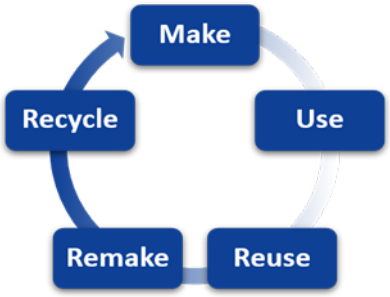
REPORT

4th ESTEP web-workshop "Resi4Future" - 11/2020

Residue valorisation in iron and steel industry: sustainable solutions for a cleaner and more competitive future Europe

08/02/2021

Mobilizing the industry towards a clean and circular economy represents a key element of the European Green Deal, in which the steel sector is a pillar of this strategy. **Circular economy** is one of the CO_2 mitigation pathways, while resource efficiency means an enhanced steel recycling (scrap use) and a reuse of by-products, as well as by-product exchange with other sectors.



During this 4-days web event in November 2020, technical solutions contributing to the overall goals defined in the Circular Economy Action Plan and the Green Deal of the European Union were presented.

In the workshop needs, best practices and innovative solutions was shared between 80 participants from Europe as well as from other parts of the world representing steel producing companies, universities, and RTO's. The four different sessions dealt with the following aspects:

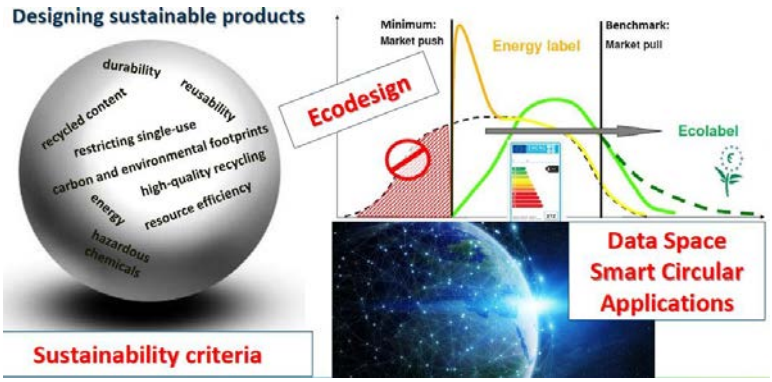
- Valorisation of residues
- Materials reuse with and recovery of metal and mineral phases
- Widening applications for slags from processes using DRI/HBI
- Carbon-rich residue streams as substitute reducing agent and energy source
- Life Cycle Assessment analysis
- Circular economy business models

Opening plenary section – EU Green Deal & Circular Economy & RFCS Project REUSteel
Chairman V. Colla

The 1st session comprised 5 presentations mostly covering general aspects related to by-products reuse and recycling in the steel sector and ongoing EU initiatives, which can support further research and development initiatives in this direction.

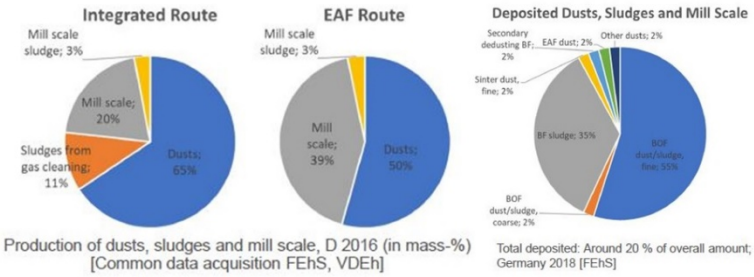
Aurelio Braconi from EUROFER introduced the European Green Deal (EGD) and the New EU Circular Economy Action Plan (CEAP), which was launched by the EU in 2020. The main actions, which are envisaged under the umbrella of the EGD were introduced, among which the new EU CEAP appears particularly significant for the steel sector, as it aims at introducing a sustainable product policy framework supporting the design of sustainable products,

empowering consumers and public buyers in the selection of "green" products, strengthening circularity in production processes, enhancing a waste policy oriented toward prevention, circularity and elimination of toxic compounds, enforcing a market for secondary raw materials. Steel fits well with this ambition due to its inherent properties and to the fact that the steel industry established circular practices since decades. Therefore the Sustainable Products Initiative can be an opportunity to get recognition and to create a market for green products, while the new approach toward waste policy can be an opportunity for co-generated streams. However, these opportunities needs to be materialised starting from CEAP content and the steel sector has already defined some priorities in order to be capable to fully exploit such opportunity. Digitalization and industry 4.0 are identified as enablers of CE.



Valentina Colla from SSSA presented the results of the ongoing RFCS dissemination project entitled *"Dissemination of results of the European projects dealing with reuse and recycling of by-products in the steel sector"*, REUSteel (GA 839227), which concerns the dissemination and valorization of the most important results on the reuse and recycling of by-products achieved in the last few decades in relevant EU-funded projects. The ongoing activities of REUSteel are based on an in-depth and critical integrated analysis of the projects and aim at results exploitation, according to the concepts of Circular Economy and Industrial Symbiosis by promoting the increase the reuse and recycling of by-products as well as the synergies between the steel industry and the other sectors. In addition, this analysis will allow defining the future research activities, taking also into account technical and non-technical barriers as well as future needs and ambitions of the EU steel industry. In the next few years, this will allow to move towards new aspects of research and the implementation of innovative solutions for improving the by-products reuse and recycling.

Gerald Stubbe from the VDEh Betriebsforschungsinstitut (BFI) presented an overview of solutions for metal recovery from iron- and steelmaking residues.
The residual materials, from which metals can be extracted were Sinter dust, BF gas dust and sludge, Converter dust and sludge, Mill scale sludge and EAF dust. The metals to be recovered

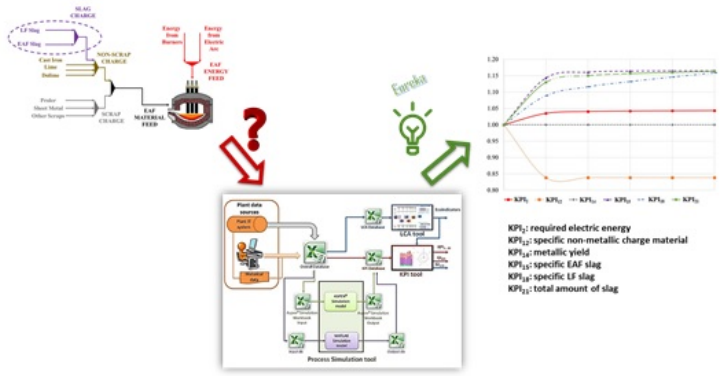


Production of dusts, sludges and mill scale, D 2016 (in mass-%) [Common data acquisition FEhS, VDEh]

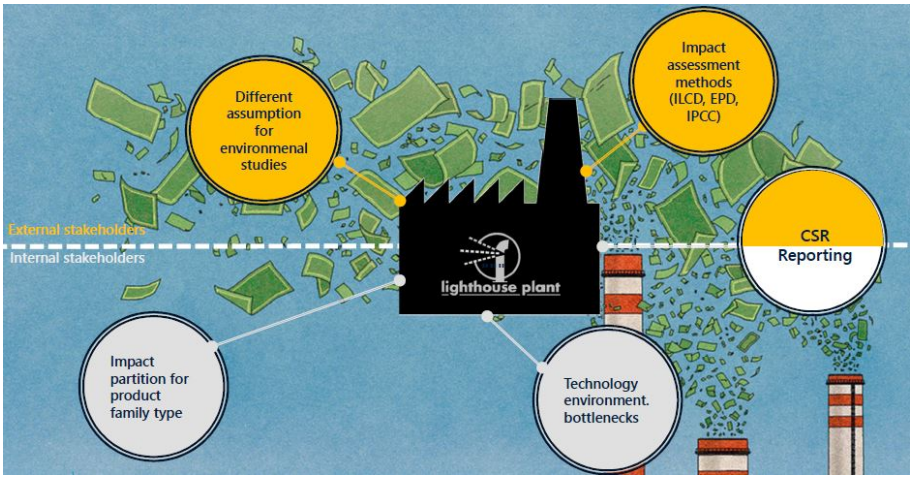
Total deposited: Around 20 % of overall amount; Germany 2018 [FEhS]

are mostly Iron and Zinc, but also alloying elements, which are relatively low in percentage, but hold a very high specific value. The evaluation criteria for recycling processes mostly concern metal yield, selectivity, specific energy and raw material consumption, specific space requirement, quantity and type of secondary residues as well as process-specific aspects. Several hydrometallurgical and pyrometallurgical processes are revised. The future requirements for residue valorisation/recycling processes mostly concern meeting of the zero-waste concepts and minimization of the CO_2 footprint.

The recovery, recycle and reuse of is sometimes hampered by lack of knowledge related to the consequences due to missing ad-hoc legislation or because pre-treatments need to be ad-hoc customized to obtain the desired recovery of materials. To solve the lack of this information and to help in decision making, simulation and optimization tools can provide significant support. Ismael Matino from SSSA presented a simulation tool and related scenario analyses, which allow evaluating the consequences of the internal reuse of slags in EAF. Moreover, the combination of different simulation and optimization tools were presented, which support the evaluation of BOF slag pre-treatment steps and optimization of the internal or external reuse of separated fractions with or without the combination with further by-products. The potential of these system lies in the possibility to make preliminary evaluations to address specific solutions before the real application, by avoiding waste of resources, efforts and undesired consequences.



Finally, Mr. Andrea Panizza from ORI Martin and Mr. Carlo Brondi from STIIMA CNR presented the outcome of the project Lighthouse Plant "Acciaio 4.0": In this project, an integrated system implements a real-time monitoring and control of an electric steelworks through plant digitalization and information exchange among machines and services. Machine learning is extensively applied to optimize the process.



Convolutional Neural Networks are applied for automatic classification of metal scrap to store it in dedicated areas divided by quality and supplier. A charge optimization model is also implemented. Finally, an on-line tool for dynamic environmental impact assessment is under development, which is connected to physical detection systems of environmental parameters

as well as to the company data inventory systems at different levels. The Lighthouse suite will be able to provide useful information for both internal and external stakeholders being fully aligned with the concepts of Circular Economy.

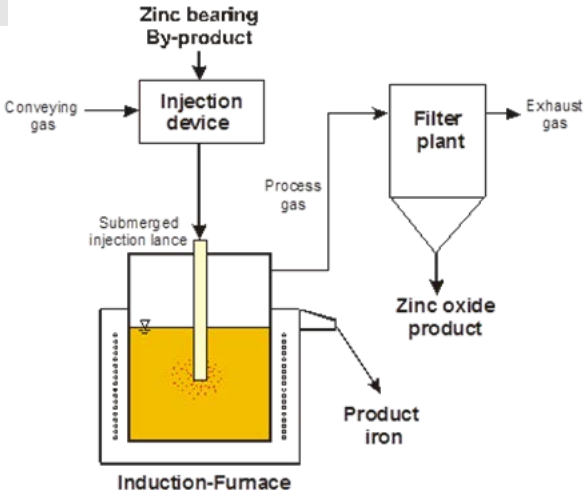
Internal residue recycling Session
Chairman E. Malfa

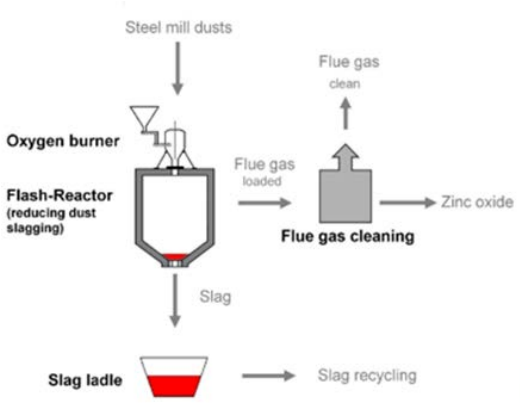
During the production of steel, large amount of residues in various forms (e.g. dusts, sludges and scale) are generated containing metal oxides. Existing processes for treatment and recycling (i.e. Waelz Process), which is used for recycling of more than 90% of steelmaking dust generated in Europe, generates a high volume of residues and it is therefore not suitable for a zero-waste approach. New treatment solutions need to be established to cope with limited landfilling capacities, increasing landfilling fees and the recent EU requirement for a closed circular economy.
Innovative recycling technologies based on different technological approaches for valorisation of these residues have been the focus of the session including both environmental and economic evaluation.

Pyro-metallurgic processes

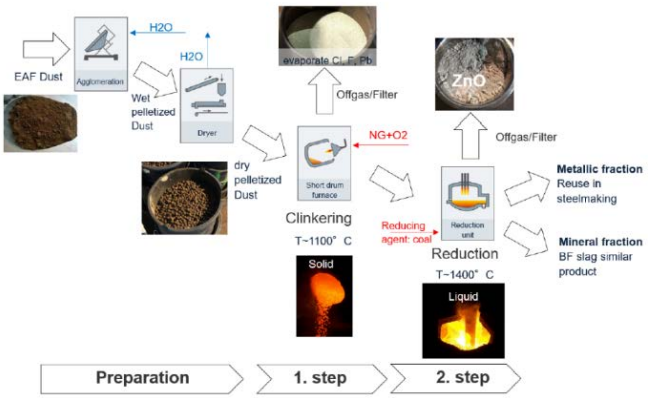
The Reclamet project presented the results obtained by Tata to recover both, the iron and zinc, through the HIsarna process In such a process, the preparation of the fine residues is a crucial step; therefore, micro-granulation, briquetting and extrusion have been applied in view of residue specific properties and the cost effectiveness of the process. The dissolution behaviours of the obtained briquettes and received scrap have been studied through pilot melting tests.

BFI research activities involve the melt bath injection of zinc and/or iron containing fine grained residues into an industrial scale induction furnace. Main aspect of the new technology is the injection of pneumatically conveyable, Zn- and Fe-bearing filter dusts via a submerged lance into the iron melt bath. The new injection technology has been built and implemented at an industrial 30 t-induction furnace, where operational trials leading to a very good zinc recovery and producing a high-quality zinc oxide product (> 60 % Zn content).





K1-MET with support of voestalpine Stahl and Montanuniversität Leoben, developed the RecoDust process ,in which BOF dust are processed pyrometallurgically. A pilot plant is operated at the Montanuniversität with a throughput of 300 kg/h, which transfers the iron content into a slag phase, which can serve as secondary iron resource for the sintering plant or the Blast Furnace (BF). The zinc content in slag should stay below 0.5 wt.-%. For upscaling to 1,000 kg/h, a new pneumatic conveying system was installed, which uses natural gas as conveying medium.



Primetals Technologies, ARP GmbH and Montanuniversität Leoben presented the 2sDR process based on a two-step approach. In a first step, fine EAF dust with a typical partial size below 5 µm is formed into small pellets with water and then dried to humidity below 6% to be charged into a drum furnace, where the halogens are vaporized by means of a natural gas burner at temperatures around 1100°C. In a second step, the clinkered dust is treated under reducing conditions in an electric arc furnace, were beside a high quality zinc oxide (ZnO), also a metallic fraction is generated, which allows a reuse in steel making as well as a mineral fraction, which can be used for construction industry. As a reducing agent, coal is injected into the furnace. The development of the 2sDR process has been finalized and successfully proven in lab scale and pilot scale testing.

<u>Leaching processes</u>

ArcelorMittal developed in collaboration with KU Leuven, first on lab-scale, subsequently on a small pilot level (TRL5), an ammoniacal process to reduce land-filling of Basic Oxygen Furnace (BOF) steelmaking sludge. The main advantage of the ammoniacal leaching procedure is its selectivity for Zn over Fe. NH_3 solution and $(NH_4)_2CO_3$ (salt) chemicals used for this leaching method are relatively cheap chemicals and they do not lead to corrosion of equipment (unlike the use of strong acids), thus offering favourable OPEX to the envisioned. That is the main difference with respect to traditional, acid-based processes. The cleaned, iron-rich residue can be fed to the BF representing major iron cost savings, while the zinc (76% yield) in the pregnant leach solution can be recovered as a zinc sulphide-precipitate product

Pictures: KU Leuven 1 L and 5 L reactors (left), Tecnalia 100 L reactor (centre) and Tecnalia filter press (right) used for intermediate upscaling steps

as a feed for the zinc industry. In the EIT Raw Materials project SAMEX, Tecnalia (Spain), ArcelorMittal (Spain) and KU Leuven (Belgium) will upscale the ammoniacal leaching process and the zinc recovery process to TRL7 aiming to engineer and build a pilot plant.

Mechanical processes

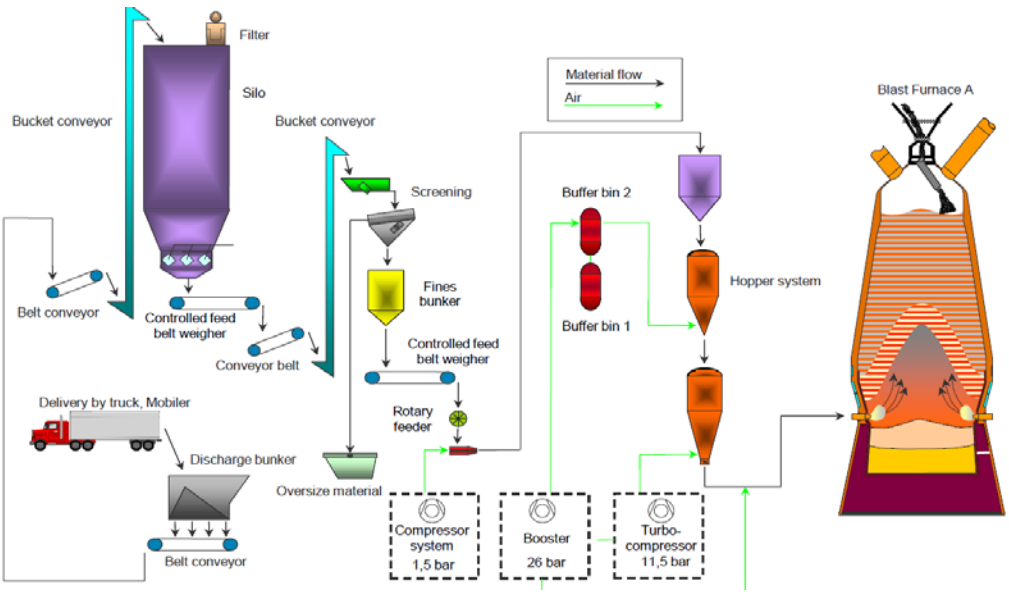
Cold-bonded briquetting offers a possibility to recycle fine-grained iron oxide containing residues. K1-MET (with the TU Freiberg and voestalpine Stahl as co-authors) presented the results obtained with an iron containing residue mixture from various fine fractions from the MIDREX® process, such as screened oxide fines and dried sludge. Two organic and one inorganic binder were used, which were pre swelled wheat starch, cellulose glue (pre-swollen and ground) and bentonite clay. Briquettes with the inorganic binder bentonite have poor reducibility and are therefore not suitable for use in the MIDREX® DR process. One chance to make a reuse possible could a combined use of bentonite and starch or cellulose as a binder remaining as a challenge for future investigations.

Secondary resources from non-steel sectors Session Chairman J. Rieger

The 3rd session comprised in total six presentations covering the aspects of alternative reducing agents and carbon substitution for primary steelmaking waste refractory treatment and industrial symbiosis.

Alternative reducing agents for the Blast Furnace process were in the focus of two contributions. A study was presented from RINA Consulting - Centro Sviluppo Materali regarding the gasification of waste plastic to generate a syngas as alternative reducing agent (partial substitution of coke and pulverized coal). It was found out that the syngas can substitute ~0.18 kg coke + pulverized coal per Nm^3 syngas.

Waste plastic can also be injected directly into the BF without being gasified before. This was part of a voestalpine Stahl contribution, in which densified waste plastics (pellets, granulate with grain size <10 mm) are injected into the BF via the tuyéres (see following Figure) with an injection level ~20-30 kg plastic per ton hot metal.



Furthermore, secondary resources from non-steel sectors can be used in the EAF. The German Bundesanstalt für Materialforschung und -prüfung (BAM) presented the possibility of using end-of-life carbon fibre reinforced polymers (CFRP) as alternative carbonaceous reducing agent in the EAF process. Batch trials were done at BAM, which showed that CFRP may be suitable as alternative carbon source.

Feralpi Siderurgica presented the concept of using briquetted automotive shredder residues (ASR) as well as other waste plastics as carbon substitute in the EAF. Briquetted ASR pieces (~3-5 cm length) were charged into the EAF via the basket. Beside this, an injection system was developed together with other partners for a charging waste plastic directly into the EAF. Good process stability and slag foaming was obtained.

Another approach of using resources from non-steel sectors was presented by Sidenor I+D focusing on the reuse of refractory waste in the steelmaking process focusing on EAF MgO-C bricks, high alumina bricks for the ladle as well as isostatically pressed bricks from the continuous casting (CC) plant.

Waste group	Product	Application
P1 MgO-C (Bulk)	New Product 1	EAF Gunning, Ladle top ring gunning, EAF Breast
	New Product 2	
	New Product 7	
	New Product 3	
P1 + P2	New Product 8	EAF Gunning
P2 MgO (Tundish masses)	New Product 4	EAF Gunning, Ladle top ring gunning
	New Product 5	
	New Product 6	

% Recycled material in 8 New Products ***UP TO 70 %***

Waste	Product	Application
High Alumina	New Product 1	Ladle top ring, ladle tapping spout, maintenance of the CC Cooling Chamber
	New Product 2	
	New Product 3	
High Alumina + Isostatics	New Product 4	
	New Product 5	
	New Product 6	
	New Product 7	
	New Product 8	

% Recycled material in 8 New Products ***UP TO 65 %***

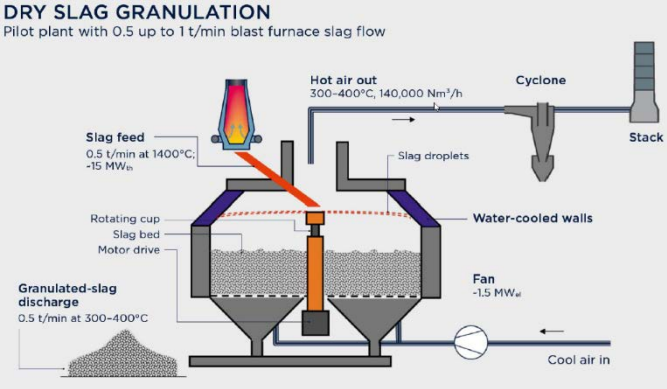
In two European funded projects, several application possibilities (waste refractories based on Magnesia and Alumina-base) were developed e.g. EAF gunning mass, or refractory for the ladle ring inducing recycling rates between 65-70% (see Figure on the left).

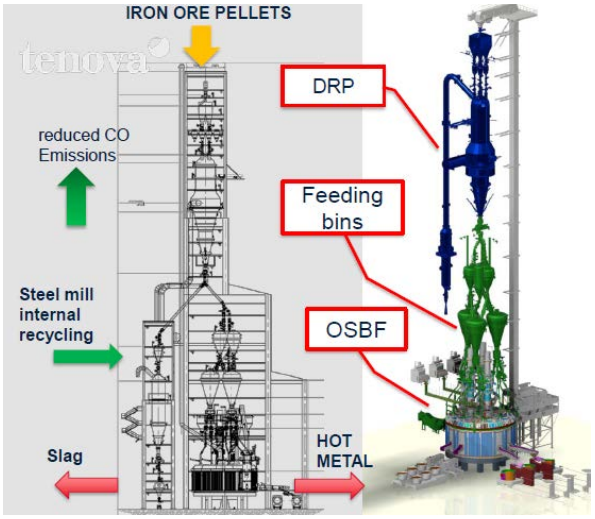
Using resources from non-steel sector follows the idea of industrial symbiosis (sector coupling). This was the focus of a contribution presented by RINA Consulting - Centro Sviluppo Materiali. The currently ongoing European funded project CORALIS (H2020 SPIRE Project, Grant Agreement no. 958337) will create new value chain relations through novel approaches facilitating long-term industrial symbiosis. Three industrial use cases will be studied within the CORALIS project. In the Brescia (Italy) case, a steel producer, a foundry, and a partner from aluminium industry cooperates to recover metal fractions from waste as well as possibilities to evaluate the use of the residue as secondary raw materials. Additionally, biochar utilization as carbon substitute will be investigated and waste heat utilization potentials will be analysed.

Slag valorization Session
Chairman A. Morillon

The 4th session comprised six presentations about different stages of slag development to meet requirements for external applications.

Thomas Fenzel (Primetals Technologies Austria) started the session and presented the final development step before the commercialization of the dry slag granulation technology. Primetals developed a dry granulation plant to produce slag with properties being similar or better compared to wet granulated slag. The plant has been tested in operational trials at 1.5 t/min slag flow with possibility to recover heat from BF liquid slag through steam generation.



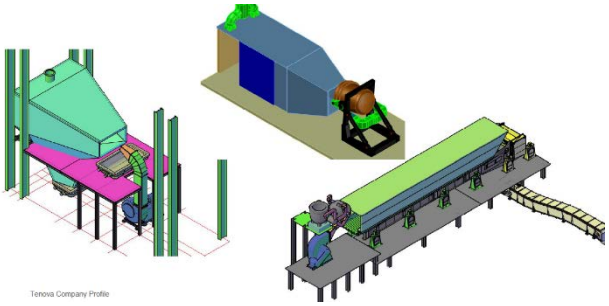


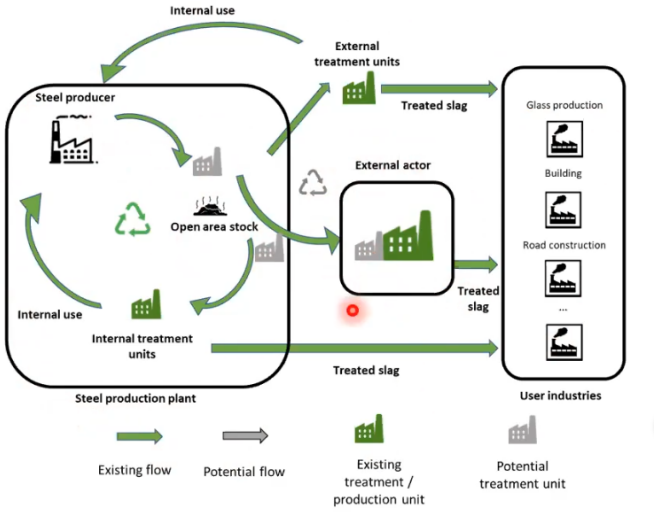
Marco Corbella and Paolo Stagnoli (Tenova) discussed the OSBF (Open Slag Bath Furnace) designed by Tenova to process low grade iron ore, while using 100% hydrogen as reducing gas. The OSBF has the same ability as a BF to run long continuous campaigns, but with higher flexibility (possibility to switch on and off). The OSBF process can produce a slag with the same or better quality then other furnaces resulting in a material, which can be valorised in concrete, cement, mortar or as aggregates.

David Algermissen (FEhS) discussed ongoing investigations to produce EAF slag that can be valorised in new applications e.g. cement, aggregate for concrete or blasting material, in anticipation of higher share of steel production going to EAF in Europe. In previous years, when EAF slag was investigated for use in cement industry, the need for too much energy and high amounts of treating agents limited the possibility. DRI based EAF slags have different properties, e.g. lower Cr opening up opportunities for EAF slag use in fields, which were limited for slag with higher Cr content.

Teresa Annuziata Branca (SSSA) discussed the use of BOF slag in agriculture in Italian soils, which are rich on alkalines and might have excess of sodium due to intrusions from coastal aquifers and irrigation with saline water. Column and lysimeter tests were conducted to assess the potential of slag. The results showed the positive effects of the slag on the investigated soil, e.g. BOF slag increased the cation exchange capacity of the soil, which resulted in higher nutrient retention. In lysimeter tests, the application of BOF slag showed replacement of Na ions with Ca ions in the soil, which resulted in higher tomato yield. The use of slag in agriculture will reduce natural resource exploitation and lead to cost reductions.

Marta Guzzon (Tenova) discussed wet and dry granulation technologies developed by Tenova to valorise steelmaking slag as green raw material. Tenova has experience in wet granulation of metal and slag, which guarantees fast cooling and high production rate but requires water treatment. Tenova dry slag granulation provides an opportunity to have no wastewater and reduction in costs with possibility to recover heat but can have limitations in the flow rate. The dry granulation can be conducted on-line or off-line. Tenova has different dry granulation solutions that can be adopted for specific needs for EAF or LF granulation, which result in production of amorphous materials.





Amin Falsafi (STIIMA-CNR) discussed a case study with five Italian scrap-based steel producers about solutions for the valorisation of LF slag in the lime value chain. In Italy, the LF slag apart from landfilling, is used as internal EAF feedstock for substitution of lime, for cement production and road construction. The challenges in using LF slag include legislation, technology, production rate, market, and economy. Exemplarily, technical challenges include volume instability, volatile composition, and disintegration. A new framework for the LF slag value chain was developed based on single steelmaker, collaboration, and regional perspectives.

Main area of activities and link with Clean Steel Partnership Road Map

The table below clusters the common topics that have been addressed during the webinar in the different contributions in three main areas and links these clusters with the Building Blocks of the Clean Steel Partnership Road Maps.

Area of interest	Key aspect and scope	Process /main topic	TRL	CSP link
Scrap	Yard management	Metal scrap tracking and handling by convolutional Neural Networks / industrial applications	9	***BB 6 – Raw material preparation***
Recovery of metal and mineral fraction from process residues	Recovery Zn and mineral fraction from filter dust	Pyro-metallurgic reducing processes: ✓HIsarna / raw material preparation ✓Induction Furnace / injection in the liquid bath ✓RecoDust / scale-up ✓2-step Dust Recycling (2sDR)	4-8	***BB 9 -CE*** Developing new processes to lower the demand for primary resources ***BB2 CO2-neutral iron-ore reduction*** Adjustment and processing of slag chemistry for H_2 metallurgy ***BB9 - CE*** ✓Conditioning the properties of the minor slag phases ✓Reduce landfill volume
	Recovery of Zn and mineral fraction from BOF sludge	Leaching processes: Ammoniacal leaching process / Upscale	5	
	Reuse of refractory waste	EAF and LF gunning / New products with magnesia and alumina base refractory waste	8	
	Slag valoristion	Slag processing Dry granulation / Ready for First Industrial Application Slag utilization ✓ EAF slag as blasting material and in asphalt / proven ✓ EAF-DRI slag in cement / lower Cr allow new opportunity ✓ LF slag in lime value chain / not yet solved - potential market but not yet developed ✓ BOF slag in agriculture / positive test in Italy	7	

Secondary carbon carriers	Polymers form waste plastic	<u>Gasification</u> to generate a syngas as alternative reducing agent (partial substitution of coke and pulverized coal in BF) / modelling <u>Charge as lump</u> in EAF bucket / ready for First Industrial Application <u>Injection as granulated</u> in BF and EAF / industrial applications	6-9	***BB 1- Gas injection technologies*** Development and demonstration of gas injection technology for the BF ***BB 3 – Melting*** Design of new solid raw material injectors for use of alternative material ***BB4 - Adjustment of today's production*** Use of slags in the cement industry ***BB 9 – CE*** Auxiliary reducing agent and slag foaming material
	End-of-life carbon fiber reinforced polymers	<u>Chare as lump</u> in EAF bucket / scale up of pilot testing	6	
	Automotive shredder residues	<u>Chare as lump</u> in EAF bucket / high substitution factor	7	
Digitalisation	Tools	<u>Monitoring</u> ✓ Slag reuse scenario analyses ✓ Dynamic environmental impact analysis (on-line LCA) <u>Simulation and optimisation</u> By-products pre-treatments evaluations Both require exploitation of R&D funded projects results	5	***BB 10 – Enabler*** **Design &** Development of a tool for continuous monitoring of the effects of circular approach/solutions on CO_2 emissions