the context of the GreenHeatEAF project, new streams, reactions and design specifications units were added to the model. Then, EAF production heats were simulated by substituting each time 10% of the energy provided through natural gas with hydrogen, and different parameters were monitored such as EAF electric energy, CO_2, CO and H_2O content in EAF off-gases, EAF off-gases temperature, H_2 content in melted steel. As expected, more H_2O and less CO_2 can be found in EAF off-gases. Interestingly, the decrease of CO2 is more evident until a blend of 20% of natural gas and 80% of H_2. In addition, hydrogen in tapped steel significantly increases: it becomes more than two times of the starting case (only NG in burners) with a full hydrogen use, while further negligible changes are observed in tapped steel and in slag. Further simulations are ongoing to provide as much as possible information for supporting and paving the way to the introduction of the use of hydrogen instead of natural gas in electric arc furnaces.

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Fuel Flexible Self-Recuperative Burners for Radiant Tube Heating Systems

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In light of the European Union's goal of becoming carbon neutral by 2050, the steel industry is actively seeking alternative energy sources to replace conventional natural gas and steel mill gases to reduce carbon dioxide emissions associated with heat treatment processes. Alternative fuels such as biogas, green hydrogen and hydrogen derivatives such as ammonia or dimethylether as well as the possibility of electrification of the systems are being considered. The present work addresses the use of hydrogen as a fuel for self-recuperative burners for radiant tube heating systems.

When converting burner-radiant-tube systems to hydrogen, it is important to consider that the current availability of green hydrogen does not meet the demand. Therefore, the development of a fuel flexible burner tube system is aimed at. This system will allow the use of hydrogen in natural gas from 0 to 100% by volume without the need for manual adjustments to the system, allowing the plant operator to react to the price and availability of fuels.

This aim represents a major challenge: the development of a stable, energy-efficient system with low NO_x emissions despite the different combustion properties of hydrogen and hydrogen/natural gas mixtures. Experimental investigations on a state-of-the-art, unmodified self-recuperative burner in a PP -radiant tube show an increase in NO_x emissions of more than 85 % to up to 745 mg/kWh when pure hydrogen is used instead of natural gas. In order to meet the NO_x emission limits defined in the conclusions of the BREF (Best Available Techniques Reference Document) for the ferrous metals processing industry, various NO_x emission reduction measures, such as flameless operation and staged combustion, which have already been proven in natural gas applications, are being investigated for hydrogen and natural gas/hydrogen mixtures combustion.

The present study investigates the influence of hydrogen enrichment from 0 to 100 vol% in natural gas on a modified self-recuperative-burner radiant tube system with a nominal power of 140 kW. The burner was retrofitted to allow flameless operation and gas staging as NO_x emission reduction methods. The change in NO_x emissions, thermal efficiency and temperature distribution along the radiant tube are presented.

Session 6 - Renewable energy and hydrogen availability in Europe

1. **Hydrogen production by methane pyrolysis**
   Speaker: Robert Obenaus-Emler, University of Leoben
2. **RecHycle - Recycling hydrogen for climate neutrality**
   Speaker: Joke Bauwens, ArcelorMittal
3. **Hydrogen online training (steelHub)**
   Speaker: Antonius Schröder, TU Dortmund
4. **Towards a skills intelligence framework. Mapping of hydrogen skills initiatives in Germany and Austria**
   Speaker: Karina Maldonado - Mariscal, TU Dortmund

Hydrogen production by methane pyrolysis

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Hydrogen will play a key role in future process technologies and energy systems based on renewable resources if it is produced with a low CO_2-footprinted. Significant contributions to a sustainable transformation are possible in the following areas:

- Coupling of the crucial sectors electricity, gas, and heat.
- Significant contribution to the long-term (seasonal) storage of renewable electrical energy at large scale and with a minimal material footprint.
- Significant reduction of the CO_2-footprint of industrial processes by (1) replacement of fossil-based energy or feedstock sources or (2) conversion of CO_2 to other (energy) molecules with hydrogen.

Hydrogen is thus a key element in the transformation of industries like the steel or cement production, and therefore adds a significant contribution to circular economy, climate-neutral mobility, industrial production, and can help to mitigate climate change additionally.
At present most hydrogen produced comes from steam methane reforming (SMR) with significant emissions (approximately 12 kg $CO_{2,e}$ per kg of H_2). Today, it is mainly used in the chemical industry for the production of ammonia and in the petrochemical industry for hydrocracking and hydrotreating of crude oil and natural gas. The use of hydrogen within the European Union was around 12 million tons in 2020. Assuming a significantly higher need for hydrogen in future decades (estimates show an increase by a factor of 8 to 10 until 2050), it is obvious that alternative production routes with a reduced CO_2-footprint are essential. These technologies include:

- Steam methane reforming with additional CO_2 sequestration (SMR + CCS)
- Water electrolysis (Alkaline, PEM, SOEC) based on renewable electrical energy
- Methane pyrolysis
- Biomass gasification

Steam methane reforming with subsequent CO_2 sequestration allows for hydrogen production based on existing infrastructure. Depending on the actual process technology, parameters and production capacity the CO_2-footprint of hydrogen can be reduced. However, the storage or use of sequestered CO_2 at scale requires further research and development. Water electrolysis has a considerably higher energy demand compared to SMR. Although novel technologies, like PEM and SOEC are promising in combination with the fluctuating production of renewable electrical energy, the necessary resources and related investments still require further developments. The production of hydrogen from biomass is an interesting approach as the organic feedstock theoretically allows for a CO_2-neutral hydrogen production. However, the availability of biomass as well as the hydrogen yield from gasification is limited.

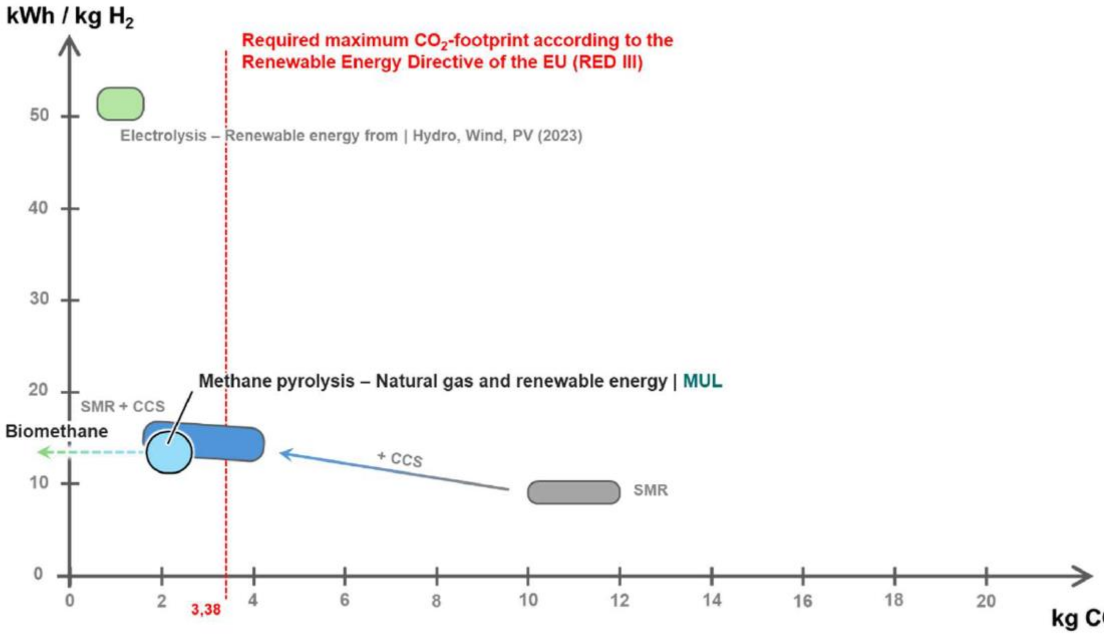

Figure 1. *Overview of hydrogen production technologies and their specific energy input and CO_2-footprint*

The production of hydrogen through methane pyrolysis, leads to solid carbon. Thus, emissions only stem from the methane production and energy input. When using renewable electrical energy and natural gas as a feedstock hydrogen with a reduced CO2-footprint is produced; methane from renewable resources may even allow for a CO2-negative product. Additionally, the energy input required for hydrogen production is considerably lower compared to water electrolysis.

Consequently, the volume of hydrogen produced by methane pyrolysis with a certain amount of renewable energy is about four to five times as high compared to water electrolysis.

From a sustainable production point of view the valorisation of the carbon product plays a key role additionally. Possible applications include high-tech (but likely low volume) applications (e.g. high performance materials, energy storage systems like supercapacitors or micro-porous carbon based tanks for hydrogen storage), and bulk applications of lower value (e.g. soil amendment in agriculture or as a raw material for the production of sustainable construction materials). These valorisation routes of carbon can thus add a significant sustainable contribution in various fields.

Presently, methane pyrolysis technologies are not available at a large, industrial scale. The current challenges for the future industrial implementation are (1) the scalability of processes that can be operated continuously and (2) the generation of high-value carbon products for small markets as well as low-price valorisation routes for bulk markets like construction industry and agriculture.

Montanuniversität Leoben is one of the leading research institutions for methane pyrolysis based on liquid metal bath or plasma technologies. Currently, roughly 120 researchers work on various topics related to the production, transport, storage, and application of hydrogen and carbon. A pilot-scale infrastructure for the total process will be in operation by the end of 2024. The ongoing research activities with industrial partners will help to further optimise the process and ultimately lead to the development of the process at demonstration scale.

Methane pyrolysis is a crucial and promising technology for the economic production of hydrogen at an industrial scale with a minimal CO_2-footprint. The additional value generated from the carbon product is likely to play a vital role in demonstrating the process economics. The intended presentation will give a general overview of methane pyrolysis, insights into ongoing research activities, and show available lab- and pilot-scale infrastructure with a strong focus on applications in iron- and steelmaking.

RecHycle - Recycling hydrogen for climate neutrality

Joke Bauwens
ArcelorMittal

The roadmap of ArcelorMittal Belgium to reduce its CO2 emissions by 35% by 2030 compared to 2018 and to become carbon neutral by 2050 consists of three axes:

1. Further improving material and energy efficiency
2. Electrification and embracing hydrogen as a reducing agent
3. Developing smart carbon concepts at the heart of the circular economy

The RecHycle project allows us to take important steps in all three axes by decarbonizing the blast furnace route by using hydrogen rich metallurgical gases in the blast furnace. This leads to a reduction of coke and powder coal consumption, resulting in a lower CO_2 emission.
RecHycle (https://www.rechycle.eu/) is a European project aiming to study the use of (green) hydrogen and recycled gases to replace coke and pulverized coal in the blast furnace of steel mills. The project is intended to contribute to the transition to a circular economy in which waste products are exploited to their full potential. More in detail, the goal of RecHycle is to investigate the use of metallurgical gases produced on site with or without external sources of hydrogen. The gases will be fed into the blast furnace to produce green steel sustainably. The project will contribute to the shift towards a circular economy where (waste) products are valorised to the maximum of their potential. Furthermore, the project will serve as a stepping stone towards further developing synergies between companies within the North Sea Port industrial area, thus creating new opportunities for innovation and economic activities. The main challenges that will be addressed throughout the development of the project involve the dynamic optimisation of gas mixtures and flows, minimising risks of hydrogen on material embrittlement, ceramic feed-inlet (Tuyeres) within the furnaces and ensuring the quality of the produced steel. RecHycle will be executed through a consortium of 6 partners from 4 different countries, including 1 industrial partner, coordinator ArcelorMittal, that is world-leading in the steel manufacturing industry and 5 research partners specialised in hydrogen-based studies.
RecHycle has received funding from the European Unions's Horizon Europe - Clean Steel partnership programme (adjustment of steel process production to prepare for the transition towards climate neutrality). Project no: 101058692. ArcelorMittal Belgium has secured funding from various sources, including the Horizon Europe programme. The Flemish government also provided support through VLAIO, the Flemish Agency for Innovation and Entrepreneurship.
The RecHycle project fits in the following topics:

- Hydrogen based steelmaking
  - Opportunity and limits
  - Operating conditions challenges and optimization
- The new challenges for the circular economy due to the transition from traditional to C-lean production processes.

Hydrogen Online Training (steelHub)

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Adjusting the skills of the workforce proactively for workplace innovation is key. The continuous adjustment of skills, co-creation of new technological and organisational solutions, and the integration of new (digital) solutions at the workplace are of utmost importance for the digital, green and (not to forget) social transformation. The European Steel Skills Alliance (ESSA) and the Skills Alliance for Industrial Symbiosis (SPIRE-SAIS) analysed technological developments and defined future skills demand, classified affected job profiles, tasks and skills for the steel and other energy intensive industries. Against this backdrop training solutions are served via the online training platforms steelHub and SKILLS4Planet. As hydrogen related skills are of growing importance they are reflected in the steelHub training solutions. The added value of integrating online modules in education and training of the companies is shown for selected hydrogen job profiles (hydrogen operation manager) and topics (occupational health and safety). Webinars, lecturing, eLearning modules include 3D and Augmented Reality tools and Simulations. Demand oriented and tailor-made training solutions are guaranteed via individual self-assessment with the Capability Assessor, which can be also used to analyse the given and needed skills level for a broader group (of apprentices, students, workers). Flexible integration options of the training modules into Learning Management Systems of companies and organization's own software suite (SuccessFactor, SumTotal, Moodle, among others) meet the unique needs of organizations of different size and type as well as individuals. Train the trainers and teacher guidance to use digital teaching solutions will complete the synopsis.

Towards a Skills Intelligence Framework. Mapping of Hydrogen Skills Initiatives in Germany and Austria

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Europe's circular economy is shaped by key expectations in four critical areas: increasing material circularity, shifting from a consumer to a user-based economy, promoting circular growth while reducing resource consumption, and advancing solutions for renewable energy and competitiveness [1]. As the concept of circularity gains interest, research on its broader implications has intensified, with a particular focus on its social, political, and ecological impacts [2-3].

In response to the growing demand for hydrogen-related skills, different European projects focused on green skills have developed a comprehensive European Hydrogen Skills Strategy [4]. This strategy provides valuable insights into the current state of educational and training programs for hydrogen skill development across Europe. However, the idea of *greening is so complex that it involves policies at different levels* and needs to be understood as such "an emergent property at the macro-level (either societal, economic or industrial) that becomes pivotal, while considerations on skills policy should be seen through these lenses" [5].

This presentation aims to contribute to three goals: 1) to better understand different hydrogen policies for the steel industry in Germany and Austria; 2) to map out the skills and stakeholder, which helps us to better understand where to focus resources and how to build a workforce that is capable of driving the hydrogen economy forward; and 3) reflect on the potential applications of the skills intelligence framework to hydrogen in the steel industry and its implications.

As one of the most carbon-intensive sectors, the steel industry is particularly affected by the transition to hydrogen. And reducing greenhouse gas emissions represents a key objective for the transition to sustainable energy systems [6]. In both Germany and Austria, hydrogen has been recognised as a pathway to follow for a transition in steel and is being integrated into steel production processes to replace traditional carbon-based methods [7-8], significantly reducing CO_2 emissions. This shift requires not only new technological innovations, but also *new social and industrial practices* that are familiar with green hydrogen technologies.

The integration of hydrogen into the steel industry therefore serves as a critical case study for understanding the wider implications of hydrogen adoption in other industrial sectors, and as *an innovative case for understanding socio-environmental transitions*. In order to support this transition, the development of a skills intelligence framework is essential [9]. Some key elements of this definition are: a) skills intelligence is the result of data processing, such as data preparation and presentation, b) data preparation and presentation should be targeted to specific audiences, c) information should be upto-date, and d) the high importance of experts in the process [9]. This framework would systematically identify and address the skills gaps in the hydrogen economy, with a particular focus on the steel industry.

Finally, the convergence of circular economy policies, green skills initiatives and sector-specific strategies creates a fertile environment for the development of a hydrogen economy in Germany and Austria.

The steel industry, as a key focus area, highlights the urgent need for a coordinated approach to skills development and the need to *create ecosystems capable of co-creation in the implementation of new technologies, new social practices, and new skills* [10]. This paper advocates the establishment of a comprehensive skills intelligence framework to ensure that the workforce, industry and society are prepared for the challenges and opportunities of a hydrogen future.

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Poster Session

1. **Getting ready for EAFs – Data-driven modelling of mechanical properties of steel sheets from chemical analysis and process parameters**
   Peter Raninger, Materials Center Leoben

2. **Physics-based modelling of tramp element effects on microstructure evolution during downstream processing**
   Peter Raninger, Materials Center Leoben

3. **ZincVal - Valorisation of zinc containing residues**
   Damiano Capobianco, Esin Iplik, Marianne Magnelöv & Yanping Xiao, RINA-CSM, Linde, Swerim & Tata Steel

Getting ready for EAFs – Data-driven modelling of mechanical properties of steel sheets from chemical analysis and process parameters

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Reducing CO_2 emissions in steel production requires increased scrap usage, which introduces unwanted impurity elements. The impact of these foreign elements on the mechanical properties is in many cases not entirely understood and predicting the impurity effects on mechanical properties of steel from processing solely with physical models is not feasible. Data-driven methods are prepared to be ready for this challenge and tested with historical process data from several years of production.

In this talk we present a data-driven approach to predict tensile strength, yield stress and other parameters of cold-rolled steel strip produced by voestalpine Stahl GmbH. The data includes a full chemical analysis, as well as many parameters measured during all working steps of the process and the resulting mechanical properties. We present our data pipeline to create a well-formed dataset suitable for further modelling tasks. This pre-processing consists of analyzing, checking and removal of unreasonable data, as well as feature engineering and normalization.

The strength and limitations of different model types applied to the available data and features will be presented. The used machine learning models include among others linear models (i.e. Ridge Regression), tree-based model (i.e. Extreme Gradient Boost) and Artificial Neural Networks. We investigate the interpretability and performance of models trained on the full set of available features or a reduced feature space, which can e.g. consist out of latent variables created by dimensionality reduction.

Concerning interpretability, we are highlighting the possibilities of feature importance determination of our models. This can be achieved directly from the weights of our linear models and in various ways for our tree-based models. But also, the predictions of any classic black-box models can be explained by calculating the Shapley values, using the SHAP (SHapley Additive exPlanations) approach. Comparison of feature importance analysis with observed trends in literature shows good agreement.

A final highlight will be the demonstration of a machine learning model integrated into a web-based tool that is trained on an openly available dataset for steel production [3]. This tool allows the user to try out input parameters for the steel production process resulting in prediction of steel properties with the associated uncertainty.

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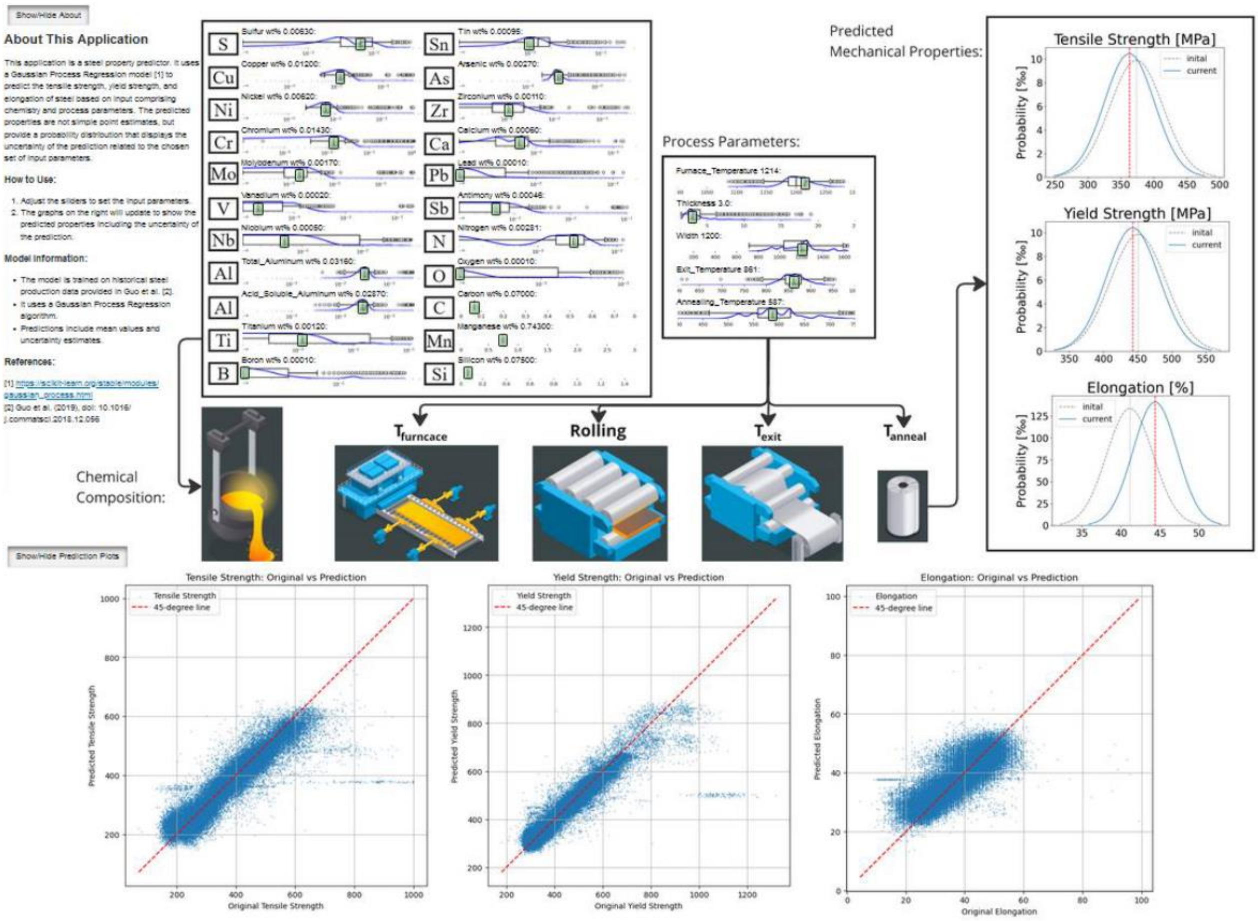
Show/Hide About
About This Application
This application is a steel property predictor. It uses a Gaussian Process Regression model [1] to predict the tensile strength, yield strength, and elongation of steel based on input comprising chemistry and process parameters. The predicted properties are not simple point estimates, but provide a probability distribution that displays the uncertainty of the prediction related to the chosen set of input parameters.
How to Use:
1. Adjust the sliders to set the input parameters.
2. The graphs on the right will update to show the predicted properties including the uncertainty of the prediction.
Model Information:
• The model is trained on historical steel production data provided in Guo et al. [2].
• It uses a Gaussian Process Regression algorithm.
• Predictions include mean values and uncertainty estimates.
References:
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S
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Mo
V
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Al
Al
Ti
B
Sn
As
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Ca
Pb
Sb
N
O
C
Mn
Si
Chemical Composition:
Process Parameters:
Predicted Mechanical Properties:
Tensile Strength [MPa]
Yield Strength [MPa]
Elongation [%]
Probability [‰]
inital
current
T furncace
Rolling
T exit
T anneal
Show/Hide Prediction Plots
Tensile Strength: Original vs Prediction
Yield Strength: Original vs Prediction
Elongation: Original vs Prediction
45-degree line
Original Tensile Strength
Predicted Tensile Strength
Original Yield Strength
Predicted Yield Strength
Original Elongation
Predicted Elongation

Physics-based modelling of tramp element effects on microstructure evolution during downstream processing

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The steel industry on its own is responsible for an estimated 11% of the total CO_2 emissions worldwide showing the need for increased recycling [1]. However, plain circular economy leads to an accumulation of unwanted impurities, which increases the scatter in microstructure formation and deteriorates material properties being the root-cause of downcycling. While available models for process design interpolate within known parameter spaces, they fail at extrapolative modelling and do not consider impurities. Yet, extrapolative models are needed to allow for high recycling rates also in microstructure-sensitive high-performance alloys.
This talk will present the power of predictive multi-scale modelling framework for tramp element effects in steel on microstructure evolution. On the one hand predictive approaches with interpolation capability in a wide range of chemical variations and process parameters will be shown. On the other hand, the introduction of extrapolation capabilities outside of experimentally investigated chemical ranges will be discussed that combines DFT-based ab-initio data, thermodynamics and mean field models. Specific examples will be shown for recrystallization in ferrite, phase transformation from austenite to ferrite and bainite formation including the effects of precipitation, grain growth, and segregation [2,3,4].
Such physical multi-scale modelling frameworks can be used for offline optimization of process parameters for mitigating impurity effects from recycling for C-lean production processes of steel. Subsequent hybridization with data-driven modeling approaches offer potential for increasing prediction quality and computational speed for inline applications for hot-rolling and annealing.

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