REPORT

March 2025

ESTEP workshop

SecCarb4Steel

Preparation and use of biogenic and non-biogenic secondary carbon carriers (SCC) in processes for iron and steelmaking

15 | 22 | 29 November 2024

Scientific committee

J. Wiencke	ArcelorMittal
G. Landra	Beltrame Group
L. Kieush	K1-MET
S. Lesiak	K1-MET
C. Prietl	Primetals Technologies Austria
B. Voraberger	Primetals Technologies Austria
F. Cirilli	RINA-CSM
T. Echterhof	RWTH Aachen
V. Colla	Scuola Superiore Sant'Anna
E. Malfa	Tenova

Organisational committee

K. Peters	ESTEP
D. Snaet	ESTEP
A. Swarnakar	ESTEP
J. Rieger	K1-MET

ESTEP ASBL

Avenue de Cortenbergh, 172B

1000 Brussels, Belgium

Tel. +32 2 738 79 43

www.estep.eu

secretariat@steelresearch-estep.eu

EU Transparency Register: ID 71063945715-33

Foreword

Progressing the iron and steelmaking industry towards a CO_2-lean goal is closely linked to the lowered use of fossil fuels and reducing agents. Biogenic and non-biogenic secondary carbon carriers (SCC) can significantly contribute by being applied in various metallurgical processes including cokemaking, iron ore sintering, blast furnaces, direct reduction of iron ore, and electric arc furnaces. Moreover, it is essential to fully account for circular economy principles, as well as social, economic, and environmental aspects.

In November 2024, a three-part webinar, which included 19 presentations, gathered around 50 participants from across Europe per session. The workshop, opened by Klaus Peters from ESTEP, focused on the challenges and opportunities of SCC in the iron and steelmaking industry. Each session was closed by lively discussions between the presenters and the audience.

During the ESTEP workshop "SecCarb4Steel", the ESTEP community got an update about recently finished and ongoing R&D&I initiatives by sharing experiences, needs, best practices, and innovative solutions for the use and valorisation of SCC in iron and steelmaking. The workshop highlighted the potentials, challenges, and future trends in producing and applying biogenic and non-biogenic SCC. Topics of high relevance are the material availability coupled with the price as well as European standardisation demands and barriers. In addition, the workshop provided a platform for industrial and scientific specialists to discuss the preparation and use of SCC in various metallurgical processes, uncovering sector coupling possibilities and allowing a deeper understanding of industrial symbiosis.

SCC generated from biogenic and non-biogenic sources represent valuable materials paving the way for a more sustainable future for the iron and steelmaking industry in line with the decarbonization pathway of "Smart Carbon Usage-Process Integration" within the frame of the Clean Steel Partnership (CSP), as stated in the Strategic Research and Innovation Agenda (SRIA). Industrial and academic R&D&I projects as well as the successful implementation of the outcomes are closely linked to the lowered use of fossil fuels and reducing agents. Thus, the efforts contribute to the overall goals defined in the Circular Economy Action Plan and the Green Deal of the European Union.

Table of content

Workshop programme

15 | 11 – Utilization of biogenic SCC in iron and steelmaking - Chair E. Malfa (Tenova)

09:00 Opening words – ESTEP
09:10 Biochar production plants: Status quo – Next Generation Elements
09:40 Towards low-carbon cokemaking: Insights on the influence of alternative materials on the coke quality and process performance – ArcelorMittal
10:00 Hydrochar as a secondary carbon carrier: A circular approach for low-carbon steel production – RINA-CSM
10:20 Application of hydrochar for a sustainable electric arc furnace process – KTH Royal Institute of Technology
10:40 Lignin-based products as biogenic secondary carbon carriers for the manufacture of furnace electrodes and refractories in iron metallurgy and steelmaking – KTH Royal Institute of Technology
11:00 Plenary discussion with authors and closure of the session

22 | 11 – Non-biogenic SCC for iron and steelmaking - Chair V. Colla (Scuola Superiore Sant'Anna)

09:00 Decarbonisation through recycling and industrial symbiosis: The use of recycled carbon raw materials in steelmaking – I.BLU
09:30 A techno-economic and environmental assessment of coke-making with non-recyclable waste plastics in Europe: Evaluation of current and future market conditions – University of Ghent
09:50 The SMART project: Recycling of plastics and waste materials in TORERO to substitute more coal injection in the blast furnace – CRM Group
10:10 Practice of recycled plastics injection into a blast furnace at voestalpine Stahl – K1-MET
10:30 Polymer injection in EAF as a secondary carbon carrier scaled at industrial level: Process KPIs and decarbonization performance assessment – Beltrame Group
10:50 Analysing the green hydrogen to green steel transition through the sustainability triple helix lens: Reflections upon HYDRA (IT06) IPCEI – RINA-CSM
11:10 Plenary discussion with authors and closure of the session

29 | 11 – Recent project activities on European level following SCC usage - Chair G. Landra (Beltrame Group)

09:00 Ecological evaluation of the utilization of secondary carbon sources in the steel industry through a Life Cycle Assessment approach – *RWTH Aachen*
09:30 TACOS: Towards a zero CO_2 sintering – *CRM Group*
09:45 OnlyPlastic: EAF working with polymers derived from plastic residue in substitution of fossil fuel – *Tenova*
10:00 Creation of new value chain relations through novel approaches facilitating long-term industrial symbiosis – CORALIS – *RINA-CSM*
10:15 Exploring the effects of the use of alternative carbon-bearing materials in EAF through dedicated simulations – *Scuola Superiore Sant'Anna*
10:30 BioCoDe: Biomass for cokemaking decarbonization. Objectives and first project results – *Acciaierie d'Italia*
10:45 Hard-to-abate? Our solution for the EAF route within the BioRECAST project – *Politecnico di Torino*
11:00 Valorisation of biomass residues for sustainable steel production – EU RFCS project of BioReSteel – *SWERIM*
11:15 Plenary discussion with authors and closure of the session

Keynote lectures

Biochar production plants: Status quo by Next Generation Elements (NGE)
15 November 2024
NGE produces customised facilities for recycling of biogenic residues utilising pyrolysis. Pyrolysis of diverse raw materials generating biochar represents a reasonable approach for carbon capture and storage (PyCCS) which has recently been acknowledged by the EU. As the iron and steel industry is forcing the integration of biochar, it is important to point out and discuss the actual production conditions and the suitability for metallurgical processes.

Decarbonization through recycling and industrial symbiosis: The use of recycled carbon raw materials in steelmaking by I.BLU
22 November 2024
The mixed polyolefins used as feedstock are composed of a variety of polymers with different technical characteristics, not suitable to be directly recycled via plastic-to-plastic. Following various sorting steps, the collected urban waste streams can be recycled to produce secondary carbon-carrying products, while being diverted from other less desirable end-of-life scenarios like energy recovery and landfill. A virtuous example of industrial symbiosis will be shared regarding the use of recycled polymers in substitution of coal in steelmaking, contributing to the achievement of the European recycling targets of plastic packaging waste, leading to significant CO_2 emission savings, as well as to the preservation of natural resources and, therefore, of carbon storages in the ground.

Ecological evaluation of the utilization of secondary carbon sources in the steel industry through a Life Cycle Assessment approach by RWTH Aachen
29 November 2024
The utilisation of secondary carbon carriers is essential to close gaps in the sustainable transformation of the steel industry. For evaluating the environmental impacts of biomass/biochar and plastic residues with a high fixed carbon content in iron and steel furnaces for substitution of fossil coke, as well as in carbon composite agglomerates in the form of self-reducing briquettes or pellets made of iron ore/iron rich residues and SCC for the exploitation of volatile matter, the implementation of a Life Cycle Assessment (LCA) helps to identify and address shifts in environmental burdens throughout the entire life cycle, from sourcing of raw materials to disposal, promoting more sustainable technology development and eco-friendly design.

Session 1: Utilization of biogenic SCC in iron and steelmaking

Biochar production plants: Status quo

Daniela Meitner[1]

[1] Next Generation Elements GmbH, Gewerbepark 22, 4101 Feldkirchen an der Donau, Austria

Abstract. The Next Generation Elements GmbH produces customised facilities for recycling of biogenic residues utilising pyrolysis. Carbon capture and storage by pyrolysis (PyCCS) has recently been acknowledged by the EU as a reasonable approach.

The Next Generation Elements GmbH (NGE) was founded in 2017. As part of an R&D project a thermo-chemical test reactor for decomposition various input materials like plastics, sewage sludge or biogenic materials was built at Johannes Kepler University in Linz, Austria.
Following the successful completion of various pyrolysis tests, a full-scale plant, known as the T:CRACKER®DH (cf. Figure 1) was built. This reactor is energetically self-sufficient and can handle many different input materials like wood, digestate, paper mill reject, sunflower seed husk and many more.

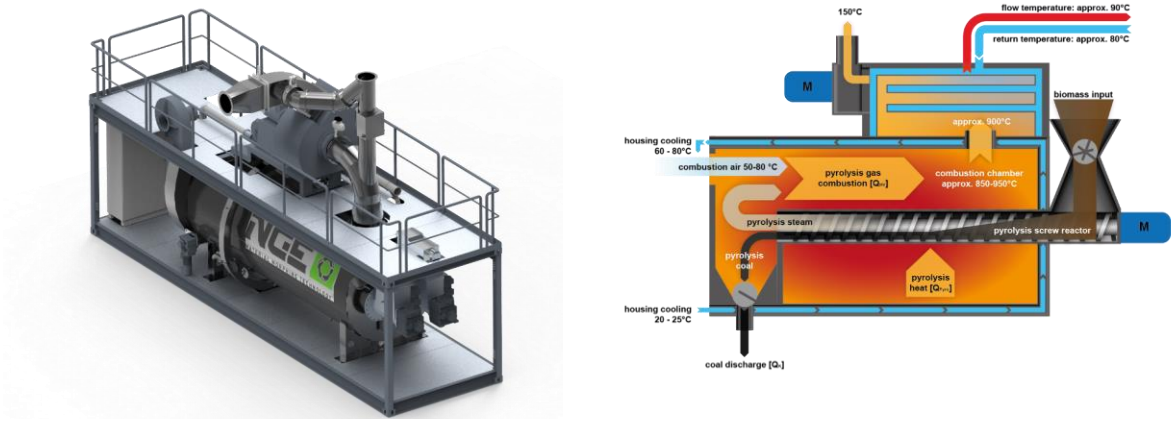

Figure 1: Direct heated thermal decomposition reactor T:CRACKER®DH from NGE (left) and schematic overview of the technology (right).

The feed material is fed into the pyrolysis chamber via a screw conveyor system and pyrolyzed at max. 700 °C. The pyrolysis gas is combusted in the combustion chamber and is used to heat the pyrolysis chamber directly. For the utilisation of the surplus thermal energy, two different solutions are offered – PyroDry and PyroPower. In the PyroDry system, the excess heat is used for drying. In the PyroPower system, the heat can be used for various thermal systems (local heating, ORC system etc.). The two main products from the pyrolysis of biomass are thermal energy (offgas) and biochar. The mass and energy distribution are influenced by composition of feedstock, temperature and residence time.
For the steel industry it is crucial to understand the characteristics of the input material. A distinction is made between wet and dry biomass as input. Wet biomass has a dry matter of 20-25% and are for instance sewage sludge, digestate, animal manures, papermill rejects and so on. The carbon content of these biochars is very low, but the phosphorus concentration is higher and more micronutrients are included. Besides, there can be diverse contaminations in the input material. As a result, the biochar has a lower specific surface, increased number of micronutrients, lower C and elevated P contents. In comparison, dry biomass such as wood, annual plants etc. has a dry matter content of around 80% and a very high C content. The biochar then also has the following properties: low P content, increased internal surface area etc.
The applications of the biochar products range from soil and substrate fertilizers, bedding and feed for animals, stabilisation additive for biogas production, CO_2 reduced construction materials, metallurgical coal for green steel production up to raw materials for phosphorus recirculation.

Beside the usage of an alternative C carrier in the steel industry, biochar offers also the possibility to create carbon sinks. It is a fact that the net zero CO_2 emissions target 2050 can only be achieved by the creation of carbon sinks; and the biochar production from biomasses with simultaneous power and heat generation is a suitable way to do that. In general, there are several market drivers which enforce the application of decentral technologies combining waste treatment, energy production and decarbonisation:

- Rules and regulation: Legal frameworks impose limitations on disposal options, often increasing costs of existing solutions.
- Energy prices: It becomes more and more attractive to recover the available energy content, even of wet biomass.
- Greenhouse gases (GHG) and carbon capture: Rising costs of CO_2 emissions make it attractive to gather carbon contained in waste and reuse or store it.
- Circularity: The market requests solutions capable of bringing the waste to a new use, such being zero-discharge.
- Decentralisation: High transport costs and uncertain economic situation push locally operating low-CAPEX solutions.

Cooperations between NGE and steel industry should be strengthened to improve sector coupling and material circularity. Firstly, the biochar property requirements are important to define boundaries for wet and dry input materials in the decomposition reactor, and technology modifications need to be implemented if necessary. Subsequently, the reactor size must be determined as the current systems are optimized for the actual customers and applications. Finally, as the regulations are gradually tightened, CO_2 savings are inevitable and, to a certain degree, enabled by biochar utilization in iron and steelmaking.

Towards low-carbon cokemaking: Insights on the influence of alternative materials on the coke quality and process performance

Majd Elsaddik[1], *Jan Wiencke*[1], *Tatiana Rozhkova*[1]

[1] Centre de Pyrolyse de Marienau (CPM), ArcelorMittal Maizières Research SA, 6 Rue Andre Campra Saint-Denis, 93210, France

Abstract. To achieve net-zero emissions (NZE) in steel production, ArcelorMittal Europe has set an ambitious target to reduce its 2030 CO_2 emissions intensity by 35% for scopes 1 and 2 (direct and indirect emissions). Different scenarios of ironmaking decarbonization show a shift toward an increased percentage of bio-carbon resources. Indeed, the use of alternative materials in cokemaking has been identified as a promising route to reduce CO_2 emissions associated with coke consumption. Biomass and its derived products as well as waste plastics are the main carbonaceous materials that can achieve a partial coal replacement in metallurgical coking blends.

The overall detrimental impact of the alternative additions on coke yield was ranked as follows: biocoal < polyolefins < solid recovered fuel (SRF) < black pellets < wood pellets. For coke strength after reaction (CSR), the ranking was: SRF < polyolefins < biocoal < black pellets< wood pellets.

To mitigate the negative impacts on coke quality and productivity, it is recommended that alternative materials with high density, low volatile matter, basicity index, and ash content be prioritized. Additionally, low particle size and the specific context of the steel plant should be considered, particularly in cases where biogenic coking gas from these materials can be used to supply other facilities. A tailored approach, evaluating the characteristics of each alternative material, will be essential in advancing the decarbonization of steel production without compromising operational efficiency.

This study investigated the potential of raw biomass, biocoal, solid recovered fuel, black pellets, and polyolefins as partial substitutes for coal in cokemaking blends. The incorporation of these materials has been tested at rates of 2% and 5% in a 400 kg movable wall pilot oven at Centre de Pyrolyse de Marienau (CPM). Various indicators, namely the wall pressure, coke yield as well as coke reactivity index (CRI), resistance to fragmentation, and coke strength after reaction with CO_2, assess the impact of these materials on the cokemaking process, coke quality, and productivity.
The carbonization was carried out in a slot coke oven. Whereas the silica bricks as outer refractory lining reached temperatures up to 1,200-1,300 °C, the temperature within the coal blend (with 2% or 5% alternative carbon materials) reached maximal 1,000 °C after several hours of coking time.
Depending on the selected alternative carbon material the grain sizes varied between 3-5 mm up to 16 mm. The ash content was maximal 12.8% in the case of SRF pellets. The highest amount of volatile matter (VM) of 95% was present in polyolefins, and the lowest was present in biocoal pellets (65.5%). A proportional decrease in coke yield with an increase in VM was determined. The maximal sulfur content of 0.3% was measured in wood and SRF pellets and minimal in polyolefins and biocoal (0.04%). Besides, biocoal is the only tested alternative which shows water resistance. The basicity index of the substitute materials strongly varied between 0.90 (wood pellets) and 2.69 (black pellets).
Results showed a decrease in coke yield with the addition of different alternative materials, primarily due to their high volatile matter content. A decrease in the wall pressure was observed when different alternative materials were added, except for a 2% polyolefin addition, where pressure exceeded the safety limit. This increase is explained by higher VM and lower bulk density, leading to volatiles trapped in the coal's thermoplastic layer at higher temperatures, generating internal pressure. In the case of 5% polyolefin addition, the porosity should be higher and thus, allowing the internal gases to leave without dangerous wall pressure generation.
The basicity index of these materials significantly influenced coke quality. Indeed, the basicity of the coal blend increased with the incorporation of alternative materials. This was translated by an increase in the CRI and a decrease in CSR. The SRF pellets, as partial input material, showed a significant influence on the decrease in CSR (cf. Figure 2). A detrimental effect was also observed on the resistance of coke to fragmentation and its mechanical strength (I40) due to the non-coking character of the alternative additions. I40 represents the resistance to fragmentation of grains with sizes of >40 mm in % after 500 revolutions in a drum measured by IRSID test.

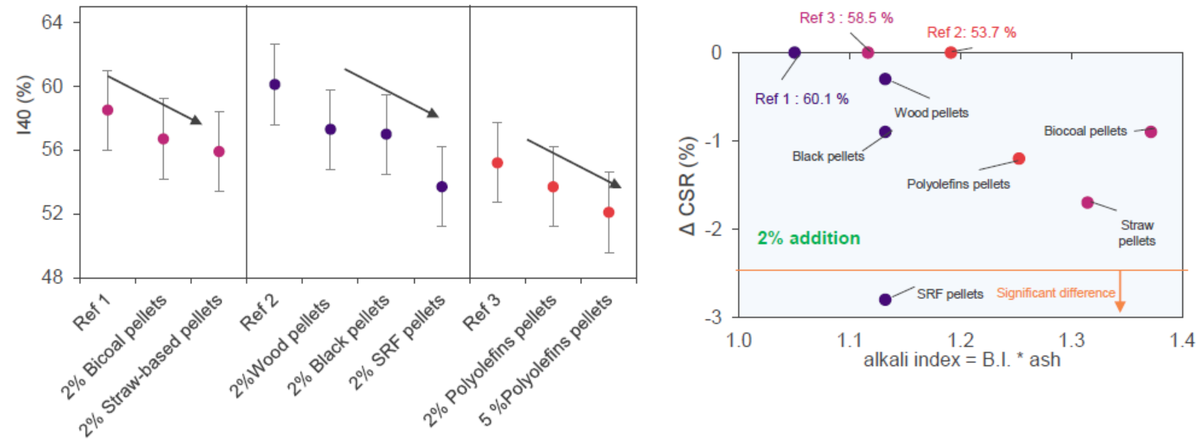

Figure 2: Effects of alternative carbon material additions on coke properties; decrease in mechanical strength (left) and change in coke strength after reaction (right).

It is recommended that bulk density and water resistance be considered with respect to handling and storage. Moreover, alternative carbon materials should be selected based on specific plant characteristics. As a perspective, biocoal pellet additions at a rate of 5% should be tested at industrial scale to determine the effects of particle size.

Hydrochar as a secondary carbon carrier: A circular approach for low-carbon steel production

Valentina Alemanno[1], Daphne Mirabile[1]

[1] RINA-CSM (Centro Sviluppo Materiali) SpA, Via di Castel Romano, 100, Roma 00128, Italy

Abstract. Nowadays, the development of new sustainable technologies in steelmaking processes has become a crucial point for process decarbonization, and great importance is attributed to the use of secondary resources containing carbon of biological origin. In this project, an in-depth investigation was carried out on briquettes and their behaviour before, during and after melting. The briquettes are made up of various materials of different natures: they have different formulations, although they are usually made up of a metallic part (which can be metallic turning or iron scale, i.e. mostly metallic iron or iron oxide), a certain amount of char or biochar, such as in this case, and a smaller percentage of binder, to improve the mechanical stability and avoid material degradation and fines formation during handling and storage.

Briquettes containing secondary carbon carriers have the double function to provide carbon to the steel bath and to allow metal recovery, promoting the reduction reaction of metal oxides by biochar.

Several briquettes were prepared having different formulations, combining the metal fraction of different nature with the same type of secondary carbon carrier (SCC), i.e. a hydrochar. The hydrochar has been obtained by treating plant residues with water in supercritical conditions (HTC, hydrothermal carbonization process).

The aim of the project is to investigate the behaviour of the briquettes in melting tests to evaluate the reducing capability of the carbonaceous part on the metal parts, and to simulate briquettes behaviour as inlet material for EAF, to assess the different aspects of the use of briquettes in the molten iron. In addition, chemical analyses were carried out not only on the briquettes, but also on the metal ingot produced after melting, to confirm the designed composition of the briquettes before melting and to measure the metal yield and the carbonization effect after melting.

The steel industry is one of the major contributors to global CO_2 emissions, making decarbonization essential for a sustainable future. The challenge lies in replacing fossil materials used in steelmaking processes with more sustainable solutions, reducing emissions without compromising process efficiency. SCC offers an innovative solution to emission reduction and promotes a circular economy approach by utilizing organic waste and different residues and transforming them into valuable resources. Using fossil substitutes represents a technological option able to mitigate CO_2 emissions without introducing new technological pathways. From a first evaluation, SCC can potentially avoid the emission of 300 kg/t of CO_2 in the integrated route and 40 kg/t of CO_2 in EAF.

The densification of material into briquettes is a suitable technological option for reusing materials of different sizes and shapes into EAF. Briquettes with biochar enable the addition of carbon to the steel bath, provide extra energy input into the EAF, and allow the reutilization of other waste, such as rolling mill scale, sludges and EAF dust.

Hydrochar is a specific type of biochar that is produced by hydrothermal carbonization of residual biomass, such as fruit peels and vegetable waste, using hot water in high-pressure conditions. The process is highly efficient and suitable for biomass with high moisture content, making it a key technique in converting agricultural-food waste into valuable carbon-rich material. It is designed as a sustainable and economically competitive alternative to fossil carbon coke for steelmaking. Besides the valorisation of organic waste and minimization of fossil fuel usage, the amount of waste deposited in landfills can be reduced. Hydrochar production leverages locally available biomass, making it an economically viable solution for reducing the costs associated with traditional fossil coke.

The experimental activities included the hydrochar characterization by chemical-physical and thermogravimetric analysis (TGA) under nitrogen and air atmospheres to determine the weight loss, combustion behaviour and decomposition character. The different samples have been used in melting tests, bringing the hydrochar in contact with molten iron bath, to check bath carburization capability. Moreover, hydrochar materials were used for briquettes' production with rolling mill scale. On the one hand, single briquettes were tested to check the suitability of hydrochar as a reducing agent, and on the other hand, contacting multiple briquettes with a molten iron bath was applied to check the occurrence of the reduction reaction, simulating the industrial environment.

The two different samples of hydrochar, in the form of powder and pyrolyzed pellet (biomass treated with HTC and with further pyrolysis treatment at 500 °C), were analysed and compared with reference values of anthracite and pet coke. The main differences were noticeable regarding ash, carbon, and volatile matter (VM) content. In the case of pellets, the high ash and VM content could originate from the pyrolyzing process and input material (waste biomass).

The melting tests were carried out using a BALZERS VSG 10 vacuum induction furnace (cf. Figure 3). At the beginning, iron was melted. After sample addition and complete melting, an ingot was cast. Regarding the final product, the contents of carbon and sulphur were of special interest. The C content after hydrochar powder addition was 0.15%, and with pellet addition, it reached 0.47%. The briquettes are composed of 65% iron scale, 15% binder and 20% hydrochar powder (negligible carburization <0.01%) or pellet (notable carburization >0.5%). Improved chemical-physical properties also request for optimization of briquette composition.

Figure 3: BALZERS VSG 10 vacuum induction furnace (left) and examples of cast ingots after hydrochar addition to liquid iron (right).

In general, the hydrochar contained higher VM content that could be reduced with thermal pyrolysis. The briquettes have good reactivity and do not cause problems in the melting process. Materials after HTC have good reducing capability, while material after HTC and pyrolysis has positive steel bath carburization capability. In case of utilization as charge material in the basket with scrap, material produced with HTC and pyrolysis is preferable. In the case of injection, further evaluation tests with industrial trials are required. When the material is used in briquettes mix with rolling mill scale, there is no significant difference whether the hydrochar is in the form of powder or pellets.

The results indicate that the physical form in which the hydrochar is pressed together with the rest of the materials influences the carburization (about 3 times higher with pellets). In addition, hydrochar works reasonably well in reducing the oxidized metal portion, such as a commercial char normally utilized in EAF. This means that hydrochar could be used in steelmaking processes as substitute or in addition to fossil materials.

Application of hydrochar for a sustainable electric arc furnace process

Yu-Chiao Lu[1], Andrey Karasev[1], Björn Glaser[1], Chuan Wang[1,2]

[1] Material Science and Engineering Department, KTH Royal Institute of Technology, Brinellvägen 23, 10044, Stockholm, Sweden

[2] Process Metallurgy Department, Swerim AB, 97125, Luleå, Sweden

Abstract. Current trends of biomass application in ironmaking and steelmaking processes are the broadening of biomass type, ensuring efficient utilization, and combining biocarbon production with nutrient recovery. With this study, we demonstrate that low-grade biomass such as agricultural waste and green waste can also be converted into a biocarbon (i.e. hydrochar) that can be used to substitute for fossil coal and coke in the electric arc furnace (EAF) process other than woody biomass. Hydrothermal carbonization (HTC) is the key enabler technology to convert low-grade biomass with a high moisture content into valuable biocarbon (i.e. hydrochar) and biofertilizer. The hydrochar produced from the HTC process has a high volatile matter content and is similar to a low- or a mid-rank coal. If hydrochar is charged or injected into the EAF only for replacing anthracite to achieve carburization of liquid steel, it results in a low utilization rate of the carbon content in the hydrochar (about 50%). However, by briquetting hydrochar powder with an iron oxide waste (e.g. pellet fine), the volatile matter content of hydrochar can be utilized efficiently to reduce the iron oxide in the briquette and the fixed carbon content both reduces the iron oxide and carburizes the iron. The produced gases from the devolatilization of hydrochar and from the carbothermic reduction of iron oxides can be combusted to provide energy or to promote slag foaming. This approach not only enhances the overall utilization efficiency of hydrochar, but also promotes the recycling and reusing of steelmaking by-products and wastes (e.g. dust, mill scale, etc.). Future studies should focus on the efficient utilization of biocarbon materials, regardless of the origin, by selecting the most suitable application route based on the biocarbon's properties and combining a few applications (e.g. reduction and carburization) where possible.

The steel production by EAF is expected to further grow within the next decades. From an actual worldwide EAF production of 411 Mt/a in 2022 (Europe: 59 Mt/a) an increase up to 863 Mt/a in 2050 (Europe: 104 Mt/a) is expected. As 12 kg carbon per ton of steel result in 44 kg CO_2/t_{Steel}, this would result in a total amount of 38 Mt/a of CO_2 emissions arising from use of fossil coal or coke in EAF. Thus, there is a biochar demand of 0.7 Mt/a (2022) and 1.2 Mt/a (2050), respectively, for EAF steelmaking in Europe. Nevertheless, in 2022 the biomass production in Europe yielded in 26 Mt/a of wood pellets and 0.6 Mt/a of charcoal. Consequently, there is a high difference in price, namely approx. 270 EUR/t of wood pellets and approx. 600 EUR/t for charcoal (anthracite: approx. 260 EUR/t). However, for forest biomass the requirements are explicitly stricter. Low-grade biomasses containing high moisture and impurity contents (alkalis, S, P) like straw represent an opportunity for the steel industry as only a minor fraction of the total straw biomass would be needed.

More in detail, the hydrothermal carbonisation at 180-250 °C and ca. 20 bar allows the production of hydrochar out of low-grade biomasses. The HTC process has a mass yield of 50 wt-% and the C content of hydrochar is 50-60 wt-%. Even tough, hydrochar is easy to pelletise, the current production in Europe is only about 12,000 t/a.

Carbon in EAF steelmaking has diverse roles; firstly, it represents a fuel while from the metallurgical point of view the carburisation of steel bath and the reducing character including slag foaming are of higher importance. With respect to fixed carbon content, pyrolyzing (cf. Figure 4) leads to an increase from 23-27 wt-% to 56-84 wt-%; simultaneously, the originally high volatile matter amount of 56-67 wt-% is depleted but the heating value is improved up to the range of the reference materials charcoal and anthracite. Besides, the unwanted ash and alkali contents elevate. As the phosphorus content of the hydrochar carriers is high, there is the opportunity to recover it for alternative applications before bringing it into EAF steelmaking.

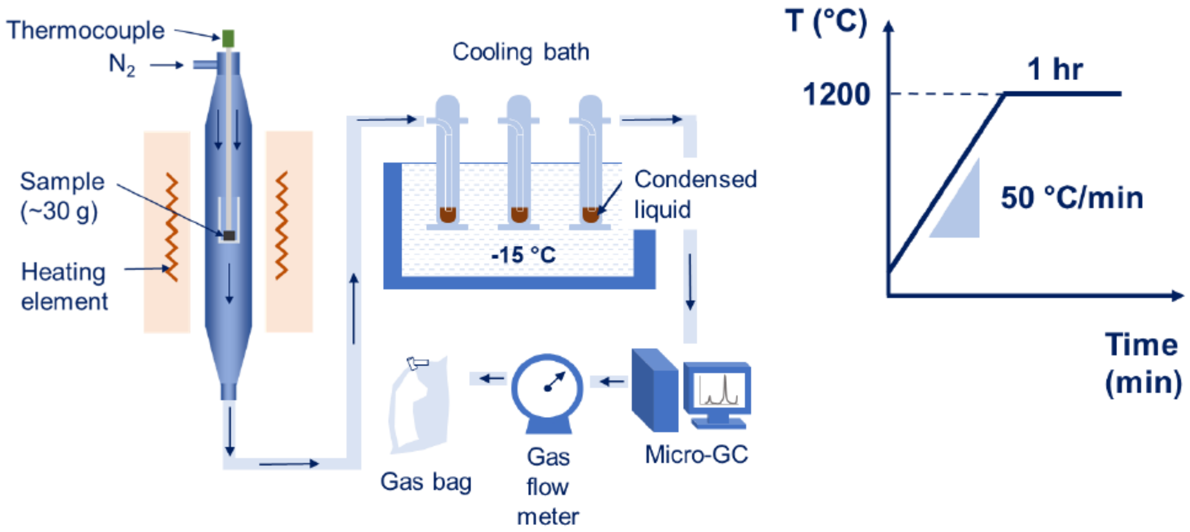

Figure 4: Experimental setup for slow pyrolysis (left) and applied temperature profile (right).

The share of solid, liquid and gaseous (CO, CO_2, CH_4, C_xH_y etc.) fractions of total carbon differs in anthracite, charcoal and hydrochar, i.e. lemon peel. The percentage of carbon dissolved divided by the added carbon represents the carburisation yield (CY). Regarding carburisation, on the one hand it depends on the fixed carbon content of the material, and on the other hand, the fixed carbon yield is influenced by the addition mode: Laboratory (approx. 100%) > top-charge, EAF (50-70%) > injection, EAF (30-40%).

A further important parameter is the self-reducibility of briquettes. For this, hematite is mixed with hydrochar (made from lemon peel, rice husk) and binder and subsequently briquetted. The self-reduction trials are executed within a thermogravimetric analyser in nitrogen atmosphere. The heating to 730 °C with a rate of 5 °C/min is followed by 1 h dwell time, a second heating period to 1,100 °C and a final dwell time of 1 h. In the weight loss vs. temperature diagram firstly, the devolatilization is visible. The next stage at 730 °C is identified as a reduction by volatiles with an abrupt weight change, and finally, the reduction by fixed carbon takes place. About 50% of the initial volatiles' content is utilized for self-reduction up to 730 °C (transformation of hematite to wustite). The reduction period up to 1,100 °C enables higher reduction degrees of up to 100%, carried out by volatiles and fixed carbon in combination. Generally, the required amount of fixed carbon for reduction is decreased from a molar ratio of 1.0 to 0.6 by volatiles.

The test setup of slag foaming trials is similar. Again 20 g briquettes of mill scale, hydrochar (carbon molar ratio of 0.1-0.3) and binder are heated to 1,100 °C in N_2 but placed in EAF slag. The slag height is determined by dipping alumina rods into the crucible. To replace 1 kg of anthracite in EAF steelmaking a total amount of 4.1 kg hydrochar is required (1.7 kg for heating and slag foaming and 2.4 kg for carburisation).

To sum up, hydrochar can be produced from a wide range of low-grade biomasses. It is characterised by high volatile matter and low fixed carbon contents. Thus, hydrochar is inefficient as a carburizer (30-70% of fixed carbon utilised). Nevertheless, it is a good reducing agent due to the combination of fixed carbon and volatiles. Besides, the sulphur content is low, and the ash amount is tolerable. The elevated phosphorus fraction needs to be extracted as part of future research activities.

Lignin-based products as biogenic secondary carbon carriers for the manufacture of furnace electrodes and refractories in iron metallurgy and steelmaking

Jesse F. White[1], *Luis M. López-Renau*[1], *Lena Reimund*[1], *Björn Glaser*[1], *Omid Hosseinaei*[2], *Jiebing Li*[2], *Johan Wallinder*[2], *Peter Rättö*[2]

[1] Material Science and Engineering Department, KTH Royal Institute of Technology, Brinellvägen 23, 10044, Stockholm, Sweden

[2] Bioeconomy and Health Division, Research Institutes of Sweden, Drottning Kristinas väg 61, 11428 Stockholm, Sweden

Abstract. Measures to reduce CO_2 emissions in iron metallurgy and steelmaking are becoming increasingly restrictive, e.g., the substitution of fossil carbon with bio-based carbon, as the availability of high-quality fossil carbon materials is declining globally. However, current technologies remain heavily dependent on fossil carbon, especially for non-reductant uses due to its unique properties, such as ability to carry high current density, high thermal conductivity, and high resistance to thermal and chemical corrosion. It is an enormous materials engineering challenge to find a viable replacement for fossil carbon in these industries. A possible alternative to reduce the carbon footprint associated with these products would be to partially or fully replace them with biomass-derived carbon. There are two notable sources of bio-based carbon, namely kraft lignin and pyrolytic lignin.
However, despite the promise of lignin-based carbon products, several challenges should be addressed before these can replace fossil carbon at scale.

Lignocellulosic biomass is a readily available renewable material that, when properly processed, can give rise to different lignin-based products that can be used as biogenic carbon carriers in furnace electrodes, carbon lining pastes and carbon-containing oxide refractories. One possible source of bio-based carbon is lignin from the kraft pulp mill using the LignoBoost process. Such technology is already well developed, and it can generate enormous quantities of kraft lignin (KL). The interest in KL lies in the fact that it may function both as an aggregate and as a binder depending on its processing.
Another possible source is pyrolytic lignin (PL), which is obtained by thermal-chemical fractionation of fast pyrolysis bio-oil and consists of a complex mixture of organic compounds from the lignin fraction of lignocellulosic biomass. In its solid form, PL can exhibit pitch-like behaviour, with a tuneable softening point, which makes it interesting for its use as a substitute for coal tar pitch (CTP), the fossil-carbon binder of choice in furnace electrodes and refractories. Due to its high content of phenolic compounds, PL is a suitable feedstock for the production of phenol-formaldehyde resins, which are the binders employed in the formulation of carbon lining pastes.
However, one of the greatest challenges of bio-derived carbon is the fact that it does not graphitize with simple heat treatment. Graphitizable biogenic carbon aggregates and binders could only be possible with efficient catalytic graphitization processing and subsequent catalyst removal. Additional difficulties observed, though equally significant, include high oxygen content, low coking value, low density, high porosity, and high reactivity to oxygen and carbon dioxide. Further research into the properties of lignin-based carbon products is of great importance in order to take the leap from the laboratory to larger scales.

Session 2: Non-biogenic SCC for iron and steelmaking

Decarbonisation through recycling and industrial symbiosis: The use of recycled carbon raw materials in steelmaking

Elisa Marchesan[1], *Elia Gosparini*[1]

[1] I.BLU Srl (Iren Group), Via Alpe Adria 6, 33010 Tavagnacco, Italy

Abstract. The mixed polyolefins used as feedstock (e.g. flexible/multilayer food packaging waste) are composed of a variety of polymers with different technical characteristics, therefore they are not suitable to be recycled for traditional plastic-to-plastic applications. Following the various sorting steps of the collected urban waste, these streams can be recycled to produce secondary carbon-carrying products, while being diverted from other less desirable end-of-life scenarios like energy recovery and landfill. I.BLU (Iren Group) is an important plastic sorter and recycler, focusing on the recycling of mixed plastic waste and producing BLUAIR®, also referred to as SRA or R-PMIX-SRA. BLUAIR® is a recycled plastic raw material, produced in compliance with the technical standard UNI 10667-17 and used in metallurgical and steel processes as a substitute of coal. It is largely used in Europe both in EAFs and BFs, intervening in the production cycle with the functions provided by the same technical standard (e.g. reducing/foaming agent). The recyclates deriving from post-consumer polyolefin-based mixed plastics successfully perform the reducing/foaming functions that are traditionally carried out by coal and anthracite. Moreover, this virtuous example of industrial symbiosis contributes to the achievement of the European recycling targets of plastic packaging waste and leading to significant CO_2 emission savings, as well as to the preservation of natural resources and, therefore, of carbon storages in the ground.

Injecting recycled polymers in BF 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. Moreover, the substitution of virgin coal in steelmaking reduces the emissions and environmental impacts linked to the extraction, transportation, and refinement of virgin fossil materials and to the avoided incineration of hard-to-recycle plastic streams. Increasing the uptake of recycled carbon-bearing materials can also reduce the EU dependence from the import of coal and anthracite, helping to counterbalance the current market mismatch, where the demand for virgin reducing/foaming agents (coal) exceeds their availability in the EU. At the same time, using SRA or R-PMIX-SRA in the steelmaking is complementary to the insufficient demand for recyclates deriving from these waste streams in plastic applications, and is crucial to boost the recycling rates of the collected plastic packaging waste.

The metallurgical sector is facing enormous challenges in the intent to cut down CO_2 emissions in accordance with the Green Deal. For some technologies, such as hydrogen and biomass production and carbon capture utilization and storage, significant barriers still need to be overcome, i.e., missing infrastructure and scalability, time as well as costs, prices and availability of materials; for example, biomass for the steel industry will have to compete with the other sectors (e.g. energy sector) in terms of available quantities, which will significantly affect the prices.

On the other hand, the usage of recycled polymers can immediately contribute to the decarbonisation of the metallurgical industry and to the circular economy by substituting virgin coal. Moreover, polymeric carbon carriers are available on industrial scale and the technology is consolidated. To date, about 10 Mt of plastic packaging waste in the EU are currently not recycled and mainly sent to incineration or landfill. By adequately treating these plastics, they can represent a suitable feedstock to produce secondary raw materials to be used in the steel industry in substitution of virgin fossil sources. By considering a 20% replacement rate in BF and a 30% replacement rate in EAF, only in the EU it would be possible to respectively substitute with recycled polymers about 3 Mt of PCI and 1.08 Mt of anthracite.

I.BLU developed and patented the reducing/foaming agent BLUAIR® as a substituting material of virgin coal in EAF and BF operation. In particular, BLUAIR® can be used in integral cycles as reducing agent in partial replacement of pulverized coal injected (PCI) and in partial replacement of coking coal for the coke production, and another application is found in electric arc furnaces (EAF) as slag foaming agent and reducing agent in partial replacement of the coal injected and as a protective agent in partial replacement of the coal charged in the steel scrap bucket. BLUAIR® is a recycled raw material deriving from plastic packaging waste to be used for the technical functions foreseen by the Italian standard UNI 10667-17:2021 and can compensate for the scarcity of virgin coal available in the EU and enable local sourcing at a fair price and lower environmental impacts, enhancing the sector's independence from extra-EU imports.

The use of BLUAIR® and its beneficial environmental impacts were evaluated in a study carried out by the university Politecnico di Torino, Italy. The report, which included the results in three different EAF steelworks, showed that overall, the injection of BLUAIR® does not negatively impact the quality of the emissions and ensures full compliance with the threshold values established by the environmental permits and monitoring regimes of each steelwork. Moreover, the emission points measurements carried out during the injection of BLUAIR® were similar or beneficial compared to the standard practice (only coal), including the monitoring of PAHs, PCBs, PCDD/PCDF, dusts, NOx, and heavy metals.

BLUAIR® as an alternative for virgin coal was tested at the Feralpi EAF steelwork within the project OnlyPlastic. RINA-CSM as the coordinating project partner performed an LCA study, comparing BLUAIR® production and utilisation as secondary reducing agent (SRA) with incineration and disposal of plastic packaging waste (PPW) as the baseline scenario. The use of the recycled carbon raw materials is beneficial in most environmental impact categories (acidification, climate change, ecotoxicity of freshwater, freshwater, marine and terrestrial eutrophication, human toxicity incl. cancer, ionising radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, energy demand, resource and water use). According to the single-score analysis (cf. Figure 5), the production process of BLUAIR® enables at least an impact reduction of at least 83% compared to the baseline scenario (disposal and incineration of plastic waste).

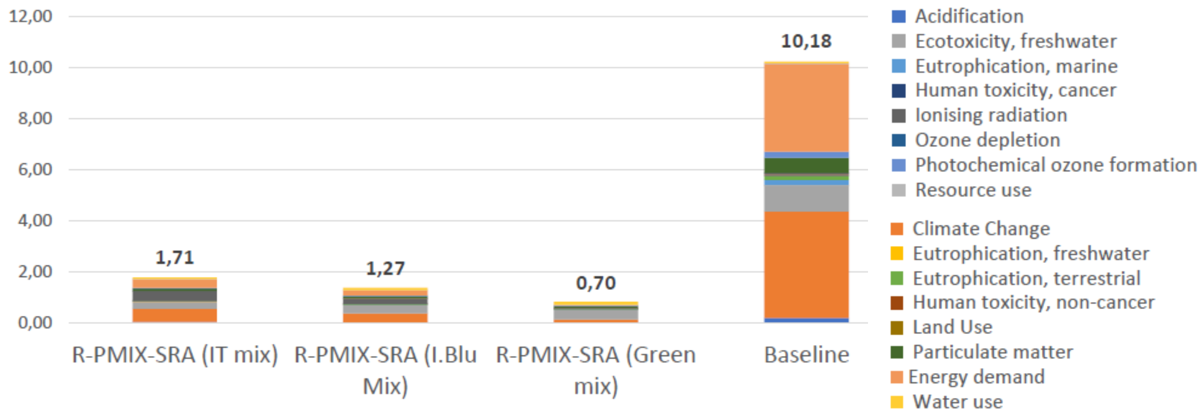

Figure 5: Single-score analysis comparing the impacts related to the innovative scenario (production of BLUAIR®) with the baseline scenario (incineration of mixed plastics and supply of coal).

Regarding liquid steel production, the LCA study showed an average impact reduction of 4% if BLUAIR® is used as carbonaceous material and a 16% reduction in climate change. The study showed the use of BLUAIR® in EAF steel manufacturing generally performs better than the conventional scenario, with lower environmental impacts for almost all impact categories.

The use of recycled polymeric carbon carriers is a consolidated industrial solution, the demand of which is steadily growing. Only in the last three years it has been possible to recycle more than 150,000 t of plastics that could not be recycled for traditional applications.

In conclusion, by taking up more recycled polymeric carbon carriers, the steelmaking industry can boost climate change mitigation, recycling, and EU independence from coal imports. A joint advocacy activity is necessary to ensure EU institutions introduce appropriate mechanisms to incentivize the substitution of virgin fossil resources with the recycled carbon contained in secondary raw materials in order to establish, i.e. in the upcoming revision/implementation of the ETS Directive and other ETS implementing acts, a zero-rated emission factor for recycled carbon-based raw materials used as reducing/foaming agents in steelmaking and a prioritization of these materials over virgin ones.

A techno-economic and environmental assessment of coke-making with non-recyclable waste plastics in Europe: Evaluation of current and future market conditions

Mario Ávila[1], Inge Bellemans[1], Sofie Verbrugge[2], Kim Verbeken[1]

[1] Department of Materials, Textiles and Chemical Engineering, Research Group Sustainable Materials Science, Ghent University, Technologiepark 46, 9052 Ghent, Belgium
[2] IDLab – UGent/imec, Technologiepark 126, 9052 Ghent, Belgium

Abstract. Given the growing economic as well as ecological challenges with current metallurgical coke production, there is a clear need to transition towards cleaner production methods. One approach is to partially replace the expensive and critical raw material in coke production, coking coal, with non-recyclable waste plastics recovered from solid waste sources – materials that would otherwise be landfilled or incinerated. This work presents the European Life SMART project and the comprehensive techno-economic assessment of a standard European coke-making plant, considering prices from 2019, 2022, and 2023. Two scenarios were evaluated: the Benchmark Scenario (BS), which involves conventional coke production using fossil coals, and the AlterCoal Scenario (AS), where 2 wt-% of the coal blend is replaced with pellets derived from non-recyclable waste plastics, referred to as solid recovered fuel (SRF). The study compares direct and indirect emissions between both scenarios and examines the influence of coke plant design on emissions and gross profit (GP). Additionally, future market conditions for the coke-making industry were evaluated in light of impending changes to the Emission Trading System (ETS).

Figure 6 gives an overview of the SMART project. As a first part, 2% of the coal charge in cokemaking were replaced by plastic waste pellets. The target was to use 30,000–40,000 t/a of waste plastics.

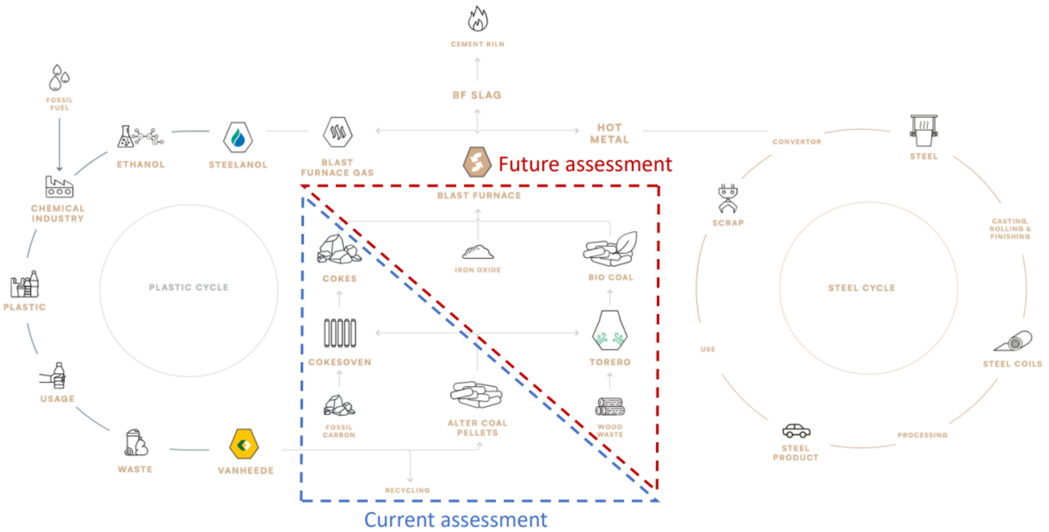

Figure 6: Life SMART project overview.

In techno-economic assessment, two scenarios for cokemaking processes, namely the Benchmark and the AlterCoal, have been analysed and compared. A detailed assessment shows that the AlterCoal scenario outperforms the Benchmark scenario in terms of gross profitability over the analyzed years.

Furthermore, the environmental benefits are significant, with an 11.2% reduction in direct emissions and a 5.7% reduction in indirect emissions under the AlterCoal scenario. These improvements are attributed to optimized coal utilization and incorporating biogenic carbon emissions.
The analysis also incorporates trends in energy market conditions, including fluctuations in the prices of coking coal, natural gas, and electricity from 2019 to 2023, with projections for future impacts. These market dynamics are expected to influence the economic viability of the cokemaking process, particularly with the forthcoming changes in EU ETS. The mass-energy balance pointed out that the AlterCoal scenario achieves improved conversion efficiencies and reduced waste generation.
The results show that direct and indirect emissions are reduced by 11.2% and 5.7%, respectively, in the AS compared to the BS. Over the three years analysed, the GP of the AS was higher than that of the BS, primarily due to the decreased reliance on coking coal, the use of relatively inexpensive SRF pellets, and an increased production of coke oven gas (COG). Finally, the forthcoming EU ETS regulations, which will include the maritime transport sector starting in 2024, are expected to significantly impact coke-making costs in the EU, likely encouraging the industry to adopt more sustainable maritime transportation methods, such as biofuels or hybrid cargo ships, to maintain profitability.

Project Title	SteelMaking with Alternative ReductanTs
Acronym	Life SMART
Grant Agreement No.	LIFE19 CCM/BE/001215
Funding Program	European Life
Project Duration	01|06|2020-31|05|2026

The SMART project: Recycling of plastics and waste materials in TORERO to substitute more coal injection in the blast furnace

Jean Borlée[1], Gaëtan Rivière[1], Bruno Cabeza[1], Damien Garot[1], Bert Riems[2], Wim Van der Stricht[2], Tom Defeyter[3], Nico Kimpe[3], Mario Ávila[4], Inge Bellemans[4], Kim Verbeken[4]

[1] CRM Group, Technologiepark 903c, Zwijnaarde, 9052 Ghent, Belgium
[2] ArcelorMittal Belgium, John F. Kennedylaan 51, 9042 Ghent, Belgium
[3] Vanheede Environment Group, Dullaardstraat 11, 8940 Wervik-Geluwe, Belgium
[4] Department of Materials, Textiles and Chemical Engineering, Research Group Sustainable Materials Science, Ghent University, Technologiepark 46, 9052 Ghent, Belgium

Abstract. The Life SMART project aims at using local waste-based non-recyclable resources in steelmaking, and to do it in such a way that their intrinsic chemical value is fully recovered, thereby reducing the need for conventional reductants (fossil coal) and enabling a substantial reduction of CO_2 emissions. The main technical options considered for charging the waste materials in the steel plant are either the direct feeding to the coke ovens (mixed in the coal blend) or the processing in the TORERO plant to produce a torrefied material ("biocoal") that can then be fed to the blast furnace as substitute to PCI coal.
Only the second technical option (torrefaction and injection in the BF) will be discussed in this paper. Regarding the torrefaction step, the main development tasks of the SMART project are on the adequate selection and preparation of waste materials (blending, densification, pelletising, etc), then on the tuning of the torrefaction technology. Due to the heterogenous composition and low calorific value of the waste feedstock, the conditions of the TORERO process, the configuration of the TORERO plant and the overall balance of all connected production units (use of the off-gas, energy integration, etc) have to be adjusted to new operating windows.

The preliminary project TORERO started in 2016 to demonstrate the breakthrough integration of torrefaction and wood pre-treatment technologies in the industrial facility of ArcelorMittal Ghent. The

technical objective was to substitute a significant fraction of the fossil coal injected in the BF with recycled wood. The TORERO plant is currently under commissioning and will produce 65,000 t/a of torrefied wood, using secondary biomass (wood waste) as a feedstock. After successful demonstration, this torrefaction capacity is expected to be increased by a factor of 10 in order to finally substitute half of the PCI coal in the BF and thus avoid 10-15% of the direct CO_2 emissions of the integrated steel plant. However, the supply of biomass on such a large scale may turn to be a limiting factor. This was the basic rationale for launching the Life SMART project in 2020: to include plastics and mixed industrial or societal waste in the feed of the TORERO demo plant.
For this project, ArcelorMittal Belgium has put together a specific consortium with the Vanheede Environment Group, the University of Ghent, Belgium and the CRM Group. The SMART project (cf. Figure 7) focuses on recycling plastics and other waste materials into the TORERO process to substitute a significant portion of coal used in BF injection.
Vanheede has first selected and supplied to CRM and to the University of Ghent an array of typical waste streams for evaluation. Complete lab and small-scale tests have been carried out to perform a first assessment of their suitability for TORERO, i.e. to fully characterise these streams, to anticipate their behaviour upon torrefaction in various conditions and to assess the quality of the torrefied product for grinding, pneumatic transport and injection in the BF.
Scale-up tests were then prepared at CRM. Pilot pyrolysis plants were revamped, switching from gas burners to electrical heating systems, to allow torrefaction/pyrolysis under inert atmosphere. Both the small 18" "batch" furnace and the pilot rotary kiln were equipped, modernised and started-up with their new heating system.

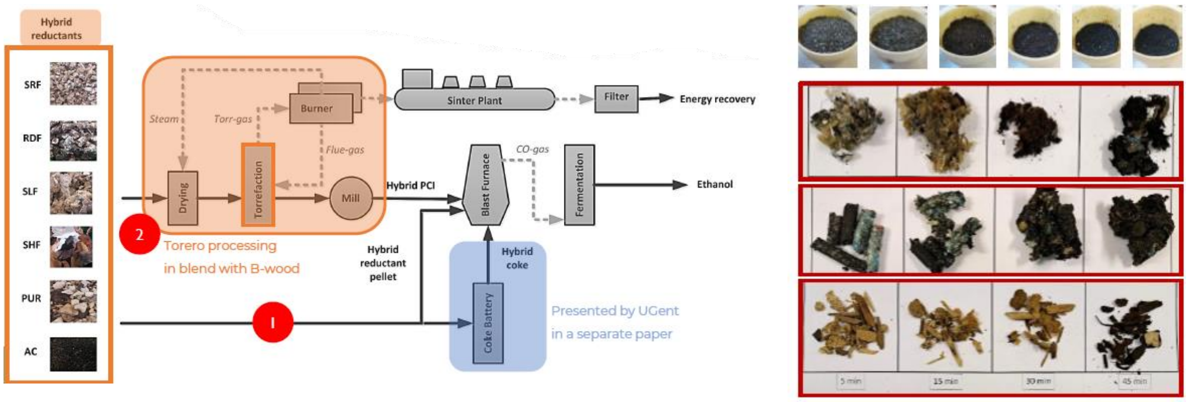

Figure 7: SMART project; recycling of plastics and waste materials in TORERO to substitute more coal injection in the blast furnace (left) and crucible tests (right).

After revamping, pilot torrefaction tests were launched. Equipment (auxiliary systems) and procedures were progressively improved (monitoring of charging and discharging rates, kiln tightness, kiln filling rate etc.) and reference tests with B-wood were first carried-out to mimic the expected TORERO operational conditions. Large samples of the selected waste recipes were then provided by Vanheede to CRM. First pilot torrefaction tests with blends of waste materials and B-wood are under way and will provide the expected support for the future industrial development in ArcelorMittal Ghent.
The main tasks include selecting and preparing waste materials through blending, densification, and palletisation. Subsequent blend optimization and tuning of the torrefaction process are key steps in ensuring efficient operations. A systematic evaluation involves a series of carbonization tests at various scales, from thermogravimetric analysis (TGA) for small samples to pilot and demo trials.
Crucible (Figure 7 (right)) and Batch18" trials confirmed material behaviour during carbonization and allowed the production of larger samples for characterization and use in realistic tests. Batch18" trials were completed with blends of B-wood and a selection of waste materials in TORERO conditions at various waste content in the blend, up to 50%. In parallel, rotary kiln (RK) pilot trials tested the

torrefaction process at scales of up to 20-100 kg/h under simulated industrial conditions. These tests included evaluations of the blends' behaviour and operating conditions, with trials scheduled for early 2025.

The behaviour of blends of wood and recycled materials during torrefaction cannot be anticipated: the addition of plastics and mixed materials to the B-wood charge in TORERO has to be tested stepwise to limit the risks in the industrial plant.

Project Title	SteelMaking with Alternative ReductanTs
Acronym	Life SMART
Grant Agreement No.	LIFE19 CCM/BE/001215
Funding Program	European Life
Project Duration	01|06|2020–31|05|2026

Practice of recycled plastics injection into a blast furnace at voestalpine Stahl GmbH

Lina Kieush[1], Christoph Thaler[2], Johannes Rieger[1]

[1] K1-MET GmbH, Stahlstraße 14, 4020 Linz, Austria

[2] voestalpine Stahl GmbH, voestalpine-Straße 3, 4020 Linz, Austria

Abstract. Blast furnaces (BF) are large counter-current metallurgical aggregates in which reducing conditions are established through the top-charging of coke and the injection of reducing agents, such as pulverized coal, via tuyeres. In conventional pulverized coal injection (PCI) technology, non-coking or weakly coking coals are injected into the raceways of BFs to partially replace coke.

The application of plastics for injection aims to recycle industrial and municipal plastic waste. Additionally, recycled plastics with a sufficient heat value of about 33,000 kJ/kg offer a viable option to replace conventional fossil carbon sources in these processes, contributing to lower CO_2 emissions. Analysis shows that injecting recycled plastics through the tuyere system, with a maximum injection rate of up to 40 kg per ton of hot metal (kg/t_{HM}), has been successfully implemented in several countries. Recycled plastics provide advantages over pulverized coal due to their lower thermal ignition temperatures, higher burning rates, and greater calorific values. This approach is currently the most effective method for replacing non-renewable fuels in the BF by utilizing alternative secondary carbon carriers.

The specialized facility for the preparation and injection of recycled plastics into voestalpine Stahl's BF A, initially built in 2006 with a capacity of 70,000 t/a, was later expanded to handle 140,000 t/a. Additionally, at voestalpine Stahl's BF A, approximately 20 kg/t_{HM} of recycled plastics are injected (at the moment, about 60,000–70,000 t/a) with a size of roughly 5–8 mm. However, partially unburned recycled plastics may be present at the end of the raceway due to the larger grain size. Moreover, it should be noted that recycled plastics generally can contain higher levels of trace elements than conventional BF feedstock materials, and these amounts should be controlled.

Advantages of the waste plastic injection in blast furnaces are lower thermal ignition temperatures, higher burning rates and elevated calorific values. Thus, diverse integrated steel plants in Germany and Japan implemented waste plastic injection during the last decades. At voestalpine Stahl GmbH in Linz, Austria alternative reducing agents, i.e. plastic waste, are injected into BF A.

Automotive shredder residues (ASR) are treated via the VW-SiCon® process which combines some mechanical treatment operations like the separation due to optical characteristics as well as due to physical properties. Suitable plastic fractions for BF operation are shredder granules and pre-densified shredder fibres. The design of the plastic injection lance influences conversion efficiency and blockage probability. Pellets, agglomerates and granulated ASR after treatment process are suitable alternatives for injection. In the high-temperature zone next to the tuyeres the waste plastics are transformed to CO and H_2.

Figure 8: Plastic injection at BF A of voestalpine Stahl GmbH; Material handling and storage (left), process air compression and injection tower (middle) as well as pressure hopper and material distribution (right).

The plastic injection in BF contributes to the heavy metal input. More in detail, 60-80% of Cd, approx. 30% of Hg and about 15% of the total Pb and Zn input arise from the plastic utilisation rather than from ores, coke and oil products. Nevertheless, the top gas cleaning at BF reaches unique dust limits of 1 mg/m_N^3 (BAT (best available technique) documents: <10 mg/m_N^3). The BF top gas cleaning consists of gravity separation of coarse particles in a cyclone and fine dedusting by wet scrubber system in a spray tower. Moreover, the top gas is used for steam production, hot blast stove heating, coal pyrolysis and electricity production.

The carbon footprint is further reduced (>5,800 t/a) by changing the transport system to railway service. Simultaneously, the risk of traffic accidents is lowered, and the material handling is more flexible on weekends. The material quality is essential to ensure stable BF operation. To avoid operation issues, the grain size distribution should be <10 mm and the moisture content 1.5%. The latter one leads to unwanted big agglomerates which do not fit in the injector system. Moreover, a minimal calorific value of 33 MJ/kg is required, and the ash content is limited to 10%.

The application of plastics for injection aims to recycle industrial and municipal waste. Plastics with a sufficient heat value (>33 MJ/kg) offer a viable option to replace conventional fossil carbon sources in BF process, contributing to lower CO_2 emissions. Thus, injecting recycled plastics through the tuyere system with a maximum injection rate of up to 40 kg/t_{HM} has been successfully implemented in several countries. However, recycled plastics generally can contain higher levels of trace elements than conventional BF feedstock materials, and these amounts should be controlled.

Polymer injection in EAF as a secondary carbon carrier scaled at industrial level: Process KPIs and decarbonization performance assessment

Massimo Masoni[1], Francesco Scortegagna[1], Franco Meda[1], Rossano Verzara[1], Andrea Costa[1], Stefano Callegari[1], Giovan Battista Landra[1], Mauro Pozzer[1]

[1] AFV Acciaierie Beltrame SpA, Viale della Scienza, 81, 36100 Vicenza, Italy

Abstract. Steel production through electric arc furnaces (EAF) uses coke or anthracite as a reducing and foaming agent. Coke is a virgin raw material obtained from fossil sources responsible for around 40-70% of direct greenhouse gas emissions of EAF steelmaking.

To reduce its use, it is possible to implement recycled polymers obtained from the end-of-life, post-consumer mixed plastics. The use of this material allows a reduction of greenhouse gas (CO_2) emissions. Thanks to its lower fossil carbon content compared to coal, and a partial content of biogenic carbon, the polymer's emission factor is quite lower than traditional fossil raw materials such as anthracite. Its use can bring a contribution in the company's decarbonization plan.

After a six-month injection testing period in AFV Beltrame Vicenza plant in Italy, during which the main process key performance indicators (KPI) have been assessed and bias checked, polymers injection reached a regular process condition. In this paper we describe the injection procedures, and the results obtained, both from metallurgical and environmental viewpoints.

The presentation focuses on using polymer injection as a secondary carbon carrier in EAF steel production, details on the experimental explanation, KPI and consumption analysis, and chemical analysis of slag and steel. Since 2019, AFV Beltrame has explored alternatives to traditional carbon sources to enhance environmental sustainability. The EAF process typically relies on carbon and anthracite for critical functions such as ensuring appropriate carbon levels in the liquid steel, reducing iron oxide in slag, and promoting slag foaming for electric arc coverage.

Polymer alternatives to carbon, tested on an industrial scale, demonstrated effectiveness in reducing iron oxide in slag due to the carbon and hydrogen in their structure. The polymers used comply with the UNI 10667-17:2021 standard and are derived from recycled plastic packing under the BLUAIR® initiative. These polymers provide a sustainable, circular solution to reduce dependence on fossil fuels, offering significant environmental and economic advantages, including a 35% reduction in CO_2 emissions, as certified by ISPRA (Italian Institute for Environmental Protection and Research), and a contribution to European recycling goals.

A pilot system (see Figure 9) was deployed for polymer injection, achieving flow rates of 20–35 kg/min through a single injection line. Testing involved altering 12-hour cycles with and without polymer injection for comparative analysis. The EAF at AFV Beltrame's Vicenza facility, with a 7.2 m diameter and 145 t capacity, was adapted to inject polymers via existing carbon injectors. Over three months of testing, up to 50% of injected carbon was successfully replaced with polymers without compromising productivity, operational stability or emissions.

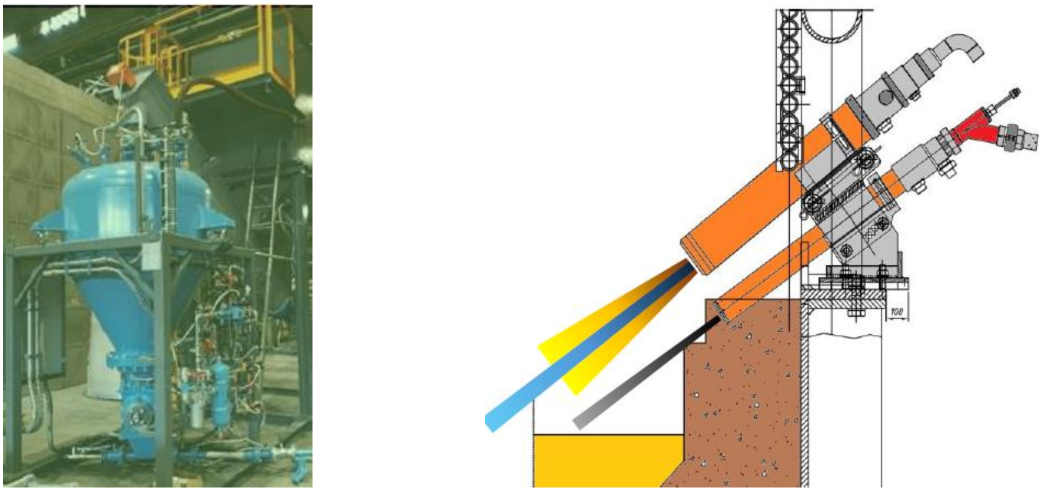

Figure 9: Pilot test system (left) and polymer-oxygen twin injector (right).

The results showed that polymer injection maintained effective slag foaming, did not alter the chemical composition of slag or steel, and reduced the steel plant's total CO_2 emissions by 5%. Furthermore, the polymer's performance did not increase pollutants.

Analysing the green hydrogen to green steel transition through the sustainability triple helix lens: Reflections upon HYDRA (IT06) IPCEI

Pietro Gimondo[1], Filippo Cirilli[1], Alice Reina[1], Simona Pace[1], Antonietta Megaro[1]

[1] RINA-CSM (Centro Sviluppo Materiali) SpA, Via di Castel Romano, 100, Roma 00128, Italy

Abstract. The HYDRA project emerges as one of the most ambitious initiatives in the steel sector, aiming to facilitate the transition to net zero emission steel production. With the aim of decarbonizing

the steel production process, HYDRA integrates innovative technologies such as direct reduction (DR) using green hydrogen and electric arc furnaces (EAF) with low (or zero) fossil substitution (integrating hydrogen and secondary carbon carriers' utilization). This initiative not only contributes to climate change mitigation but takes a multidimensional approach to sustainability. The shift from green hydrogen to green steel is a key to achieving sustainable steel production, replacing traditional coal with a low-emission alternative; in this general frame, circular economy can contribute to the achievement of the ambitious target of steel production decarbonization, reducing in parallel the dependency on virgin raw materials.
Consistently with the EU's growing focus on low-emission energy production and the circular economy, HYDRA is part of a policy framework aimed at replacing fossil fuels with renewable energy sources and implementing circular models and is consistent with the EU's strategic objectives.

The integration of secondary carbon carriers (SCC) in the production route DR+EAF based on green hydrogen can support the achievement of the decarbonization target. SCC can have several applications. As solid materials, they can be used in the mix of the pellets, as reducing agent, potentially reducing the hydrogen demand for DR process. Moreover, in the EAF, SCC carburize the steel bath, promote slag foaming and provide energy to the melting process, to allow materials recovery (briquettes with wastes and SCC). After gasification process, the produced syngas can be used as reducing agent in DR process and to replace natural gas burning in EAF or in reheating furnaces, respectively.
The role of SCC is included in the HYDRA project, trying to reduce hydrogen demand in the DR plant and serve as a substitute for coal in EAF. SCC functions include their incorporation into iron ore pellets, use as carburizing agents and energy sources in EAF, and gasification to produce syngas for various industrial applications. The utilization of SCC in the DR+EAF production route can bring significant advantages, as polymers can decrease the process hydrogen demand in the direct reduction and by injecting polymers in the EAF process up to 100% of pulverized coal can be replaced.
To demonstrate how functional HYDRA is to pursue sustainability goals, its results will be analysed using the three dimensions of the triple helix of sustainability (see Figure 10) as a key to interpretation.

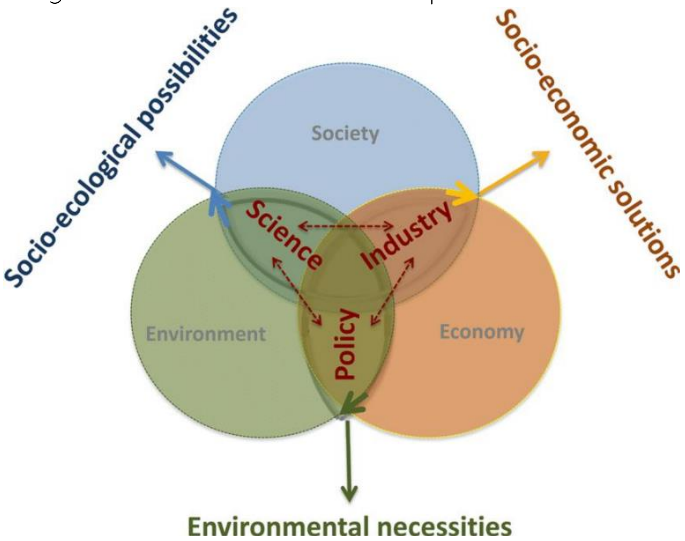

Figure 10: Triple helix of sustainability.

From an economic perspective, the HYDRA project significantly reduces dependence on fossil fuels while optimizing the utilization of renewable energy resources. Integrating SCC can also mitigate dependency on green hydrogen, reducing risks from potential shortages or reliance on non-renewable electricity. This transition leads to enhanced process efficiency and a substantial decrease in long-term operating costs through green steel production, i.e. cuts operational costs using polymers instead of hydrogen. This not only aligns HYDRA with the EU's sustainability goals but also enables the industry to capitalize on the increasing global demand for low-carbon materials, fostering a more resilient and competitive economy.

From an environmental perspective, the project aligns with the objectives of the European Green Deal and the EU Hydrogen Strategy, directly addressing the reduction of CO_2 emissions through the adoption of clean technologies, such as integration of green hydrogen and the recycling of materials. These efforts reduce the environmental impact of steel production, making HYDRA a mainstay in the fight against climate change. The HYDRA project aims to reduce CO_2 emissions from steel production by up to 95%, from an average of 1.9 tons of CO_2 per ton of steel to a few kilograms, significantly mitigating the industry's environmental footprint.

Moreover, on a social level, HYDRA promotes the creation of new skills and job opportunities in hard-to-decarbonise sectors, supporting a just and inclusive transition towards more sustainable production models. Consequently, the project improves air quality, creates green jobs in clean technology sectors, and enhances public perception of the steel industry.

It was concluded that RINA-CSM, through HYDRA, could contribute to the objectives of the European Green Deal and the European Hydrogen Strategy by supporting low-emission energy production and material recycling, aiming to create a sustainable steel model.

Project Title	Hydrogen: innovative plants and related processes for the production of green steel in Europe
Acronym	HYDRA (IT06)
Grant Agreement No.	IPCEI-I1_0000002 - CUP B29J23000700004
Funding Program	IPCEI Hy2Use
Project Duration	01|01|2023-31|12|2028

Session 3: Recent project activities on European level following SCC usage

Ecological evaluation of the utilization of secondary carbon sources in the steel industry through a Life Cycle Assessment approach

Carsten Gondorf[1], *Felix Kaiser*[1], *Thomas Echterhof*[1]

[1] RWTH Aachen, Kopernikusstraße 10, 52074 Aachen, Germany

Abstract. The utilization of secondary carbon carriers is essential to close gaps in the sustainable transformation in the steel industry. This includes the use of biomass/biochar and plastic residues with a high fixed carbon content in iron and steel furnaces for substitution of fossil coke, as well as in carbon composite agglomerates in the form of self-reducing briquettes or pellets made of iron ore/iron rich residues and secondary carbon carriers for the exploitation of volatile matter. For evaluating the environmental impacts of such secondary carbon carriers, the implementation of a life cycle assessment (LCA) helps to identify and address shifts in environmental burdens across different stages or processes, promoting more sustainable technology development and eco-friendly design. The paper gives insights of LCA approaches for evaluating the use of secondary carbon carriers, designed to analyse and assess the inputs, outputs, and potential environmental impacts of a product system throughout its entire life cycle, from sourcing of raw materials to disposal.

The presentation addressed the ecological evaluation of SCC in the steel industry using the LCA approach. The primary goal was to explore alternatives to fossil carbon sources, assess their environmental impacts, and optimize processes for sustainable steel production.

As a basics, LCA systematically analyses input/output flows and potential environmental impacts of a product system throughout its lifecycle. Additionally, material flow analysis (MFA) systematically assesses the state and the changes in flows and stocks of materials within a defined system over time. The methodology for LCA calculations involves defining objectives, system boundaries and the functional unit. Three emission scopes were evaluated:

- Scope 1: Direct emissions (e.g. directly released greenhouse gas (GHG) emissions that are directly attributable to the product system like exhaust gases from the combustion process).
- Scope 2: Indirect emissions from energy sources (e.g. indirect GHG emissions attributable to the product system like the emissions of the electricity mix used to provide the electrical energy required by the product).
- Scope 3: Emissions from upstream and downstream activities (e.g. material extraction, recycling).

The principles of mass and energy conservation were applied to steel production processes, enabling the evaluation of energy input and output flows, emissions and material consumption through balance sheets.

Secondary carbon sources play a critical role in enhancing sustainability in steel production. Alternative fuels such as biochar, agricultural residues and municipal waste-derived carbon are substitutes for fossil fuels. Processed secondary carbon can replace pulverized coal in furnaces through carbon injection. Additionally, materials like coke breeze, carbon black and fly ash are recycled in sintering or electric arc furnaces. Carbon capture and utilisation (CCU) technologies transform flue gases into syngas for steelmaking, while biochar is employed as a reduction agent or binder in residue-based agglomerates. Plastics are also recycled into pyrolysis oil or synthetic gas for injection, contributing to the circular economy.

Biogenic carbon substitution in EAF (see Figure 11) was explored using biochar, such as palm kernel shells, in scenarios where fossil carbon usage was reduced by 100%, 50%, and 0%.

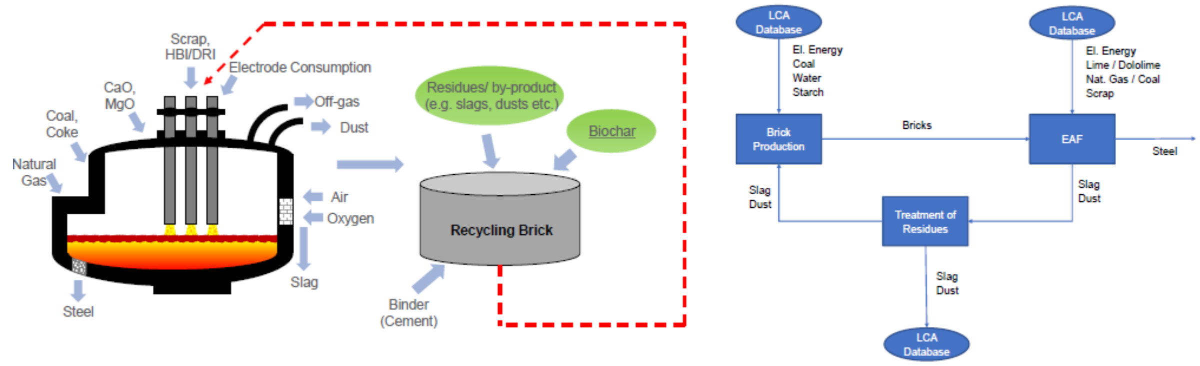

Figure 11: Use of biochar as reducing agent (left) and use of organic bio-binders (right).

The results demonstrated decreased CO_2 emissions and lower overall demand for fossil carbon with increased biogenic carbon utilization. In another study, integrating residues and biochar into agglomerates improved slag properties, including higher Al_2O_3 and CaO levels and lower FeO concentrations. The approach also increased hydrogen concentration in off-gas without significant differences in energy consumption, showing minimal impact on global warming potential and other environmental categories. A third case study focused on plastics for injection, where plastic grinding waste was processed into feedstock for steel production. This approach achieved a carbon footprint 1.7 times lower than coal, though indirect emissions from electricity represented a significant portion of the CO_2 footprint.
LCA proved to be a robust framework for evaluating the ecological impacts of secondary carbon sources. Integrating these materials demonstrated potential for reducing CO_2 emissions, decreasing dependence on fossil carbon, and supporting circular economy principles. However, certain limitations were identified, including issues with data transparency, variability in databases, and assumptions in modelling. Additionally, simplifications in LCA methodologies introduced uncertainties that require further investigation.
There are also several limitations of the LCA:

- Data transparency (e.g. through suppliers).
- Influence of the databases used.
- Partly simplification.

Additionally, it was concluded that the comprehensive mass and energy balance for the processing system is the most important foundation for LCA approaches.

TACOS: Towards a zero CO_2 sintering

Hubert Fouarge[1]

[1] CRM Group, Rue du Bois Saint-Jean, 8, 4000 Liège, Belgium

Abstract. In order to help steelmakers to comply with ever stringent environmental constraints, the TACOS project aimed at evaluating solutions bringing significant decrease of CO_2 and other main pollutants (NO_x, SO_x, VOCs) in the sintering process. These solutions involved

- High bed heights operation for improved process internal thermal efficiency
- Waste gas recirculation
- Use of alternative heat inputs:
  - Alternative solid fuels (such as biomass)
  - Combustible gases (such as blast furnace gas) for injection at the strand surface
  - High temperature fumes produced in an external combustion chamber, thus allowing valorisation of a wide range of alternative heat sources

For evaluation of the impact of these solutions on sintering process performances and emissions, tasks consisting in modelling work (mathematical model), lab trials, sinter pot trials and industrial measuring campaigns and trials have been performed.
Since these solutions have significant impacts on blast furnace (BF) process, a special focus was also placed on their impact on sinter quality (especially on its vertical segregation) and BF performances. For that purpose, a wide set of complementary tools not used in daily industrial practice was available amongst the project partners.
The replacement of fossil solid fuel by alternative carbon source (including pyrolyzed olive pits) have been successfully tested at the pot trial and industrial scale, thus allowing for drastic CO_2 emission reductions (10% at the industrial scale). Combining alternative carbon sources with high temperature fumes injection even allowed to produce sinter with 0% fossil solid fuel at the pot trial scale. Additionally, other process modifications were tested and resulted in varying degrees of CO_2 emission reductions (up to 35% reduction of solid fuel thanks to the use of high temperature fumes).

The TACOS project focuses on reducing CO_2 emissions from the sintering process. By integrating alternative solid fuels (ASF), process modifications, and advanced technologies, the project aims to align with stringent environmental regulations. Several alternative solid fuels, such as residues from gasification of wood chips, char from thermal pyrolysis of husk (grain), torrefied biomass, material from hydrothermal conversion of biomass, coffee grounds, residue from instant coffee production, eucalyptus wood (pyrolyzed wood chips) as well as various streams of urban waste were considered. The key characteristics of the ASF were discussed. Reduced volatile matter content in alternative solid fuels minimizes pollutant emissions, while the reactivity and ash content play crucial roles in influencing sinter quality and pollutant profiles. Using ASF effectively decreases CO_2 emissions without compromising sinter quality.
Laboratory and pot trials demonstrated the effectiveness of pyrolyzed eucalyptus flakes, achieving up to a 60% reduction in fossil fuel consumption while improving productivity and emissions profiles. Industrial trials using pyrolyzed olive pits revealed a 7% decrease in CO_2 emissions. However, the pollutant outcomes included a 25% decrease in NO_x emissions and a 30% increase in SO_x emissions.
The integration of pyrolyzed biomass, such as eucalyptus flakes, led to reduced dependence on fossil fuels, enhanced fixed carbon content, and improved productivity. This approach also decreased NO_x emissions by up to 75%. Advanced process layouts, exemplified by the VeLoSint process (Figure 12), combined ASF with high-temperature fumes injection, resulting in a mix with 0% fossil fuel usage. This configuration achieved an 18% productivity gain and reductions in SO_x and NO_x emissions, although it increased VOC emissions.

Figure 12: VeLoSint laboratory testing facility.

Process layouts like VeLoSint enhance flexibility in fuel use and facilitate significant reductions in greenhouse gases. However, ASF increase other pollutants, such as VOCs and SO_x. The economic viability of these approaches depends on their cost-competitiveness compared to traditional fuels.
Additionally, the lack of industrial-scale pyrolysis solutions presents challenges in ensuring a consistent supply of ASF during trials. Waste gas recirculation (WGR) has been shown to optimize fuel savings by up to 15%. In addition, fuel gas injection at the strand surface effectively replaces solid fuels with biofuel-based gases, achieving 10% solid fuel savings and improving the reducibility index (RI) and reduction degradation index (RDI). The VeLoSint process, which combines ASF with external combustion chambers, decreases CO_2 emissions by 31%.
Some ASFs are suitable for the sintering process itself, thus allowing for CO_2 emission mitigation without a negative impact on productivity and quality. But they can lead to increases in other pollutants. Besides, the economic viability of their use at the industrial scale remains to be proven since ASF would need to be about as cheap as traditional solid fuel, which was not the case at the time of the project. Nevertheless, specific layouts like VeLoSint and fuel gas injection make it possible to valorise a wide range of alternative, renewable heat sources and various by-products.

Project Title	Towards a zero CO_2 sintering
Acronym	TACOS
Grant Agreement No.	Project No. 847322
Funding Program	Research fund For Coal and Steel (RFCS)
Project Duration	01|06|2019-30|06|2023

In the frame of the RFCS-funded project TRANSinter No. 101112600, the following solutions will be studied and beneficiate from the learnings of TACOS:

- Replacement of fossil solid fuel by ASF produced by thermochemical treatment of low-value waste.
- A new waste gas recycling layout called Zero Emission Sintering, which allows for carbon capture at the sinter strand.

The combination of both solutions could lead to negative CO_2 emissions at the sinter strand.

OnlyPlastic: EAF working with polymers derived from plastic residue in substitution of fossil fuel

Mattia Bissoli[1], Enrico Malfa[1], Mauro Gizzi[1], P. Frittella[2], F. Fredi[2], M. Tellaroli[2], Elisa Marchesan[3], Elia Gosparini[3], Loredana Di Sante[4]

[1] Tenova (Techint Group), Via Gerenzano, 58, 21053 Castellanza, Italy
[2] Feralpi Siderurgica, Via Carlo Nicola Pasini, 11, 25017 Lonato, Italy
[3] I.BLU Srl (Iren Group), Via Alpe Adria 6, 33010 Tavagnacco, Italy
[4] RINA-CSM (Centro Sviluppo Materiali) SpA, Via di Castel Romano, 100, Roma 00128, Italy

Abstract. Alternative materials able to replace fossil carbon sources is a topic of great interest among European steel mills. The primary production route (based on blast furnace) already uses recycled granulated polymers from plastic residue (also defined as secondary reducing agent, SRA) to replace injected pulverized coal. SRA usage also in the secondary production route (based on electric arc furnace, EAF) has been evaluated both as lump material (charged in buckets) as well as in granulated form, suitable for injection by means of tailor-made wall mounted systems (a.k.a. lances). Preliminary investigations identified this last approach as very promising.
OnlyPlastic aims to substitute in the Feralpi Lonato EAF the reducing and foaming agents (both charged and injected) obtained from fossil carbon sources (like coal, coke, pet coke) with densified recycled polymers from plastic packaging waste. This SRA is obtained by means of a new process able to transform a hard-to-recycle heterogeneous mix of plastic into a new secondary raw material.

Feralpi Siderurgica became the first EAF-based steel plant adopting a slag foaming practice fully based on polymers. The injection is made possible thanks to new injection system realized by Tenova tailored for low-density high-volatile materials. The benefits are: 100% of coal used in EAF substituted, reduction of CO_2 in ETS count emission, recycling of mixed polymers waste in a process production (avoiding landfill/incineration and aiming at natural resources preservation), plastic recycling targeting EU strategies on circular economy and, in parallel, reduction of production costs.

The OnlyPlastic project (see Figure 13) demonstrates the feasibility of substituting fossil fuels with polymers derived from plastic residues in EAF. The aim is to decarbonize steel production, enhance circularity using hard-to-recycle materials, maintain production quality and process stability while reducing greenhouse gas emissions and landfill waste by replacing coal with a secondary reducing agent in EAF steelmaking. The project addresses key questions and defines best practices regarding the material selection, the injection technology, and the replication potential of this approach between steelmaking and other industrial sectors.

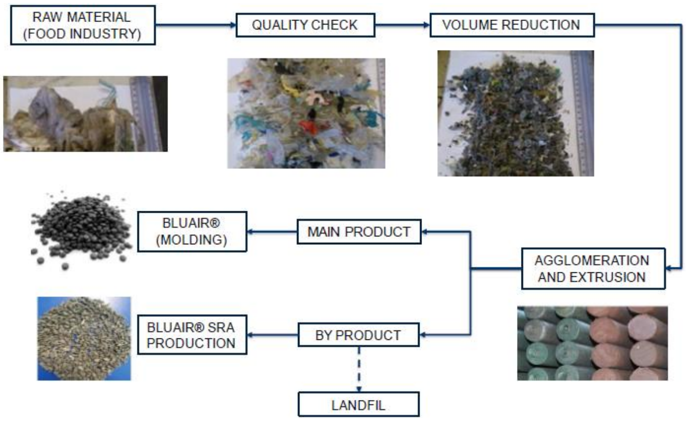

Figure 13: Schematic project overview.

The material selected is the BLUAIR® SRA, a mix of polyolefin-based hard-to-recycle plastics compliant with the Technical Standard UNI 10667-17. The materials used are residue that are left behind from previous sorting processes of post-consumer plastics (mainly flexible/multilayer food packaging), aimed at extracting traditional homopolymers such as PET, HDPE, PP, etc. This SRA offers several advantages compared to traditional unsorted plastic residues, like low chlorine, sulphur and ash content, as well as heavy metals. It is also characterized by high carbon and hydrogen contents, ensuring an efficient foaming and FeO reduction.
The injection of SRA into modern EAFs represents a technological challenge due to the low density and high reactivity of the material. Within the project, two injection systems were tested (Figure 14). The first one (called Tenova KT® TWIN SRA) is based on the state-of-the-art injection technology for EAFs, adapted for SRA injection. The second solution is a new development called Tenova KT® MULTI, which combines SRA and lime injection to provide advanced process control and simplifying installation in complex layouts.

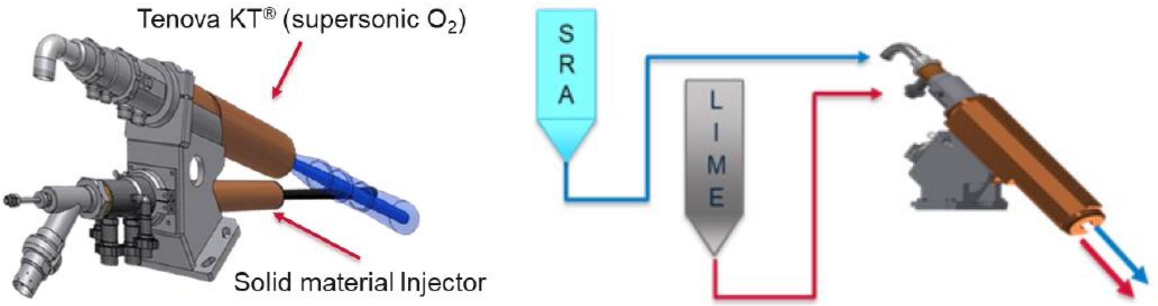

Figure 14: Tenova KT® TWIN SRA injector (left) and new Tenova KT® MULTI injector (right).

Industrial trials at Feralpi Lonato evaluated the feasibility to substitute coal with SRA in terms of acoustic index (ACI), emission profiles and process stability. The trials confirmed consistent slag foaming and acceptable ACI indices. No significant variations in product quality or electric consumption were observed compared to coal. Emissions of dioxins and furans were reduced by 56%, and VOC emissions decreased by 41%. Life cycle assessment (LCA) insights revealed that using BLUAIR® SRA instead of coal could decrease total CO_2 emissions by up to 16% (direct and indirect) and minimize the landfilling of hard-to-recycle plastics.

An analysis on the exploitability of the OnlyPlastic project evaluated the possibility to replicate this approach alongside Europe. A regional analysis of steel mills and plastic sorting facilities indicated that SRA is a viable alternative when production sites are within 30 km of each other. This is due to the impact (both in terms of CO_2 emissions and costs) of the SRA transportation on the global impact of this approach. The analysis identified the northern Italy, Spain and the French/German areas close to the Benelux border as regions of interest for exploiting these concepts, thanks to the proximity of SRA production to EAF sites and the availability of the plastic materials for SRA production.

In conclusion, the project successfully demonstrated the feasibility at industrial scale of the of coal substitution with SRA from plastic residue compliant to the Technical Standard UNI 10667-17 to control slag foaming in EAF. Significant adverse impact on production or emissions were not registered. This project allowed to gain experience on the critical aspects for the SRA implementation, resulting in a series of best practice. BLUAIR® SRA should be selected as material to avoid hazardous pollutant emissions, whereas tailored solutions for SRA injection, like the Tenova KT® systems, should be adopted to maintain an optimal slag foaming. Lastly, this experience provides to policymakers' elements for new legislative frameworks.

Project Title	EAF working with polymers derived from plastic residue in substitution of fossil fuel
Acronym	OnlyPlastic
Grant Agreement No.	Project No. 899415
Funding Program	RFCS
Project Duration	01|09|2020-31|08|2023

Creation of new value chain relations through novel approaches facilitating long-term industrial symbiosis – CORALIS

Filippo Cirilli[1], *Loredana Di Sante*[1], *Daphne Mirabile*[1]

[1] RINA-CSM (Centro Sviluppo Materiali) SpA, Via di Castel Romano, 100, Roma 00128, Italy

Abstract. Industrial symbiosis (IS) has gained increasing attention in the last years due to its high potential for energy and resources savings. Under this framework, CORALIS project has been designed as a demonstration project for the generation of real experiences on the deployment of IS solutions. The overall approach of CORALIS is to be demonstrated in a total of three industrial parks (demo cases), each of them supported by an IS facilitator, a neutral actor in charge of guiding the IS initiative and exploiting its full potential. In addition, three industrial clusters have been analysed for the future implementation in IS.

The lighthouse demonstrators showcase specific implementations in the industrial area. In Escombreras Valley, Spain the goal is to improve water management and consumption, eliminate Ca waste, and reduce the overall CO_2 emissions at the park level. In Frovi, Sweden, the project addresses resource efficiency, lessening the environmental impact, and, as a niche market leader, obtaining a front-runner advantage. In Brescia, Italy the aim is to obtain a deeper understanding of industrial waste and reduce landfilling in line with the objectives set by public authorities and associations in the region. Regarding the industrial clusters, in Basauri, Spain, the feasibility of recovering waste heat from EAF to supply steam to neighbouring industries is explored. In Linz, Austria, the integration of renewable hydrogen production is examined, fostering collaboration between Borealis Agrolinz Melamine and the voestalpine

steel industries. At Izmit, a Turkish petroleum refinery, the main driver to join CORALIS, relies on the potential cost reduction in the treatment and valorisation of waste.
This paper is focused on the description of the Brescia district use case. Four companies have been involved in this use case: Ori Martin and Feralpi (steelmaking), Fonderia di Torbole (cast iron foundry) and Raffmetal (secondary aluminium production).

The aim of the CORALIS project is to create pathways for the decarbonization of resources in energy-intensive sector value chains through the implementation of viable industrial symbiosis approaches combining new business and management strategies with innovative technology-based enablers. The project focuses on demonstrating IS in diverse industrial areas, covering different sectors, geographical dimensions, and resources, improving the knowledge basis and laying the foundations for exploiting the potential of industrial symbiosis in the EU process industry (cf. Figure 15).

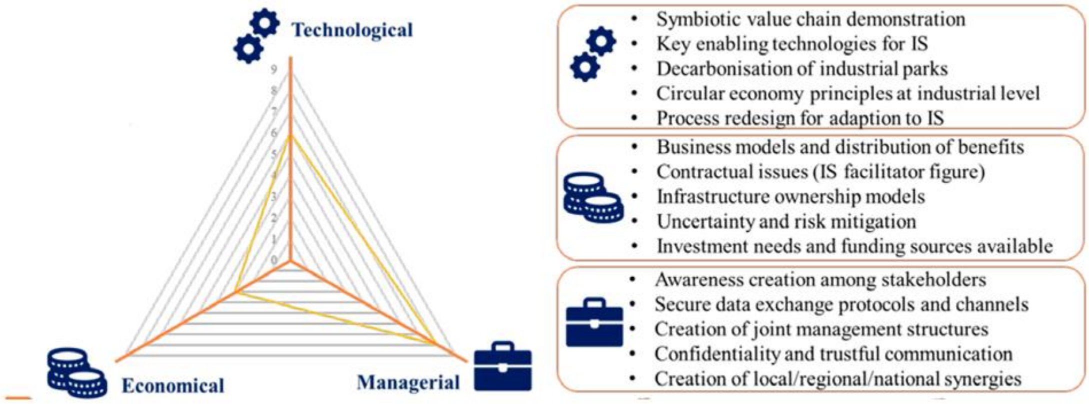

Figure 15: CORALIS triple perspective for IS readiness level.

Several industrial initiatives and case studies highlight the practical application of IS principles. RINA-CSM, as facilitator of the Italian demo-case, helped with the exchange of materials and information. In addition, different pilot plant tests have been performed to analyse the behaviour of briquettes (carburization of metal bath, yield, risks etc.). In Torbole the recovery of metals and sand from sandblasting operations is combined with the exploration of biochar as a substitute for anthracite or graphite. However, complex authorization processes present challenges for biochar usage, when it is not classified as commercial product but is a residue of thermal process. At ORI Martin, briquettes composed of metal scales underwent industrial testing, although authorization delays for materials like sludge and fumes slowed progress. At Raffmetal, efforts focused on metal recovery and heat valorisation in secondary aluminium production, identifying key parameters for syngas generation and energy development during pyrolysis. At Feralpi, a deep experimentation has been done to generate ferroalloy and synthetic slags from inert and LF slag and silica residues and to valorise the metallic oxides from rolling mill scale, EAF dust, scales and sludge, currently landfilled.
The project achieved significant technical milestones. Briquette compositions were defined for industrial use or ferroalloy generation, and systems for sand-metal separation and aluminium heat recovery were designed. It emphasized the importance of uniform technology levels among IS participants and highlighted the need for financial support to encourage adoption.
Lessons learned from the CORALIS project underline the complexity and time-consuming nature of authorization processes, although collaboration agreements among IS participants were generally straightforward. Financial and legal challenges remain significant barriers, underscoring the need for supportive frameworks to facilitate the widespread implementation of IS practices. In general, the social acceptance of IS are very good, as the sensibility to the environmental topics has increased a lot during the last years.
The reached technical targets were:

- definition of briquettes composition suitable for industrial use (metal part or oxides recovery)
- design and implement a system for sand/metal separation and reuse of sand
- design a plant to recover metallic aluminium and heat

Project Title	Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis
Acronym	CORALIS
Grant Agreement No.	958337
Funding Program	Horizon 2020
Project Duration	01|10|2020-31|03|2025

Exploring the effects of the use of alternative carbon-bearing materials in EAF through dedicated simulations

Ismael Matino[1], *Valentina Colla*[1], *Orlando Toscanelli*[1], *Antonella Zaccara*[1], *Aintzane Soto Larzabal*[2,3], *Asier Zubero Lombardia*[3], *Jon Hermosa*[3]

[1] Scuola Superiore Sant'Anna, Via Moruzzi 1, 56124, Pisa, Italy,

[2] Sidenor I+D, Bilbao, Spain,

[3] Sidenor Aceros Especiales, Bilbao, Spain

Abstract. In the context of the decarbonization of the electric steelmaking route to contribute to the achievement of the Green Deal objectives, the replacement of fossil C-bearing materials is envisaged as one of the promising solutions. It is expected, indeed, that using alternative non-fossil materials significant amount of CO_2 emissions can be avoided. However, although some first research studies of the use of renewable (e.g. biomass/biochar) and alternative (e.g. tires) C-bearing materials can be found in literature already in the first years of 2000, there are still unknown aspects that require dedicated investigations. Therefore, this is one of the aspects addressed in the project GreenHeatEAF. Both, industrial pilot trials and simulation tests are envisaged in the project.

Simulation is considered a powerful tool for exploring a vast area of scenarios to investigate the effects of the use of these materials in the electric arc furnace (EAF). For this reason, a previously developed model simulating the whole EAF scrap-based production route was firstly enhanced to manage the use of alternative C-bearing materials in EAF and afterwards used for different kind of scenario simulations and sensitivity analyses. In addition, knowing that biomass features are often unsuitable for direct use in metallurgical processes, some upgrading processes were modelled. The aim of this modelling work is to explore the possibility of integrating these processes in electric steelworks to both recover available heat and decrease steelworks dependence on an emerging market (i.e. biochar market) which is expected to rise (with consequent costs increase) in the future. An overview of the models and the simulation results is provided.

The GreenHeatEAF project investigates the potential of replacing fossil carbon-bearing materials with alternative non-fossil materials in EAF. This aligns with the European Green Deal's decarbonization targets and aims to reduce fossil CO_2 emissions.

It was pointed out that digital simulations complement industrial trials by minimizing disruptions to standard production plans, exploring broader testing scenarios, and supporting effective planning, monitoring, and predictive control strategies. The flowsheet model used in these simulations replicates the entire scrap-based EAF steelmaking process, including stages such as melting, oxidation, tapping, refining and heat exchange.

The first version of the flowsheet model was developed in Aspen Plus during the EIRES RFCS project and gradually refined and upgraded within different projects. The main involved steps and considered phenomena are:

- sum of effects in terms of both mass and energy flows, chemical and physical balances, reactions as well as thermodynamic equilibria and transformations.
- Aspen Plus internal and customized unit blocks are combined with ad-hoc calculators and design specs units to reproduce the various phenomena involved (e.g. melting, oxidation, tapping, refining, degassing, heat exchange).

The model is easily adaptable and transferable. Tuning, validation, and testing are performed on different steel grades and steelworks, e.g. Sidenor. Generally, industrial data related to some thousand sheets are used.
The flowsheet model allows for the simulation of scrap-based EAF steelmaking routes until the start of continuous casting and the effects of changing operating conditions and feeds. It enables computing and monitoring the evolution of main process parameters during the different process steps like temperatures, liquid steel and slag amount as well as composition, energy exploitation, CO_2 emissions and efficiencies.
Among the model improvements carried out within GreenHeatEAF, some of them are finalized to manage the use and injection of novel energy and carbon sources, e.g. biomass, biochar, and evaluate related effects. Moreover, biomass upgrading opportunities were investigated. Both literature and real industrial data, i.e. supplier data on alternative carbon carriers and real industrial data concerning preliminary trials of using biochar introduced in Sidenor EAF were exploited to improve the model.
Various simulation scenarios have provided insights into the feasibility of alternative carbon sources. In one scenario, the partial replacement of fossil carbon with materials like tires and biochar was tested. Tires contributed high chemical energy but increased sulphur content, while anthracite produced higher CO_2 emissions than biochar. Another scenario focused on a sensitivity analysis of biochar properties, such as fixed carbon, sulphur and moisture content, revealing near-linear correlations between key parameters and biochar composition. A third scenario demonstrated the feasibility of fully substituting fossil carbon with biochar, showing no significant deviations in process or product performance.
Industrial trials within the GreenHeatEAF project further evaluated alternative materials. Tests with plastics revealed that while they provided carbon, they compromised slag foaming and raised safety concerns due to elevated temperatures and fumes during 100% plastic usage. Trials with tires indicated lower slag foaming performance than coal, with increased mixture ratios triggering alarms because of heightened fume temperatures. These trials underline both the potential and the challenges of integrating alternative materials into EAF steelmaking.
All in all, flowsheet models and simulations are useful to explore uncertainties arising when changes in standard procedures are investigated within electric steelmaking, e.g. replacement of fossil C-bearing materials. From the simulation side, the use of SCC does not show significant critical effect neither on the process nor on liquid steel quality. No significant deviations are observed in energy consumption, while a significant reduction of fossil CO_2 can be obtained.
However, from the industrial trials side, using alternative C carriers does not negatively affect some process or product parameters, but a high ratio of SCC can compromise the safety of operations and lead to poor slag foaming. The main result is that the use of biochar seems to have no critical effect on the liquid steel quality and no significant deviations were observed on energy consumptions. Other effects of the use of the considered alternative C-bearing materials are still unclear and under investigation. To conclude, simulation and industrial trials are complementary in providing useful information to understand the advantages and drawbacks of using alternative C carriers in EAF and creating guidelines for their extensive usage.

Project Title	Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO_2 decrease
Acronym	GreenHeatEAF
Grant Agreement No.	101092328
Funding Program	Horizon Europe
Project Duration	01|01|2023-30|06|2026

BioCoDe: Biomass for cokemaking decarbonization. Objectives and first project results

Angelo Sorino[1], Alessandro Vecchio[1]

[1] Acciaierie d'Italia, Via Appia SS km 648, Taranto, 74123, Italy

Abstract. Reducing industrial CO_2 emissions and decarbonisation of hard-to-abate industry are two of the main priorities of the European Green Deal. In this context, the BioCoDe project addresses the key

challenge of decarbonising the steel industry by partially replacing the fossil coal currently used in the coke production process with up to 10% C-neutral biomass or biochar from the local agroforestry or wood sector. BioCoDe aims to demonstrate the first industrial-scale replacement of fossil feedstock with biomass/biochar, including activities at different scales from laboratory screening to a large experimental pilot campaign and validation with industrial trials at the Acciaierie d'Italia cokemaking plant in Taranto, Italy. In the BioCoDe project, biomass/biochar will play a crucial role as a secondary carbon carrier that can enable the sustainability of the industrial process, while establishing biomass as a reliable, green and convenient raw material for lower emission coke production, promoting the principles of the circular economy and fostering local and European synergies between agriculture and industry. The project includes a detailed study of biomass characteristics, not only from a physico-chemical perspective, but also in terms of availability for application in large quantities in industrial processes; and the study of product and by-product changes, as well as plant adaptation related to the proposed solution.
The BioCoDe project will pave the way for a more sustainable steel industry by validating the benefits of such a circular approach to the decarbonisation of the steel production process, considering the main critical aspects of biomass availability at local level and its influence on coke quality.
During the first year of the project, the most readily available biomasses in the Taranto area were identified and procured. These biomasses were chemically and physically characterized and tested, through specific technological assessments, as additives to the fossil mixture to predict their behaviour in subsequent coking tests. The evaluation of the impact of thermal and mechanical pre-treatments, aimed at maximizing the biomass substitution rate within the fossil mixture, is currently underway.

The BioCoDe project aims to reduce CO_2 emissions in integrated steel production by introducing biomass and biochar into the cokemaking process. The project's innovative approach integrates up to 10% biomass into the fossil mix in industrial coke ovens, contributing to decarbonization and fostering local economic development. The goal of this project is to validate biomass integration on an industrial scale (TRL 7). The structured project approach begins with the selection and characterization of biomass or biochar (cf. Figure 16), followed by laboratory-scale testing, pilot-scale testing using coke ovens of varying capacities (10 kg, 60 kg, and 300 kg), and finally, industrial-scale testing to validate the best-performing solutions.

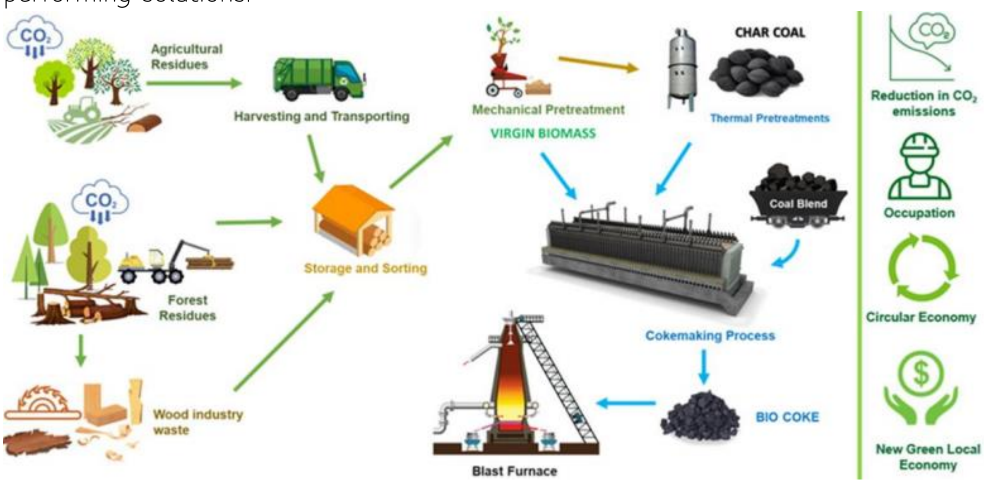

Figure 16: Schematic overview of BioCoDe project.

Biomass characterization focused on various types (see Figure 17), including wood waste such as pallets and fruit boxes, agroforestry residues like olive branches and pine, and transformation process residues like olive pomace.
Analysis revealed that biomass generally has higher volatile matter but lower fixed carbon and calorific value than coal. Some biomasses contain high alkali and phosphorus levels, which are undesirable for

cast iron production. Based on these findings, only four types of biomasses: pallets, pine, olive logs, and wooden boxes were deemed suitable for cokemaking. Pre-treatments like torrefaction or carbonization were identified as essential to improving their properties.

Figure 17: Various types of biomasses for characterization.

For biochar characterization, three biochars derived from wood were selected, each produced through pyrolysis and gasification processes. Biochar A was obtained using pyrolysis at 480 °C, biochar B underwent a two-stage process involving pyrolysis at 380 °C and gasification at 1,000 °C, while biochar C was produced via pyrolysis at 600 °C. Among these, biochar B demonstrated the best performance, with a superior heating value of 21.66 MJ/kg and a fixed carbon content of 34.77%. Additionally, biochar B exhibited better thermal stability and lower levels of heavy metals, such as lead, compared to the other samples.
Thermogravimetric analyses indicate the thermal stability and degradation behaviour of each biochar. Biochar B, with its dual-stage treatment (pyrolysis followed by gasification), is more resistant to thermal decomposition, making it particularly suitable for high-temperature applications typical in coke production.
Using untreated biomass instead of hard coal can reduce the efficiency of coking, so thermal pre-treatment such as torrefaction or carbonization is required. The situation greatly improves with biochar, which has proven to be more suitable for the project's goal.
The next steps will be the preparation and characterization of biochar from selected biomass, followed by a pilot test campaign on an increasing scale before final use in the cokemaking cells at the Taranto steel plant.

Project Title	BIOmass for COkemaking DEcarbonisation
Acronym	BioCoDe
Grant Agreement No.	101112264
Funding Program	RFCS
Project Duration	01|07|2023-31|12|2026

Hard-to-abate? Our solution for the EAF route within the BioRECAST project

Viviana Negro[1], Alessio Riorda[1], Andrea Salimbeni[2], David Chiaramonti[1,2]

[1] Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino, 10129, Italy
[2] RE-CORD (Renewable Energy Consortium for R&D), Viale J. F. Kennedy, Scarperia e San Piero, Firenze, 50038, Italy

Abstract. Green steel is an EU priority and the de-fossilization of the steel sector is a major challenge due to the heavy reliance on fossil coal as an energy carrier and reducing agent for oxide ores. The aim of the BIORECAST project is to evaluate and validate the on-site conversion of residual biomass into biocoal and sustainable bioenergy that can be used as alternative sustainable fuels for the steelmaking process to increase the sustainability of the EAF process. The project focuses on the

carbonization of widely available biomass and biowaste streams (i.e. sewage sludge, woody biomass and agricultural residues) by means of an optimized slow pyrolysis process. Afterwards, the produced char is then subjected to a chemical leaching process to simultaneously remove contaminants that can affect steel quality and produce inorganic components for soil application. In total, 3 tons of biocoal will be produced and tested in industrial scale EAF.
A further, important focus is on the integration of slow pyrolysis units in steel production facilities to ensure both heat integration through the reuse of the EAF waste heat and the utilization of the pyrogas either for direct energy generation in the EAF or for the sustainable generation of bio-electricity. In this project, mass and energy balance models will be developed to simulate the integration of a pyrolysis plant within a steelmaking facility. These simulations will assess the technical and economic feasibility of different configurations. This approach aims to maximise waste heat recovery, improve energy efficiency, and enhance the overall cost-effectiveness of the process, supporting the project's contribution to sustainable steel production.

The BioRECAST project aims to decarbonize EAF steelmaking by utilizing biowaste as a renewable energy and carbon source. It also seeks to valorise EAF waste heat, aligning with Europe's Green Transition objectives for the steel industry. The main objectives of the project are fostering the consumption of biowaste streams as renewable carbon and energy sources for the steel sector and, at the same time, valorising the waste heat of EAF steelmaking.
The BioRECAST framework leverages biowaste sources, including urban biowaste, agricultural residues, and industrial sludge, as feedstock for sustainable steelmaking. Through thermochemical conversion via slow pyrolysis, the process generates biochar, with a yield of 25-30%, and pyrogas, which constitutes approximately 70% of the output. These products have distinct roles: pyrogas are directly utilized for combustion or energy generation, while biochar serves as a carburization and reduction agent in EAF steelmaking.
Pyrogas applications are explored in two structures; the first (Figure 18 (left)), pyrogens are used for direct combustion through innovative burners to supply energy. In the second (Figure 18 (right)), it is employed as a source of bioelectricity and bioheat generation. To further enhance sustainability, the framework integrates the reuse of waste heat from EAF operations. Heat exchangers are designed to capture and recycle this heat, improving the efficiency of the pyrolysis process and reducing overall energy consumption.

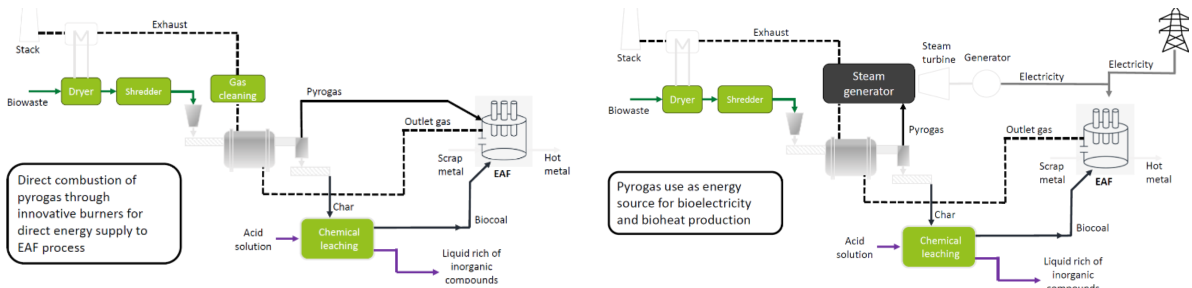

Figure 18: Pyrogas use in BioRECAST project: direct combustion of pyrogas in EAF burners (left) and pyrogas as energy source for bioelectricity and bioheat production (right).

Key findings from the project highlight the renewable potential of biocoal derived from biowaste as a viable alternative to fossil carbon. Pyrogas has shown promise as a bioenergy source for both combustion and electricity generation. Additionally, the integration of EAF waste heat significantly enhances the sustainability of the process.
This approach has a substantial economic and environmental impact. By integrating biocoal and pyrogens into EAF operations, significant reductions in CO_2 emissions can be achieved, potentially generating credits under the Emissions Trading System (ETS). This integration supports the circular economy by repurposing biowaste streams and aligning industrial practices with sustainability goals.

To conclude, the production of biocoal from bio-waste could be a key player in the green transition of steelmaking processes. Beside the environmental benefits of the solution, from an economic standpoint, this could be a game-changer. It opens the possibility of benefiting from credits associated with reduced CO_2 emissions in a sector covered by ETS. Nevertheless, further analysis will be conducted in the coming years to determine the optimal integrated solution.

Project Title	BIO-based Residues Conversion to Advanced fuels for sustainable STeelproduction
Acronym	BioRECAST
Grant Agreement No.	101112601
Funding Program	RFCS
Project Duration	11|2023-04|2027

Valorisation of biomass residues for sustainable steel production – EU RFCS project of BioReSteel

Chuan Wang[1]

[1] Swerim AB, 97125, Luleå, Sweden

Abstract. The transition of the European steel industry towards carbon neutrality is a critical aspect of achieving a more sustainable and environmentally responsible future. In this context, the BioReSteel project aims to develop a novel approach for utilizing biomass residues as a key carbon source in electric arc furnace (EAF) steelmaking, replacing traditional fossil fuels. This project focuses on addressing the challenges of sustainable steel production by valorizing hydrochar, a type of biocoal produced through hydrothermal carbonization (HTC), from wet biomass feedstocks.

BioReSteel's objectives include the exploration, development and testing of hydrochar as an alternative to fossil coal in EAF processes. By leveraging locally available biomass residues, the project envisions substituting up to 2% of Europe's fossil coal demand, leading to an estimated annual reduction of 2.5 million tons of CO_2 emissions. Additionally, the project integrates a circular economy approach by recovering phosphorus from biomass, which can be repurposed as a valuable fertilizer, contributing to the conservation of critical raw materials and the reduction of environmental contamination.

The project will involve a series of experimental studies, ranging from laboratory-scale tests to industrial EAF trials. These trials will assess the feasibility of using hydrochar in various stages of the EAF process, such as hydrochar injection and top-charging, while ensuring that the phosphorus content is minimized to acceptable levels for steelmaking. Furthermore, alongside technical assessments, the project will also perform life cycle assessments (LCA) and techno-economic evaluations to ensure the long-term viability and sustainability of the proposed solutions.

BioReSteel contributes to the broader goals of the European Green Deal and the Circular Economy Action Plan by reducing reliance on fossil fuels, lowering CO_2 emissions and optimizing the use of residual biomass. Through its interdisciplinary consortium of industry and research partners, the project is set to provide a significant step forward in decarbonizing the steel sector while addressing key sustainability challenges.

BioReSteel aims to replace fossil carbon in the electric arc furnace (EAF) with biocoal, produced from low-value locally available wet biomass residues employing hydrothermal carbonization process. The methodology of the BioReSteel concept (Figure 19) will be proved through laboratory and EAF testbed trials. Furthermore, the industrial EAF trials will be performed at three EAF plants to test hydrochar injection, hydrochar top charging, and bio-oxide agglomerates to prove the concept's flexibility and generality.

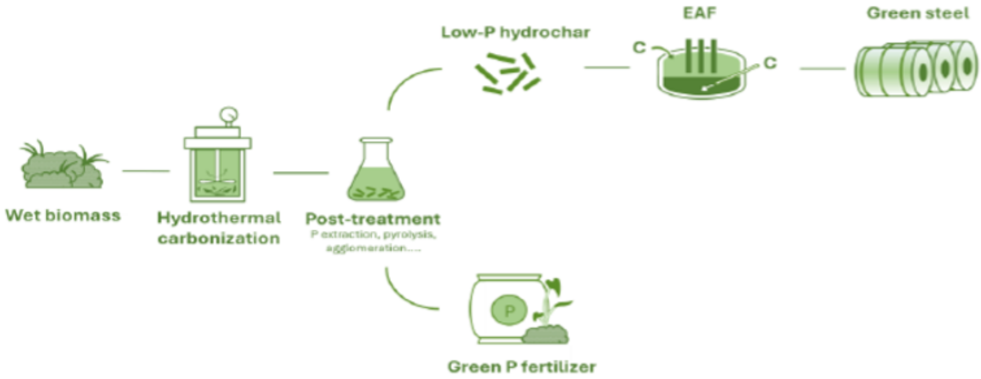

Figure 19: Value chain in BioReSteel project.

The BioReSteel project targets a 2.5 Mt/a reduction in CO_2 emissions across the European steel industry by replacing fossil carbon in EAF steelmaking with hydrochar derived from biomass. This substitution aims to reduce energy costs in EAF operations by 30% by replacing 50% of fossil fuels with biocarbon. Additionally, the project focuses on producing solid inorganic phosphorus-based fertilizers from biomass waste, contributing to both industrial and agricultural sustainability.
Hydrothermal carbonization is a central process in this effort, operating at moderate temperatures of 180–300 °C with subcritical water as the reaction medium. Compared to traditional pyrolysis, HTC offers significant advantages, including lower energy consumption, reduced pollutant generation, and the potential for nutrient recovery (e.g. nitrogen, phosphorus and potassium).
In EAF applications, hydrochar performs multiple functions. It serves as a heating agent, a carburizing material, and a reductant for self-reducing briquettes, while also enhancing slag foaming, a critical factor in steelmaking efficiency.
Laboratory and pilot trials conducted at Swerim AB involved a 10 t EAF and focused on hydrochar injection, top-charging hydrochar, and bio-agglomerates top-charging. Industrial trials extended this research to three large EAF plants (cf. Figure 20). At Pittini in Italy, a 150 t EAF was used for hydrochar injection. ORI Martin in Italy utilized an 85 t EAF to test top-charging hydrochar and mill-scale briquettes. CELSA in Spain employed a 150 t EAF to test top-charging hydrochar pellets.

Figure 20: Top charging of hydrochar pellet at EAF (150 t) of Pittini, Italy (left), top charging of hydrochar/mill-scale briquettes at EAF (85 t) of ORI Martin, Italy (middle) and hydrochar injection trials at EAF (150 t) of CELSA, Spain (right).

Key findings from the trials indicate that hydrochar is an effective substitute for fossil carbon in EAF steelmaking, delivering both environmental and economic benefits. Hydrothermal carbonization produces hydrochar that meets the required properties for EAF use, including high calorific value and low levels of impurities. Integrating biocarbon into the process supports circular economy principles by repurposing biomass residues, reducing waste and lowering dependency on non-renewable resources.

Project Title	Valorisation of wet biomass residues for sustainable steel production with efficient nutrient recycling
Acronym	BioReSteel
Grant Agreement No.	101112383
Funding Program	RFCS
Project Duration	01|10|2023-31|03|2027

List of abbreviations

a ....Year
ACI...................ACoustic Index
AS ....Alter coal Scenario
ASF..................Alternative Solid Fuels
ASR..................Automotive Shredder Residues
BAT ....Best Available Technology
BF ....Blast Furnace
BS.....................Benchmark Scenario
CCU.................Carbon Capture and Utilisation
CCUS ....Carbon Capture Utilisation and Storage
CHP.................Combined Heat and Power
COG ....Coke Oven Gas
CRI...................Coke Reactivity Index
CSP..................Clean Steel Partnership
CSR ....Coke Strength after Reaction
CTP..................Coal Tar Pitch
CY ....Carburization yield
DR....................Direct Reduction
EAF ....Electric Arc Furnace
ETS ....Emissions Trading System
EU ....European Union
FC ....Fixed Carbon
GHG ....GreenHouse Gases
GP.....................Gross Profit
HDPE ....High-Density PolyEthylene
HM ....Hot Metal
HTC ....HydroThermal Carbonization
I40 ....Resistance to Fragmentation
IS......................Industrial Symbiosis
ISPRA.............Italian Institute for Environmental Protection and Research
KL ....Kraft Lignin
KPI ....key performance indicators
LCA.................Life Cycle Assessment
M ....Million
MFA ....Material Flow Analysis
NGE................Next Generation Elements
NZE.................Net-Zero Emissions
ORC ....Organic Rankine Cycle
PAH ....PolyAromatic Hydrocarbons
PCB ....PolyChlorinated Biphenyls
PCDD ....PolyChlorinated Dibenzo-p-Dioxins
PCDF ....PolyChlorinated DibenzoFurans
PET ....PolyEthylene Terephthalate
PL.....................Pyrolytic Lignin
PP.....................PolyPropylene
PPW................Plastic Packaging Waste
PyCCS ....Carbon capture and storage by pyrolysis
R&D&I...........Research, Development and Innovation
RFCS..............Research Fund for Coal and Steel
RDI ....Reduction Degradation Index
RI......................Reducibility Index
RK....................Rotary kiln
SCC ....Secondary Carbon Carriers
SRA ....Secondary Reducing Agent
SRIA ....Strategic Research and Innovation Agenda
SRF.................Solid Recovered Fuel
TGA ....ThermoGravimetric Analysis
VM...................Volatile Matter
VOC ....Volatile Organic Compounds
WGR...............Waste Gas Recirculation
WP...................Work Package

Legal notice