

Special session on Industrial Symbiosis

Luleå-Sweden, 17:00-19:00 June 15 2026

SYMBIO STEEL

XIII European Slag Conference, Special Session on Industrial Symbiosis

Agenda

17:00-17:20 Industrial Symbiosis in the Steel Industry: guidelines and roadmap in by-products use from RFCS Symbio-Steel project

Speaker: Agnieszka Morillon, David Algermissen, FEhS

17:20-17:40 Analysis of relevant results, trends and perspectives of Industrial Symbiosis solutions

Speaker: Valentina Colla, Scuola Superiore Sant'Anna

17:40-18:00 KPI-Based Assessment of Industrial Symbiosis Solutions within the RFCS Symbio-Steel Project: Slag Recycling Evaluation

Speaker: Lina Kieush, K1-MET

XIII European Slag Conference, Special Session on Industrial Symbiosis

Agenda

18:00-18:20 Industrial Symbiosis between Biomass Processing and Steelmaking: Insights from the BioReSteel Project

Speaker: Chuan Wang, Swerim AB

18:20-18:40 Slag as the supply chain interface – biocarbon meets scrap and H-DRI

Speaker: Erland Nylund, Swerim AB

18:40-19:00 On Industrial symbiosis enablers: the importance of facing and solving technical and policy issues

Speaker: Daphne Mirabile, *RINA CONSULTING - CENTRO SVILUPPO MATERIALI SPA*



Industrial Symbiosis in the Steel Industry: guidelines and roadmap in by-products use from RFCS Symbio-Steel project

Agnieszka Morillon
David Algermissen, Valentina Colla, Teresa Annunziata Branca, Alice Petrucciani, Claudia Sergi, Daphne Mirabile, Filippo Cirilli, Lina Kieush, Johannes Rieger, Chuan Wang, Erland Nylund, Han Yu, Tova Jarnerud Örell, Delphine Snaet

SYMBIO STEEL

Symbio-Steel project title: **Fostering Industrial Symbiosis solutions for the steel sector by results monitoring and dissemination from national and EU funded projects coupled to definition of cross-sectorial synergy scenarios**

Coordinator: **Scuola Superiore Sant'Anna (Italy)**

Partners: **ESTEP – European Steel Technology Platform (Belgium)**
Institut für Baustoff-Forschung (Germany)
K1-MET GMBH (Austria)
Rina Consulting – Centro Sviluppo Materiali SPA (Italy)
Swerim (Sweden)

Duration: **October 2023 to September 2026**

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Objectives of Symbio-Steel project

- Identify and assess the most promising industrial symbiosis (IS) solutions developed in recent and ongoing national and EU-funded research projects for the steel sector.
- Promote the exploitation and wider adoption of successful research outcomes by disseminating best practices, technologies, and implementation of experiences across the European steel industry.
- Evaluate the contribution of IS to steel decarbonisation, resource efficiency, circularity, and next-generation low-carbon steelmaking pathways.
- Identify barriers, drivers, and cross-sector collaboration opportunities that can accelerate the implementation of circular solutions and IS networks.
- Develop practical guidelines and recommendations to support industry stakeholders in scaling IS solutions and fostering sustainable value chains.



Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Approach of Symbio-Steel project

- **Monitor Research Outcomes**
  - Collect and review results from recent and ongoing EU-funded and national projects related to IS in the steel sector
  - Identify the most promising technologies, practices, and valorisation pathways
- **Assess Industrial Relevance**
  - Critically evaluate technical maturity, environmental benefits, and implementation potential
  - Analyse future challenges arising from steel decarbonisation technologies
- **Engage Stakeholders**
  - Gather insights from steel producers, researchers, technology providers, and by-product users
  - Identify barriers, opportunities, and future industrial needs
- **Develop Cross-Sector Synergies**
  - Explore opportunities for collaboration between steel, cement, construction, chemical, energy, and recycling industries
  - Promote IS and circular material loops
- **Deliver Guidelines & Roadmaps**
  - Define recommendations for future by-product utilisation
  - Establish research priorities and strategic roadmaps supporting a low-carbon and circular steel industry



Symbio-Steel transforms research results into practical guidelines for IS, enabling the sustainable use of by-products in a decarbonised steel industry

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Impact of Symbio-Steel project

- Raise awareness of IS opportunities
- Accelerate transfer of research results into practice
- Strengthen stakeholder engagement and collaboration
- Support evidence-based industrial and policy decisions
- Promote adoption of circular and low-carbon solutions



Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Future challenges for IS in decarbonised steelmaking

- As European steel industry is transitioning toward climate-neutral production new steelmaking technologies are changing material and energy flows
- IS remains essential for circularity and resource efficiency
- Existing IS networks depend on stable by-product streams and established partnerships

It is essential that during decarbonisation of the steel industry IS is preserved and strengthened to ensure a low-carbon, resource-efficient steel ecosystem



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Technologies driving the transition

Technology	Main Benefit
Hydrogen-based DRI + EAF	Low-carbon ironmaking
Increased Scrap-Based EAF	Reduced primary raw materials
Smelting Reduction Routes	Utilisation of lower-grade ores
Hydrogen Plasma Smelting Reduction	Fossil-free reduction pathway
Iron Ore Electrolysis	Direct electrified iron production
BF + CCUS	Reduced emissions from existing BF assets

- **By-product Variability**
  - Changes in slag composition and mineralogy
  - Different quantities and qualities of dust and sludge
  - Altered energy and gas streams

  Reduced predictability for downstream users
- **Quality Assurance**
  - Need for advanced characterization
  - Real-time monitoring and predictive modelling

  Maintaining trust and reliability across value chains
- **New Processing Requirements**
  - New treatments of residues
  - Management of trace metals
  - CO2 capture and storage
  - Development of scalable and energy-efficient conditioning technologies

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Guidelines

VERIFY

- Assess whether future by-products can continue to be used in established applications
  - Examples for slags: cement production, aggregates, road construction, metal recovery, fertiliser
- Questions:
  - Are technical properties maintained?
  - Are environmental criteria still met?

ADAPT

- Develop treatment and conditioning solutions when specifications change
  - Potential actions:
    - stabilization
    - granulation
    - metal removal
    - carbon reduction and/or particle size optimisation

INNOVATE

- Identify new valorisation pathways
  - Potential opportunities:
    - advanced construction materials
    - mineral recovery
    - carbon capture integration
    - novel industrial symbiosis partnerships

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Priority areas for future research

Slag

- Characterisation under new steelmaking routes
- Treatment technologies
- New market applications

Dust & Sludge

- Recovery of Fe and Zn
- New recycling routes
- Adaptation to increasing EAF production

Energy, Gas & Water Streams

- Circular resource management
- Cross-sector utilisation
- Industrial cluster integration

Digitalisation

- Real-time monitoring
- Quality prediction
- Traceability systems

Reliable and market-ready by-products despite changing production technologies

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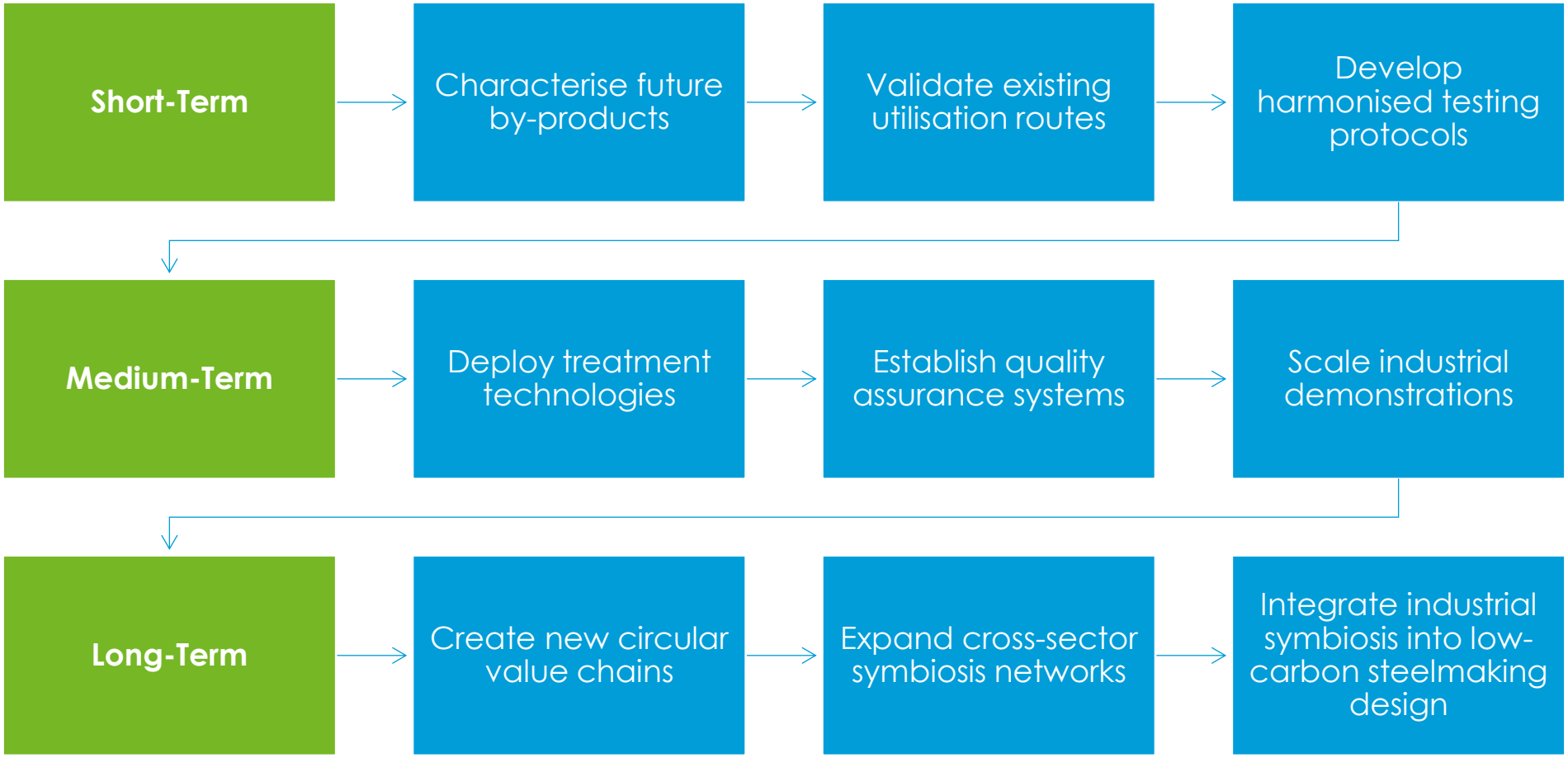
Building future IS networks



IS should not be viewed as a by-product management activity, but as a strategic component of future low-carbon steelmaking

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The Symbio-Steel workshop

Trends & Perspectives

SymbioSteel survey involving stakeholders

KPI-Based Assessment

Quantifies environmental, technical, and economic benefits

Supports investment and implementation decisions

Integration of biomass and steelmaking

Insights from the BioReSteel project

Material Flows

Slag as the interface between biocarbon, scrap, and H-DRI

Enablers & Policy

Technical and policy conditions for deployment

Regulatory frameworks influence adoption

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Analysis of relevant results, trends and perspectives of Industrial Symbiosis solutions

V. Colla[1], T. A. Branca[1], A. Petrucciani[1], A. Morillon[2], D. Algermissen[2], C. Sergi[3], D. Mirabile[3], F. Cirilli[3], L. Kieush[4], J. Rieger[4], C. Wang[5], E. Nylund[5], H. Yu[5], T. Jarnerud Örell[5], D. Snaet[6]

[1]Scuola Superiore Sant'Anna, TeCIP, ICT-COISP, Pisa, Italy, [2]FEhS Institut fuer Baustoff-Forschung e.V., Duisburg, Germany, [3]RINA CONSULTING - Centro Sviluppo Materiali SPA, Castel Romano, Italy, [4]K1-MET GmbH, Linz, Austria, [5]Swerim, Lulea, Sweden, [6]European Steel Technology Platform ASBL, Brussels, Belgium

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Contents



- The Symbio-Steel project
  - Main objectives
- Stakeholders' Consultation
  - The main aim
  - The survey
  - Final achieved results
- Results, trends and perspectives of Industrial Symbiosis solutions
  - Conclusions

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The Symbio-Steel project



The main Objectives

- Symbio-Steel focuses on the current state, upcoming techniques, and developments of Industrial Symbiosis implementation, to reach proactive cross-sectorial cooperation and integrations.

Overall objective

- Paving the way to a wider uptake of Industrial Symbiosis solutions in the steel sector, exploiting and spreading knowledge on most promising and available results, supporting synergies with other industrial sectors.

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Stakeholders' consultation

The main Aim

- gathering information on possible solutions to **improve the synergies** already existing, but also to get **new ideas** for the development of **new symbiosis scenarios**, potentially involving new industrial or civil sectors.



- entailing the engagement and involvement of **all relevant stakeholders** to understand their needs, difficulties and barriers to create and promote effective connections, to gather their experience as a lesson for stakeholders new to the topic.

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Stakeholders' consultation



Promoting an effective use of all the knowledge acquired by determining **gaps**, **barriers**, and **challenges** which can hinder or slow down the development of new **Industrial Symbiosis scenarios** between **multiple industrial sectors**

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Stakeholders' consultation



The Survey

- Consultation and connection of the main actors of the Industrial Symbiosis activities **inside** and **beyond the steel industry**



- The active consultation through the compilation of a tailored survey necessary to identify the **present status**, **gaps**, **boundary conditions** and **future opportunities**

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Stakeholders' consultation



The Survey

- was converted into a digital form thanks to the online platform **SurveyMonkey®** and was spread (in the form of link and QR code) to the steel community through the network of all partners and during different events:

  - ESTEP Spring Dissemination in Krakow
  - Swerim Recycling Day (online)
  - ESTAD (European Steel Technology and Application Days) in Verona
  - ESTEP Annual Event in Udine
  - ESTEP Spring Dissemination in Bruxelles

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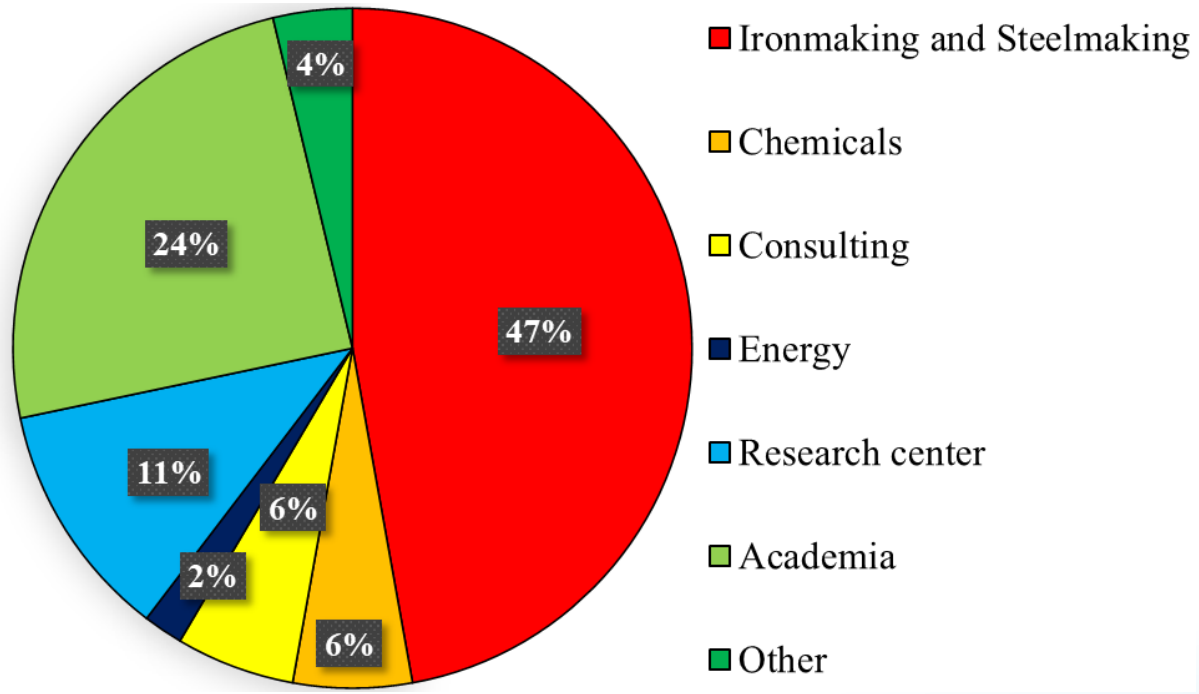
Stakeholders' consultation

Final achieved results

- The main sectors in which the participants in the survey operate



- Ironmaking and steelmaking industry (47 %)
- Academia (24 %)
- Research organizations (11%)
- Other (e.g. technology providers) (4%)

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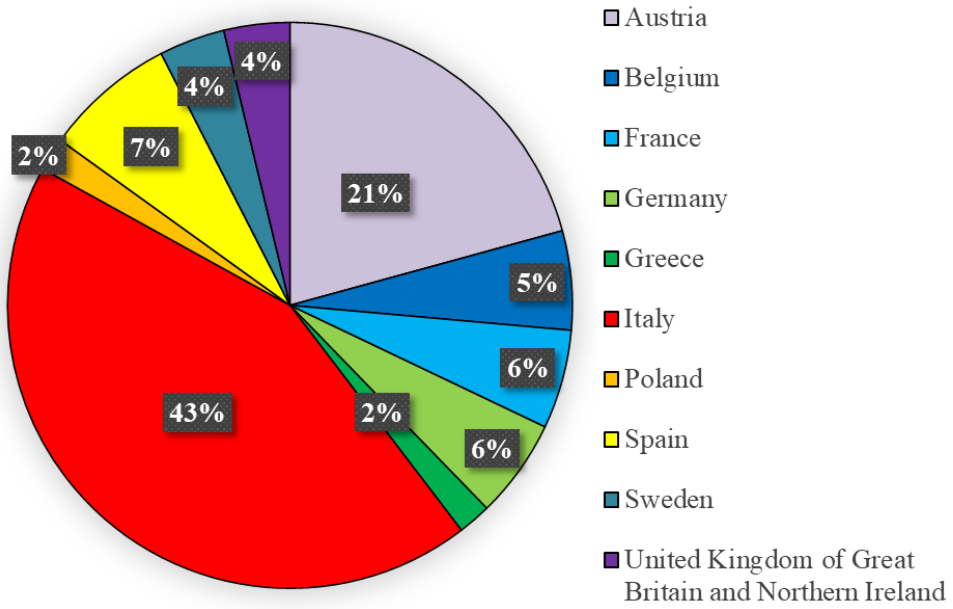
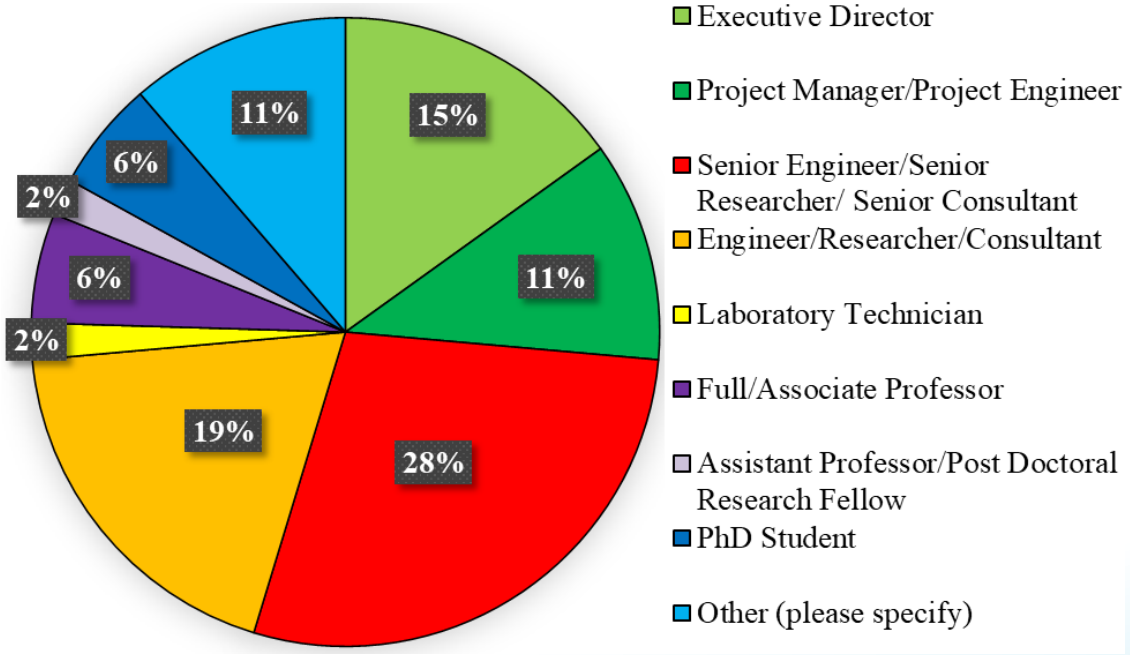
Stakeholders' consultation

Final achieved results

- The country of the participants



- The main job roles of the participants



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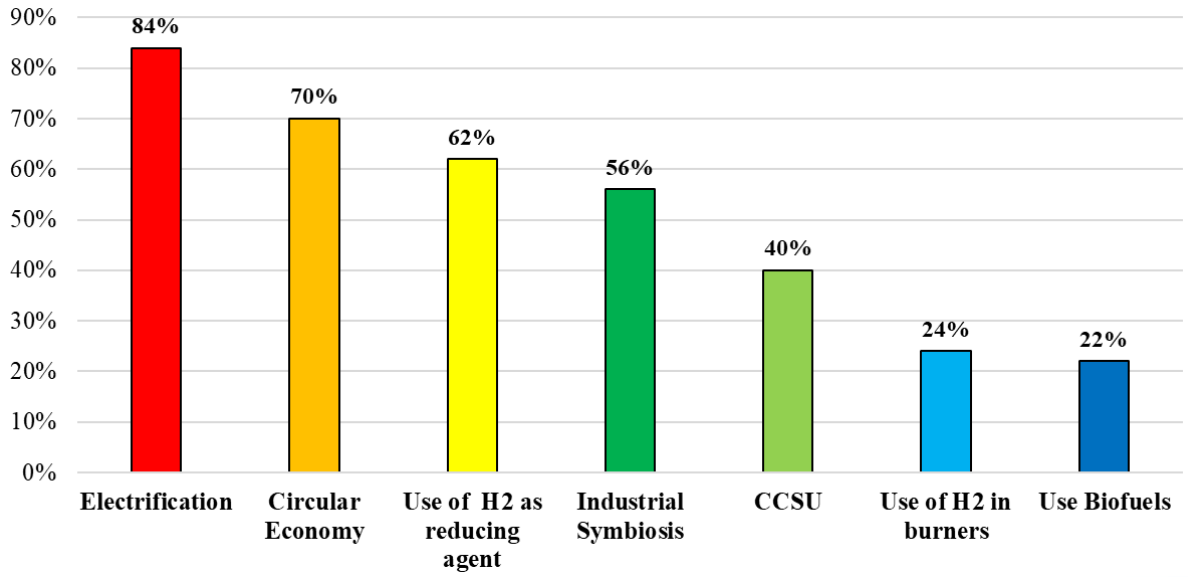
Stakeholders' consultation

Final achieved results

- Ranking of the **technological innovations** perceived as main decarbonization drivers in steelmaking in the next decade



- **Electrification**
  → the most promising technological innovation
- **Circular Economy** and **Industrial Symbiosis**
  → the strategic role of Symbio-Steel
- **Use of Hydrogen both as reducing agent and as fuel in burners**
  → the paramount role played by European initiatives (e.g. Hybrit pilot plant, Hydra project)
- **Carbon Capture, Storage and Utilization (CCSU)**
  → a viable decarbonization strategy

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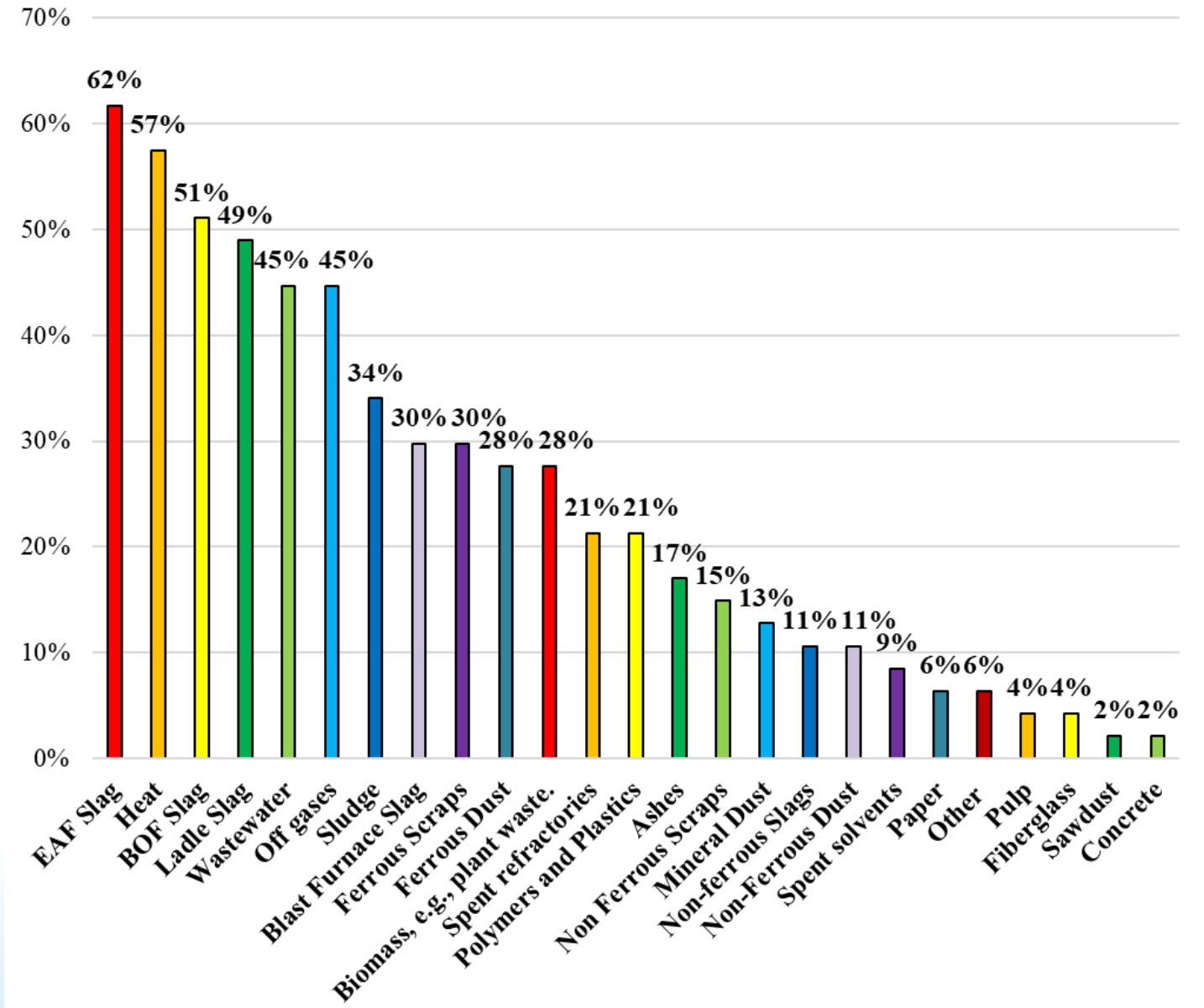
Stakeholders' consultation

Final achieved results

Ranking of the **underutilized resources** in the organization/company of participants

→ Slags are perceived as the most critical ones



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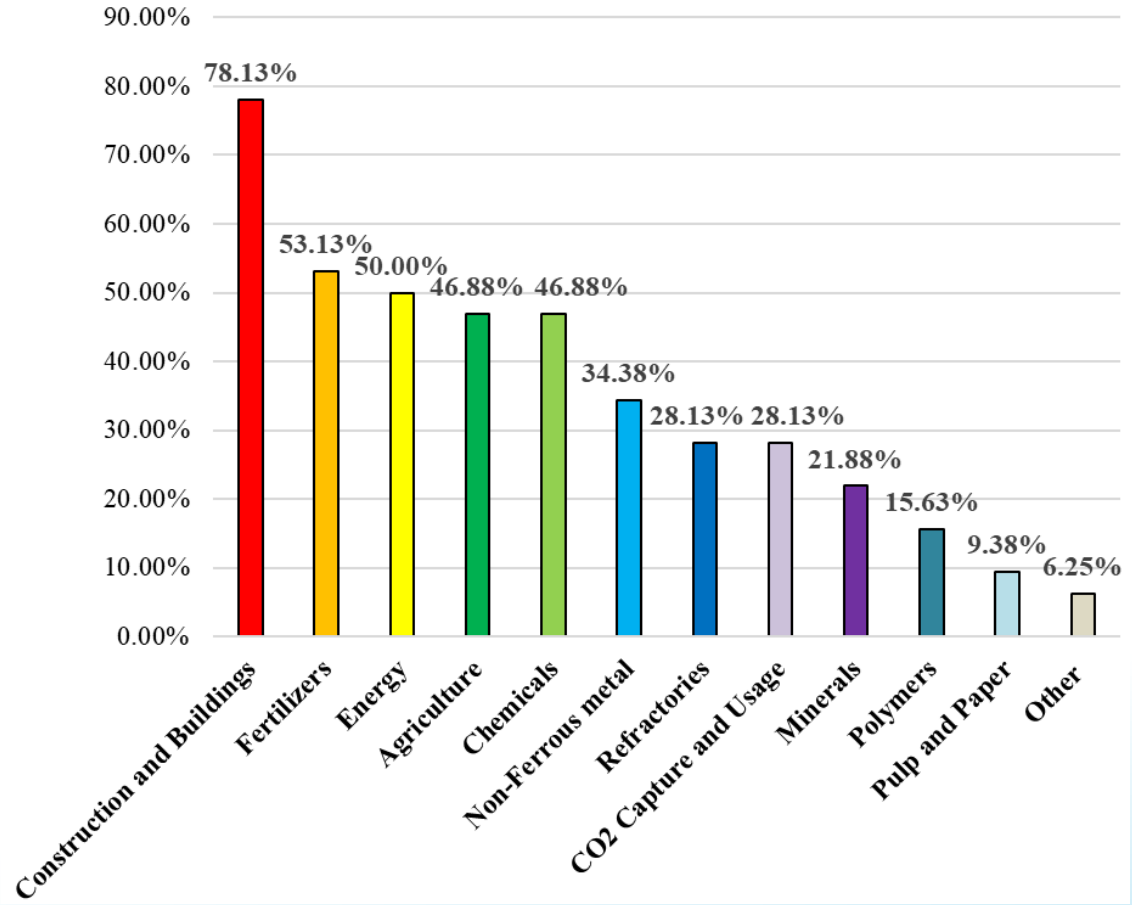
Stakeholders' consultation

Final achieved results

- Ranking of the **industrial sectors** which are considered more interesting to employ the underutilized resources identified within steel shops.



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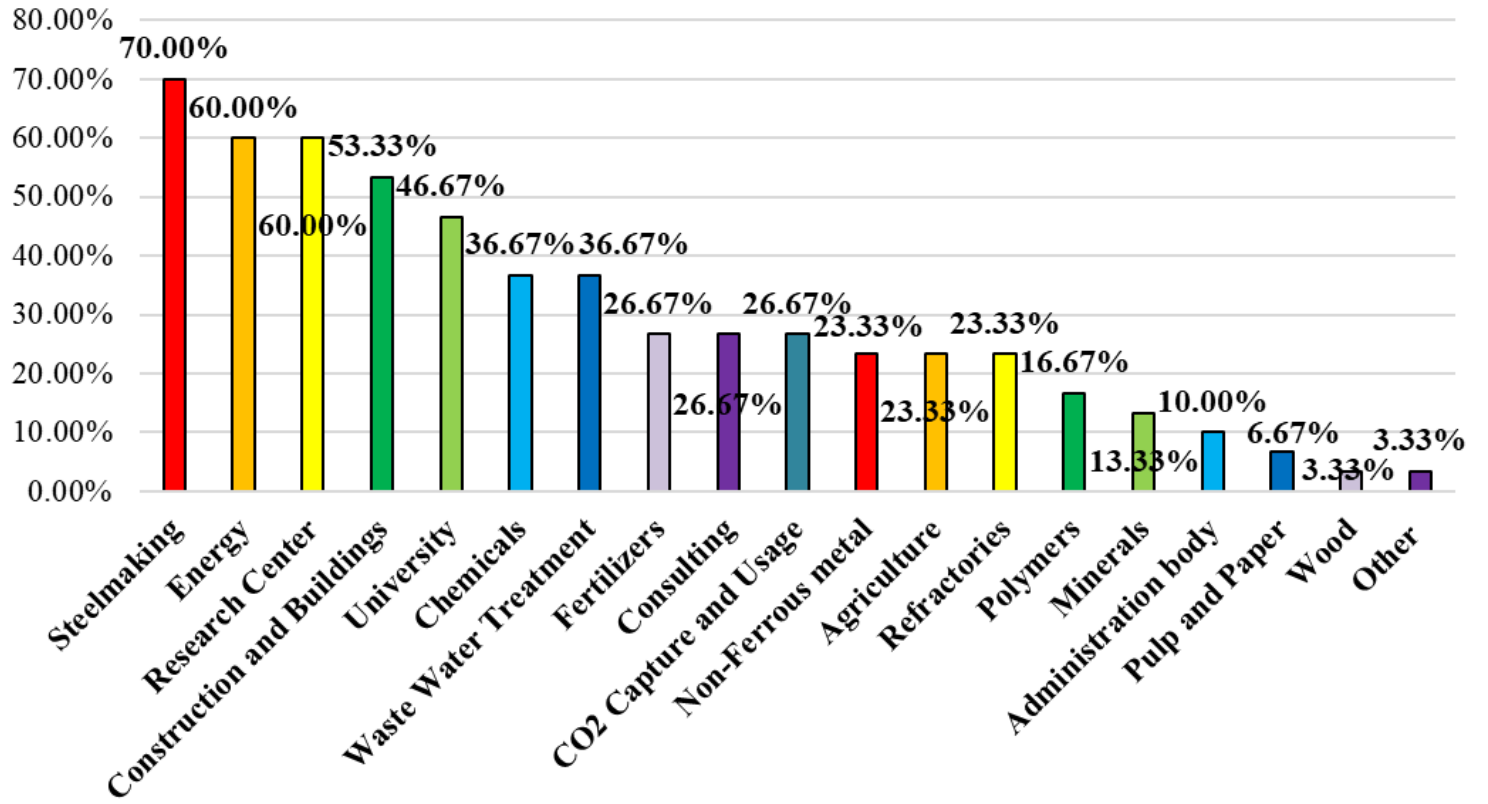
Stakeholders' consultation

Final achieved results

- Ranking of the organizations, companies and industrial sectors involved in the **Industrial Symbiosis practices** reported by the respondents



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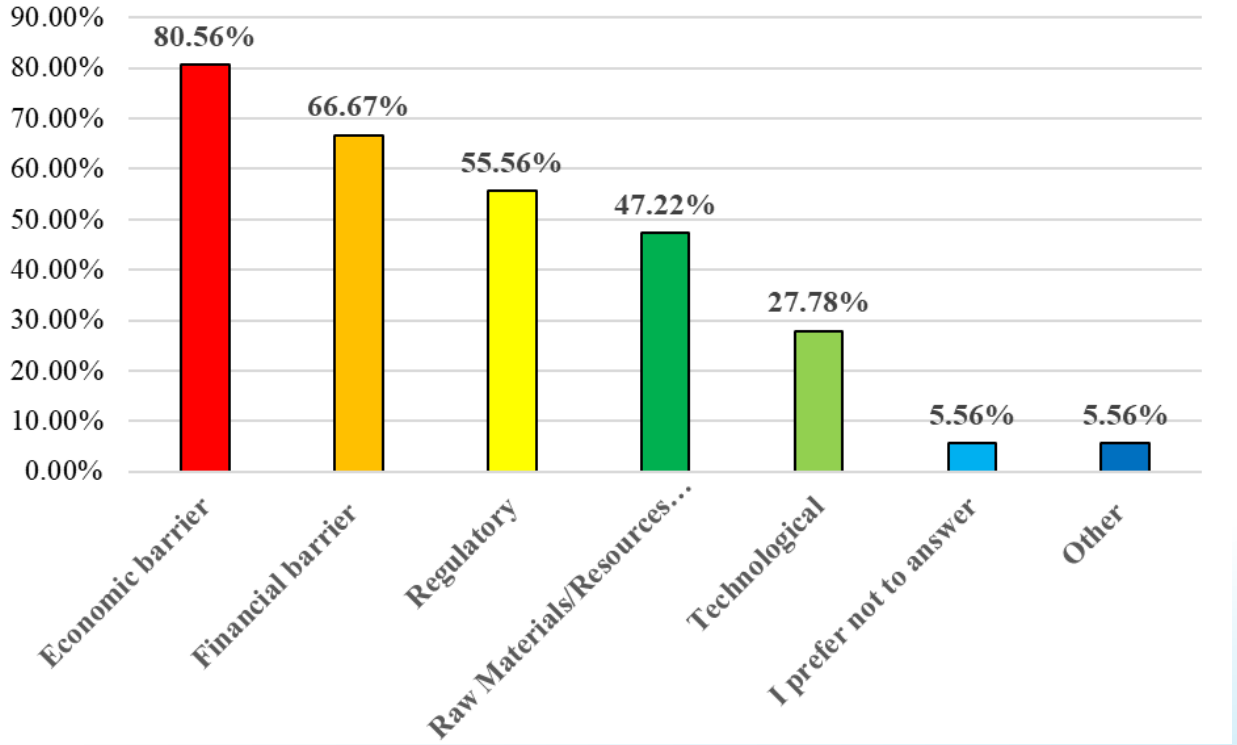
Stakeholders' consultation

Final achieved results

- **Barriers** hindering the adoption of **low-carbon technologies** in steelmaking that are perceived by the respondents



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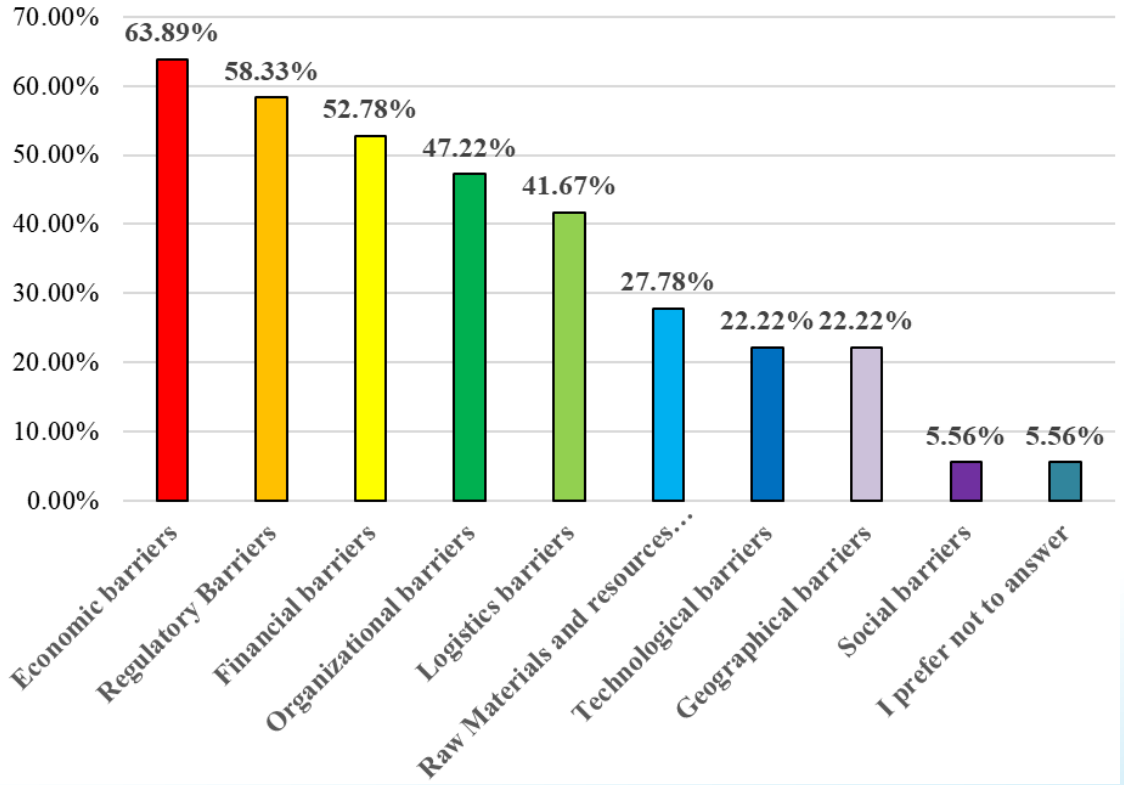
Stakeholders' consultation

Final achieved results

- **Barriers** hindering the adoption of a **symbiotic approach** in the steel sector or in other sectors



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Results, trends and perspectives of Industrial Symbiosis solutions

Conclusions

Technological innovations as main **decarbonization drivers** in steelmaking:

- **Electrification** is still poorly attractive for countries strongly dependent on fossil fuels
- **Circular Economy** and **Industrial Symbiosis** → the strategic role of the Symbio-Steel project in Industrial Symbiosis implementation
- The use of **Hydrogen** as reducing agent (e.g. the Hybrit pilot plant and the Hydra project).
- Carbon Capture, Storage and Utilization (**CCSU**) is a viable decarbonization strategy

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Results, trends and perspectives of Industrial Symbiosis solutions

Conclusions

- Slags are perceived as the most critical underutilized resources →creation more efficient networks among the different stakeholders for their efficient transaction
- High-grade **waste heat** can be recovered for internal use in high-efficiency applications to reduce fuel consumption, power generation, direct heating in manufacturing
- **Wastewater** and **off gas:** their reuse in greenhouses and for chemicals production, e.g., ethanol, methanol, etc.
- Carbon-bearing materials: **biomasses** were followed by **polymers** and **plastics**
- Identified underutilized resources in steelworks could be reused in **construction** or **fertiliser** sectors, to produce **energy**, e.g. by providing heat and CO_2 to greenhouse, and **chemicals**, e.g, biomethane and bioethanol

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and Steel (RFCS) C

Results, trends and perspectives of Industrial Symbiosis solutions

Conclusions

Companies of most participants are already involved in **Industrial Symbiosis practices**

The main **barriers** hindering the adoption of low-carbon technologies and of Industrial Symbiosis solutions are **economic**, **financial**, and **regulatory**

The current global situation and financial pressure on EU-based companies would benefit from **economic incentives** to encourage the adoption of Industrial Symbiosis practices

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Thank you!

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XIII European Slag Conference
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KPI-Based Assessment of Industrial Symbiosis Solutions within the RFCS Symbio-Steel Project: Slag Recycling Evaluation

L. Kieush[1], J. Rieger[1], V. Colla[2], T. A. Branca[2], A. Petrucciani[2], C. Sergi[3], D. Mirabile[3], F. Cirilli[3], A. Morillon[4], D. Algermissen[4], C. Wang[5], E. Nylund[5], H. Yu[5], T. Jarnerud Örell[5], D. Snaet[6]

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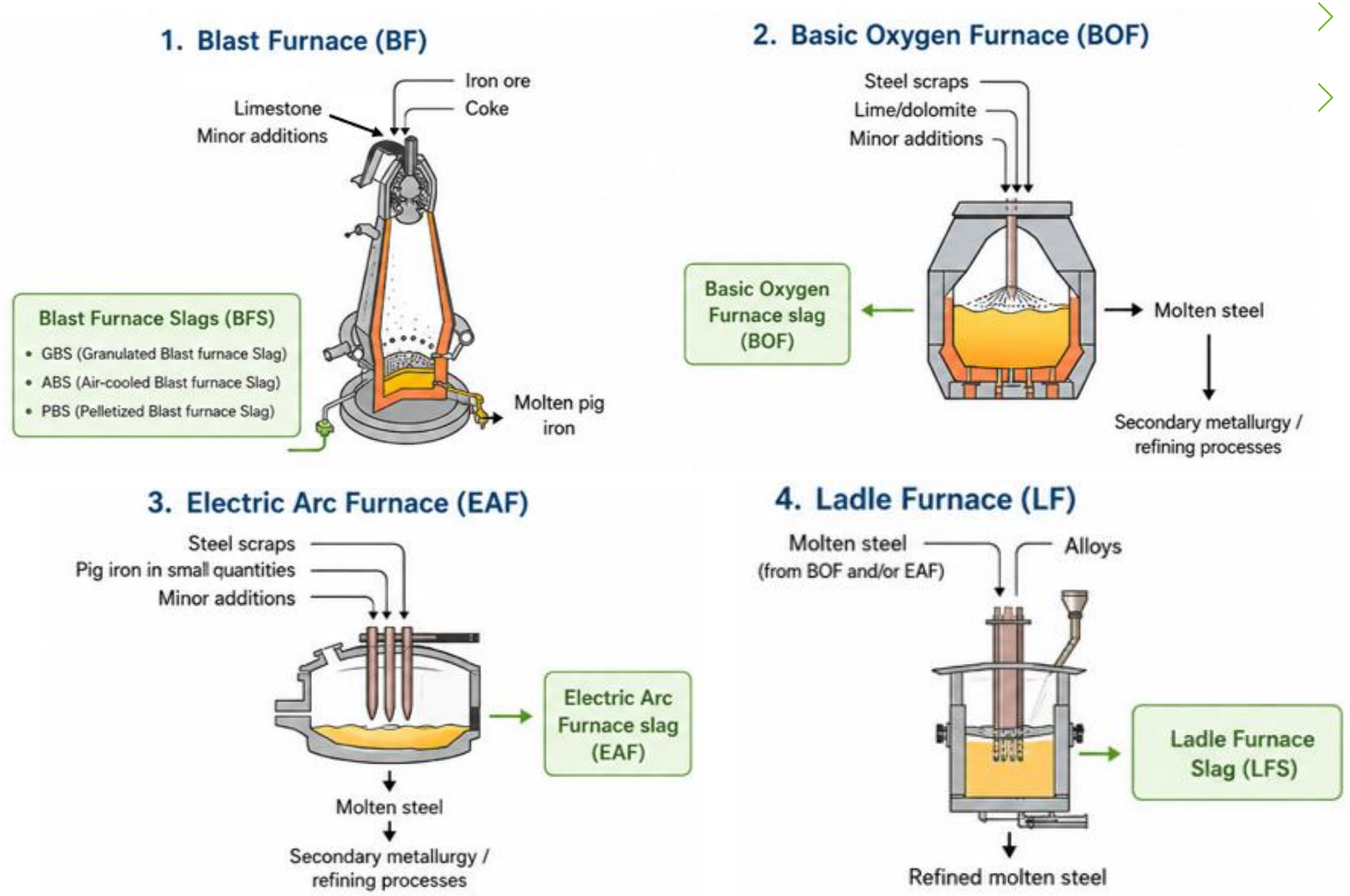
Why Slag Recycling Matters?

- ✓ Slag is one of the largest by-produc streams of iron and steelmaking, with significant untapped valorization potential.
- ✓ Industrial symbiosis enables cross-sector reuse, transforming slag into secondary raw materials for construction, agriculture, wastewater treatment, metal recovery, etc.
- ✓ Slag recycling supports circular economy goals by reducing landfill, conserving virgin raw materials, and lowering environmental impacts.



Piemonti et al. Exploring the Potential for Steel Slags Valorisation in an Industrial Symbiosis Perspective at Meso-scale Level, Waste and Biomass Valorization (2023) 14:3355–3375, https://doi.org/10.1007/s12649-022-01940-5

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Objective and Methodology

- ✓ Within the RFCS project "Symbio-Steel", the KPIs were obtained or extracted from a series of research and innovation projects funded by the EU and national programs, targeting IS practices in the energy- and resource-intensive industries.
- ✓ Some of the selection criteria: relevance to industrial symbiosis, steelmaking/slag applicability, clear quantitative information.

List of the defined KPIs in the RFCS Symbio-Steel Project

1	2	3	4	5	6	7	8	9	10	11
Energy efficiency	Direct CO_2 emissions (Scope 1) reduction	Reduction in virgin raw material usage	Enhancing the recycling of low-quality steel scrap	**Slag recycling rate**	Dust and sludge recovery and reuse	Recycling rate of iron-rich residue streams	Replacement rate of fossil carbon materials	CO_2 capture rate from process/off-gasses	Share of carbon content in process gas (CO_2/CO) transformed into products	Technology Readiness Levels (TRL)

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Case Studies of Successful Slag Valorization: RFCS project "Impact of Long-Term Application of Blast Furnace and Steel Slags on Soil Health and Crop Yield"

Project title	Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health
Project abbreviation	SLAGFERTILISER
Duration	01/07/2011–01/06/2015
Funding programme	RFCS
KPI No.	V
KPI Name	Slag recycling rate
Method to obtain	Calculated
Unit	%
KPI value	100
Baseline value unit	-
Baseline value	-
Reference value unit	%
Reference value	100
Remarks	Slag, used as a liming/fertilizer material, showed comparable success to equivalent natural materials.

- ✓ **SLAGFERTILISER** examined BF, BOF, and LF slags as liming agents and fertilizers in multi-country field trials. Results confirmed their effectiveness in agriculture compared to limestone and phosphate fertilizers, with environmental benefits.

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Case Studies of Successful Slag Valorization: RFCS project "Control of slag quality for utilization in the construction industry"

Project title	Control of slag quality for utilization in the construction industry
Project abbreviation	SLACON
Duration	01/07/2012–01/12/2015
Funding programme	RFCS
KPI No.	V
KPI Name	Slag recycling rate
Method to obtain	Calculated
Unit	%
KPI value	82.5
Baseline value unit	%
Baseline value	0
Reference value unit	%
Reference value	80–85
Remarks	Slag was reused in construction applications.



- ✓ **SLACON** demonstrated that steelmaking slags can substitute natural aggregates in road construction while maintaining durability.

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Case Studies of Successful Slag Valorization: RFCS project "Using slag as sorbent to remove phosphorus from wastewater"

Project title	Using slag as sorbent to remove phosphorus from wastewater
Project abbreviation	Slasorb
Duration	07/01/2009–31/12/2012
Funding programme	RFCS
KPI No.	V
KPI Name	Slag recycling rate
Method to obtain	Calculated
Unit	%
KPI value	100
Baseline value unit	-
Baseline value	-
Reference value unit	%
Reference value	100
Remarks	All BOF slag fractions used in experiments were reused as sorbents.

✓ In **SLASORB**, BOF and EAF slags were successfully applied as sorbents for phosphorus removal from wastewater.

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Case Studies of Successful Slag Valorisation: Horizon project "Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis"

Project title	Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis
Project abbreviation	Coralis
Duration	01/10/2020–31/03/2025
Funding programme	Horizon 2020
KPI No.	V
KPI Name	Slag recycling rate
Method to obtain	Reported
Unit	%
KPI value	100
Baseline value unit	-
Baseline value	-
Reference value unit	-
Reference value	-
Remarks	KPIs are considered within the Italian demo case.

- ✓ The **CORALIS** project investigated recovery of metals from EAF and LF slags and ferroalloy production process starting from LF slag and aluminium residues under TRL 6.

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

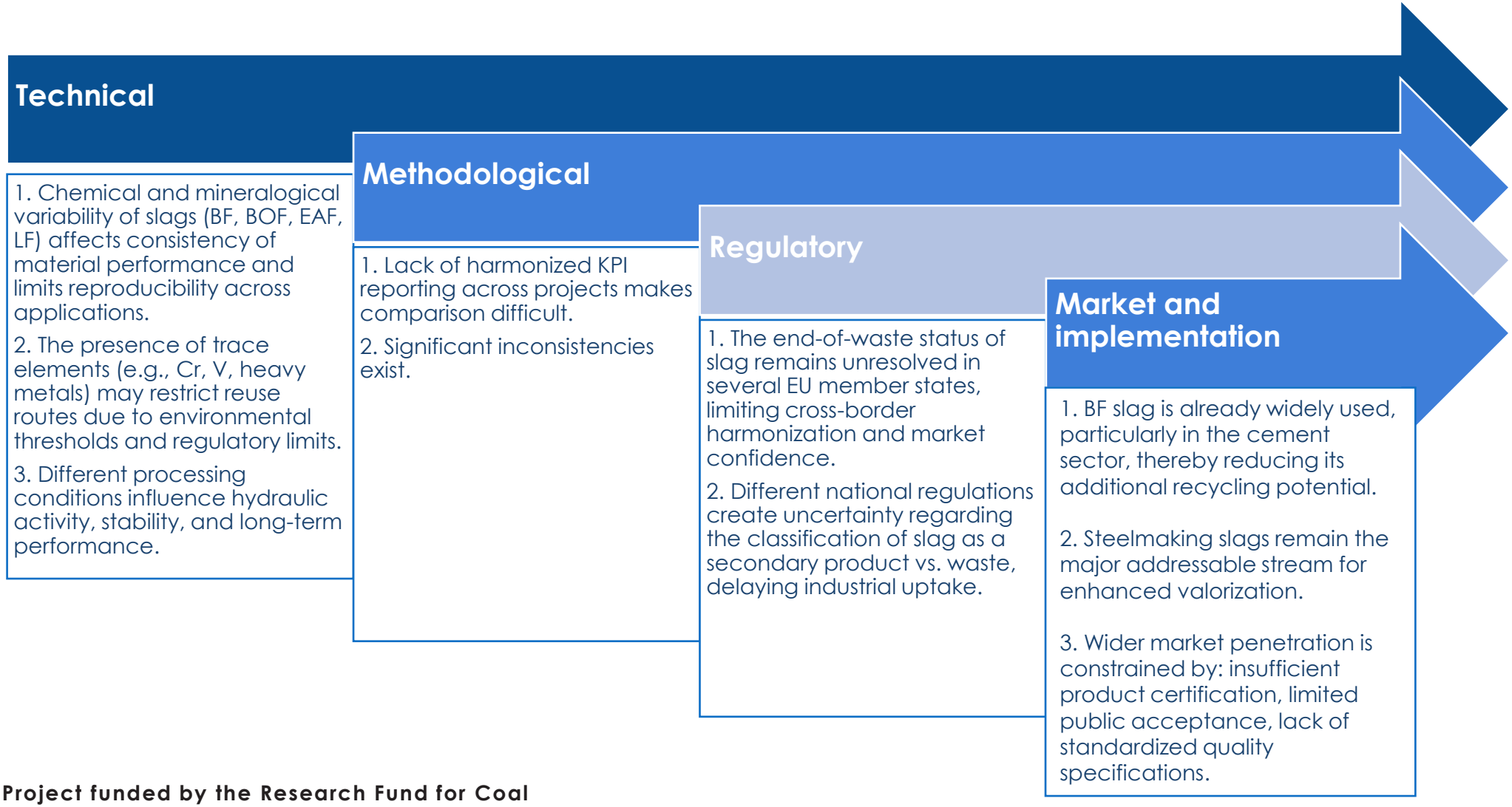
Case Studies of Successful Slag Valorization: RFCS project "Reuse of slags from integrated steelmaking"

Project title	Reuse of slags from integrated steelmaking
Project abbreviation	Slagreus
Duration	01.06.2019-30.11.2022
Funding programme	RFCS
KPI No.	V
KPI Name	Slag recycling rate
Method to obtain	Reported
Unit	%
KPI value	Up to 25
Baseline value unit	%
Baseline value	0
Reference value unit	%
Reference value	Up to 25
Remarks	The limiting factor was the Cr content, which restricted substitution by a factor of 5 in certain applications.

- ✓ **Slagreus** focused on the sustainable reuse of slags from integrated steelmaking, specifically BOF slag. The project aimed to recycle the Fe-enriched BOF slag fraction internally as a substitute for iron ore fines in sinter plants and utilize the Ca- and P-enriched fraction externally as cement additives or fertilizers.

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Main Challenges for Slag Recycling and Industrial Symbiosis



Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Conclusions

- ✓ **Industrial symbiosis solutions for slag recycling are technically feasible**, with several successful examples demonstrating near-full reuse in agriculture, construction, wastewater treatment, metal recovery, etc.
- ✓ **Scientific and operational scalability remains limited** due to:
  - chemical variability of slags;
  - inconsistent KPI reporting (different units, methods, and baselines);
  - lack of harmonized standards for assessment.
- ✓ **KPI „Slag recycling rate“ is highly relevant**.
- ✓ **Regulatory barriers remain significant**, particularly the unresolved end-of-waste status in several EU member states, slowing market uptake despite demonstrated environmental and economic benefits.
- ✓ **Market deployment is further constrained** by limited public acceptance and the absence of standardized certification for slag-based products.
- ✓ **Steelmaking slags represent the key opportunity for future recycling efforts**: while BF slag is already highly utilized in cement production, ~15.9 Mt of steelmaking slags remain a major addressable stream for enhanced recycling and industrial symbiosis in the EU, according to EUROSLAG/FEhS data published in 2024.
- ✓ **Future progress requires harmonized KPIs, better data availability, and stronger policy alignment to accelerate slag valorization** across sectors.

https://www.recycling-magazine.com/2024/07/16/ferrous-slag-based-products-replace-44-million-tons-of-natural-rock/

Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

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Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or RFCS. Neither the European Union nor the granting authority can be held responsible for them.



Industrial Symbiosis between Biomass Processing and Steelmaking: Insights from the BioReSteel Project

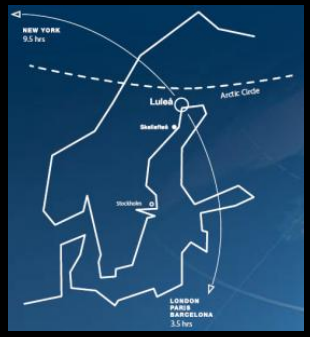
Chuan Wang

Researcher leader, Resource efficiency and environment

SYMBIO STEEL

Swerim AB





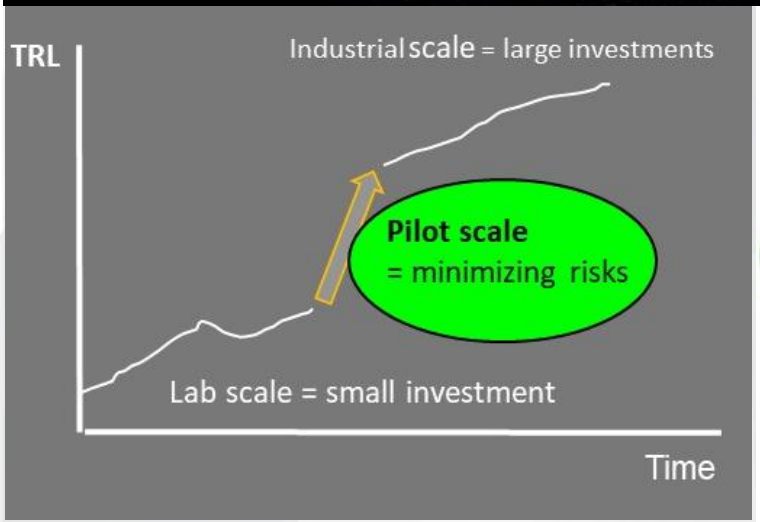
Swerim – **Research institute for mining, metallurgy and material**, in Sweden founded on **1st October**, 2018
- a world class research institute
- **MEFOS** (1963) & - **KIMAB** (1921)

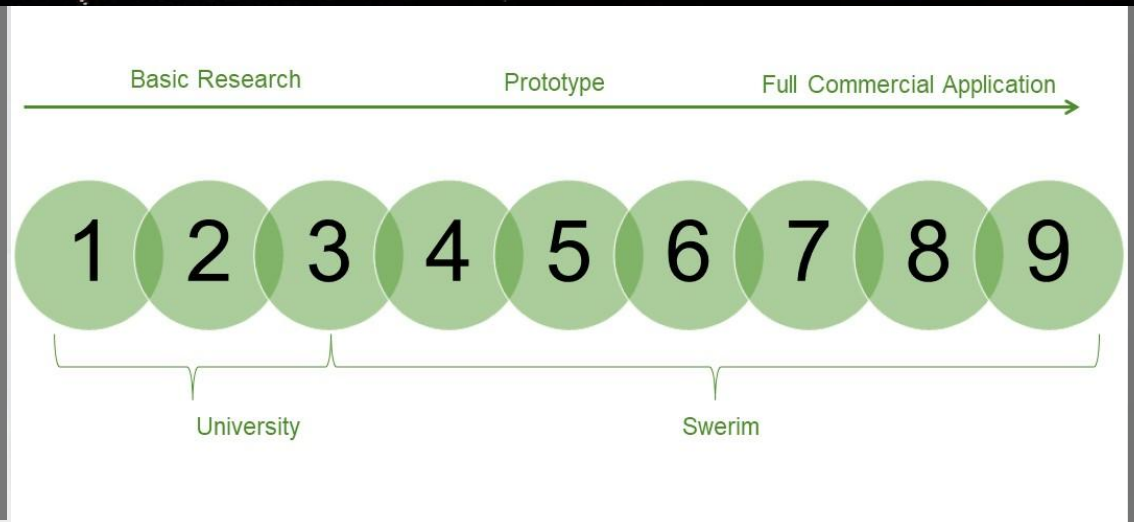
- Located in Luleå and Stockholm
- Turnover > 300 million SEK
- Approximately 200 employees
- Unique test and demonstration facilities (>1.5BSEK)
- Customers from all over the world

”Our vision is a sustainable and competitive industry.”

Research in high TRL-levels

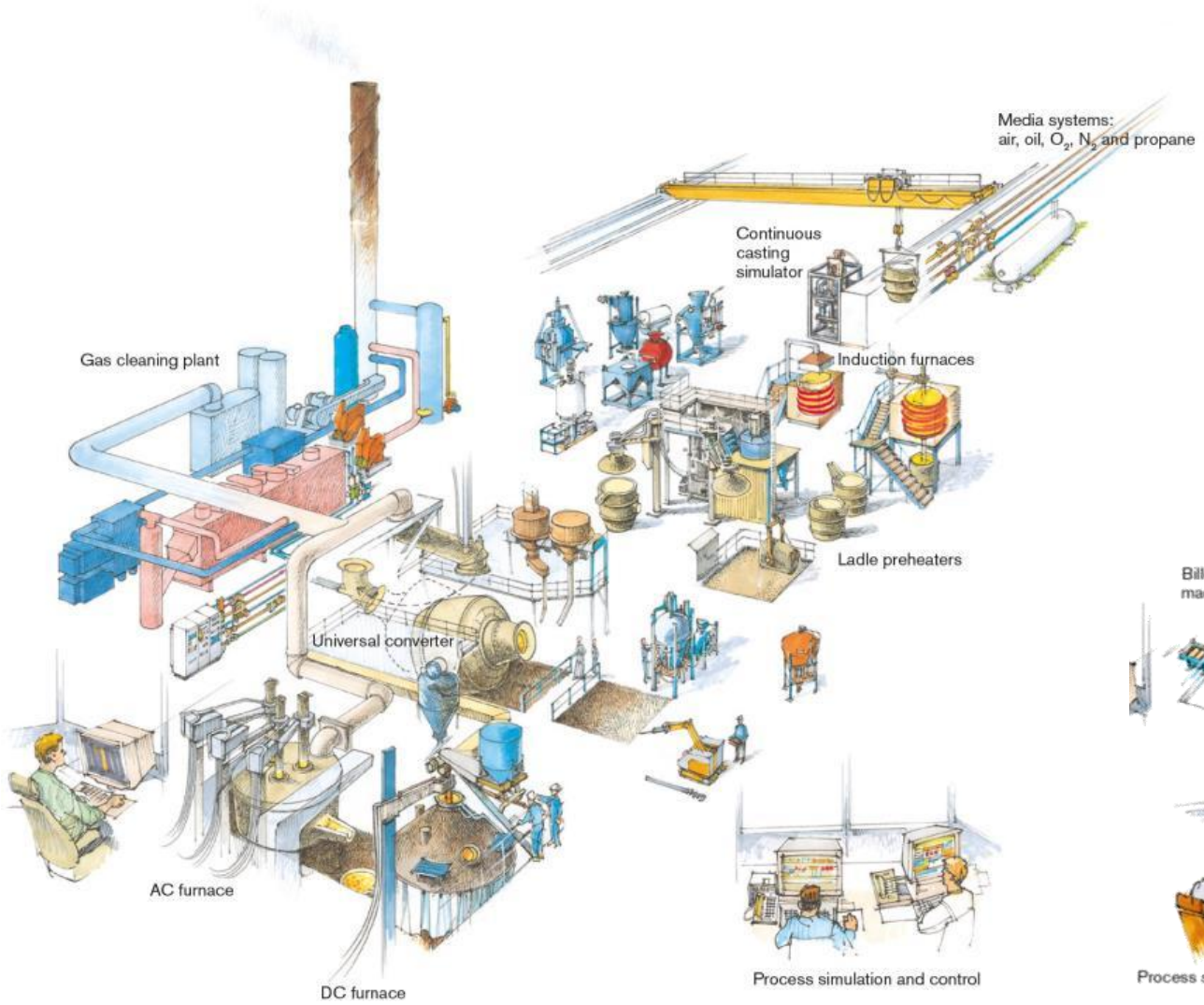




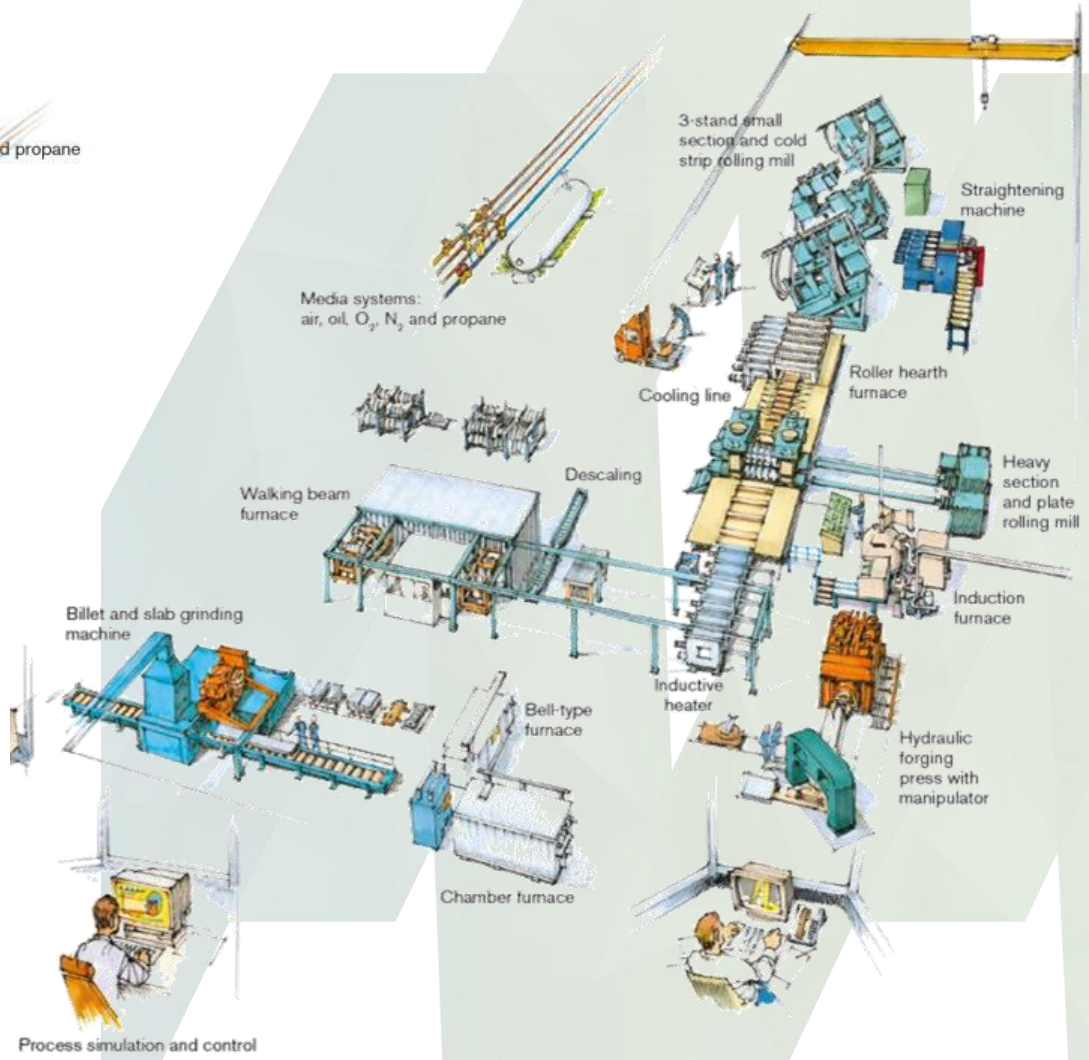


- Designing, building, rebuilding and adapting facilities to match customer-specific conditions.
- Running processes or process solution that no one else has done before − with safety first.

Luleå Pilot Facilities



Process metallurgy



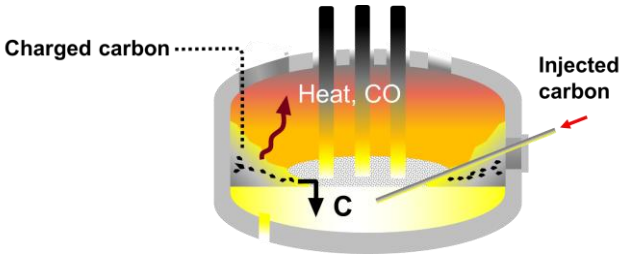
Heating and metalworking



BioReSteel

Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling

- Coordinator: Chuan Wang, Swerim AB
- Call: RFCS-2022, RPJ
- Start date: 01/10/2023
- End date: 30/09/2027
- Total costs: 3 420 795.00 €



- Reductant
- Carburization
- Slag foaming

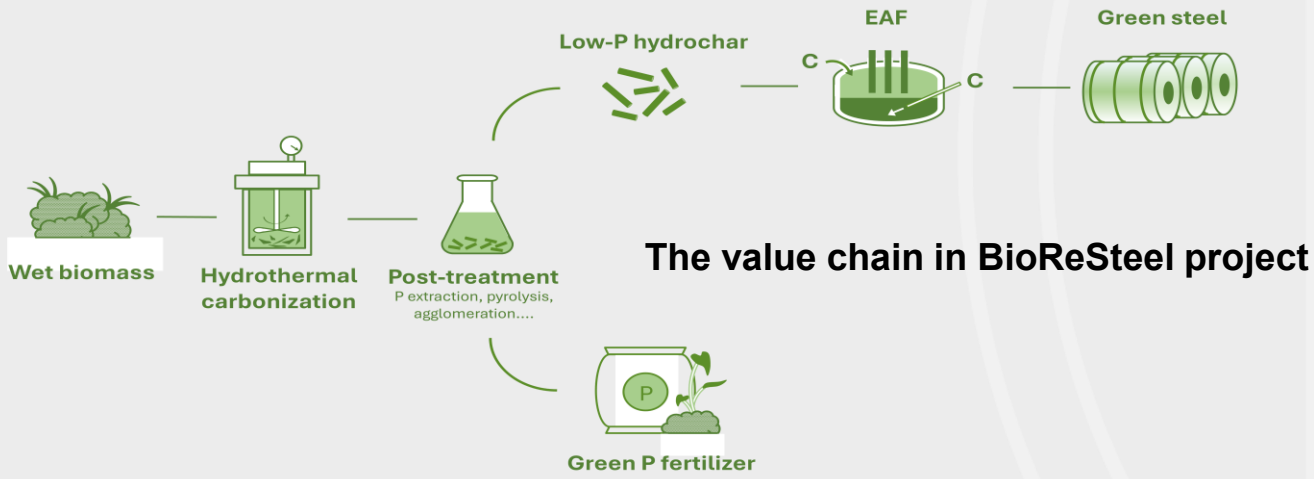
Co-funded by the European Union

Energimyndigheten, programråd, SK

Objective & methodology

Objective: to replace fossil carbon in the electric arc furnace by biocoal, produced from low-grade locally available wet biomass residues by means of a hydrothermal carbonization process.

Methodology: The BioReSteel concept will be proved by an experimental study by the means of laboratory and EAF testbed trials. The industrial EAF trials will be performed at three EAF plants to test hydrochar injection, hydrochar top charging and bio-oxides agglomerates in order to prove the concept's flexibility and generality.



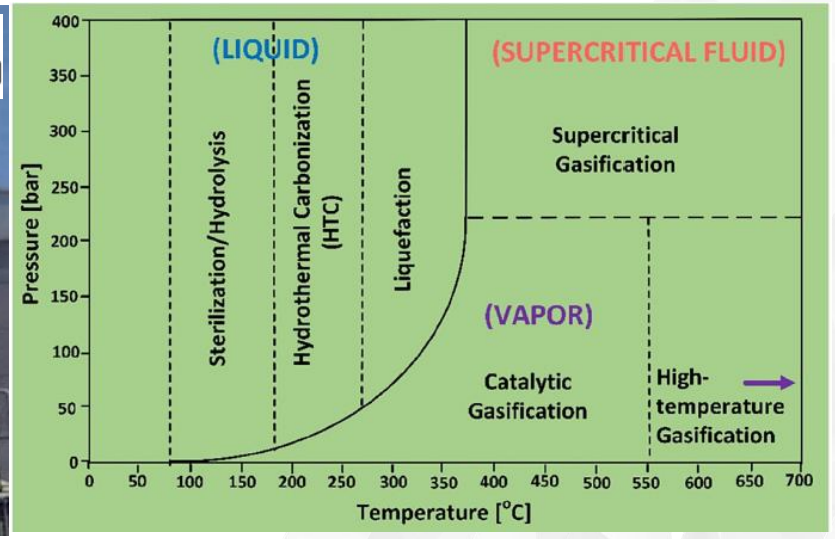
The value chain in BioReSteel project

HTC vs. pyrolysis

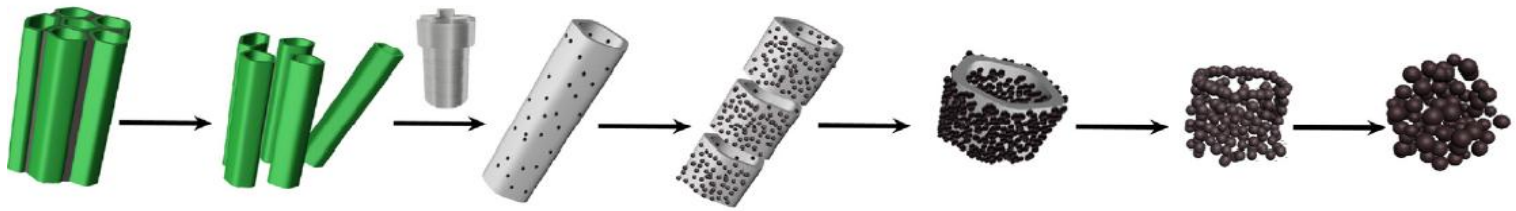
- Compared with traditional pyrolysis carbonization, hydrothermal carbonization has the characteristics of mild reaction conditions, low energy consumption, less pollutant generation, nutrient recovery (NPK)

Carbonization method	Reaction medium	Temperature (℃)	Time	Mass yield	Product ash	Calorific value	Energy consumption	Pollutant emission	Content of S, P, alkali
Pyrolysis	Absence of air	> 350	Long	Low	High	High	High	High	High
HTC	Subcritical water	180-300	Short	High	Low	High	Low	Little	Low





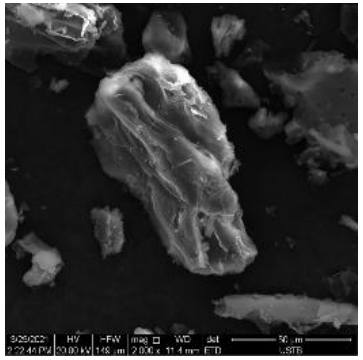


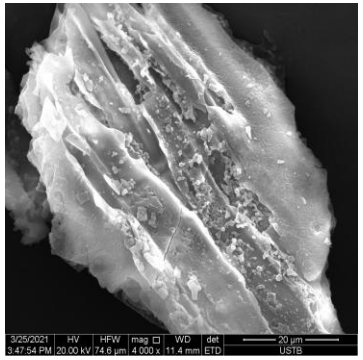


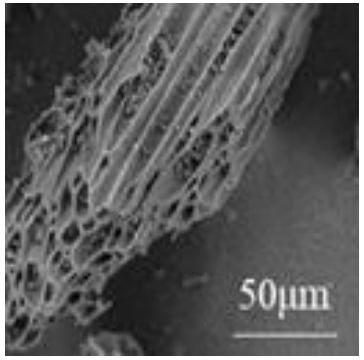


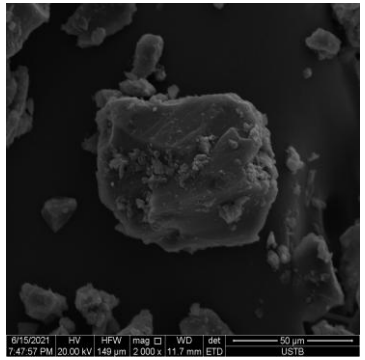
Forest waste, hydrochar and biochar

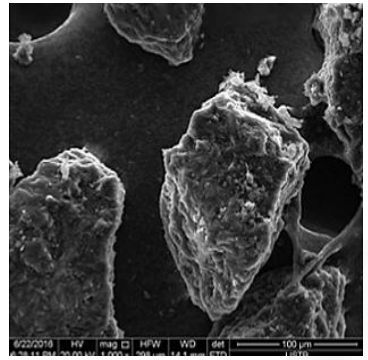
Forest waste (FW) original | Hydrochar | Biochar | Anthracite | Coke











	Pore volume (cm^3/g)	Specific surface area (m^2/g)	Reactivity (%, 900 °C CO_2)	Na+K (%)	Carbonization degree
Forest waste (FW)	0.00338	0.59	100%	0.473	Disordered
Hydrochar (via HTC)	0.00261	0.91	52%	0.033	Low
Biochar (via pyrolysis)	0.01827	3.30	56%	>1	High
Coke	0.00870	0.96	0%	0.073	High
Anthracite	0.00195	0.97	0%	0.155	High

Liang, W., et al. (2022). Hydrothermal carbonization of forest waste into solid fuel: Mechanism and combustion behavior. Energy, 246, 123343.
Wang, G., et al. (2018). Structural features and gasification reactivity of biomass chars pyrolyzed in different atmospheres at high temperature. Energy, 147, 25-35.
Wang, P., et al. (2018). Co-combustion characteristics and kinetic study of anthracite coal and palm kernel shell char. Applied Thermal Engineering, 143, 736-745.

The BioReSteel concept – to be validated









P extraction



- The experiment work has been done by UPV
- **Phosphorus (P) extraction** was performed on hydrochar and pyrolyzed hydrochars derived from OFMSW, GW and OP, using diluted nitric acid
- Treatment achieves reduction of P content by >95% for pristine hydrochar
- Final P content in extracted hydrochar <500 ppm







Two measurable targets (KPI) are achieved: P removal >95%; final P content <500 ppm (<0.05%)!

	Initial [ppm]	Extracted [ppm]	Extraction efficiency [%]
GWH	2894	58	98.0
OFH	9514	400	95.8
OPH	2751	39	98.6

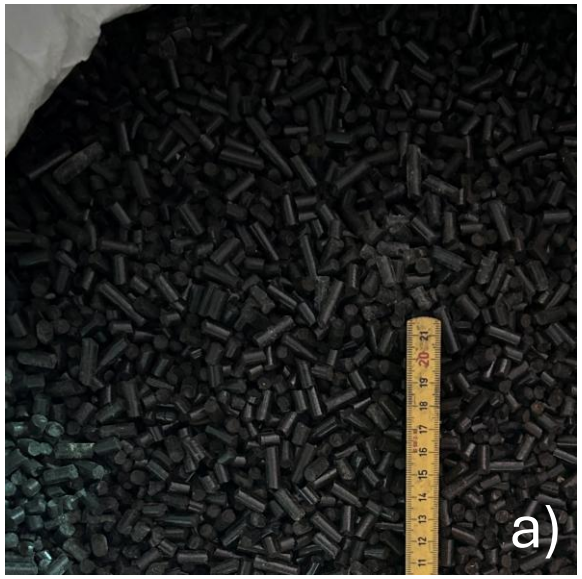
BioReSteel pilot trials at Swerim



Heat size:	10 ton
Transformer:	4.9 MVA
Furnace sheel diameter:	2.8 m
Furnace diameter, lined:	2.1 m
Electrode diameter:	250 mm

Oxy-fuel burners, EMS system

Hydrochar materials



Pristine hydrochar pellets



Pyrolyzed hydrochar



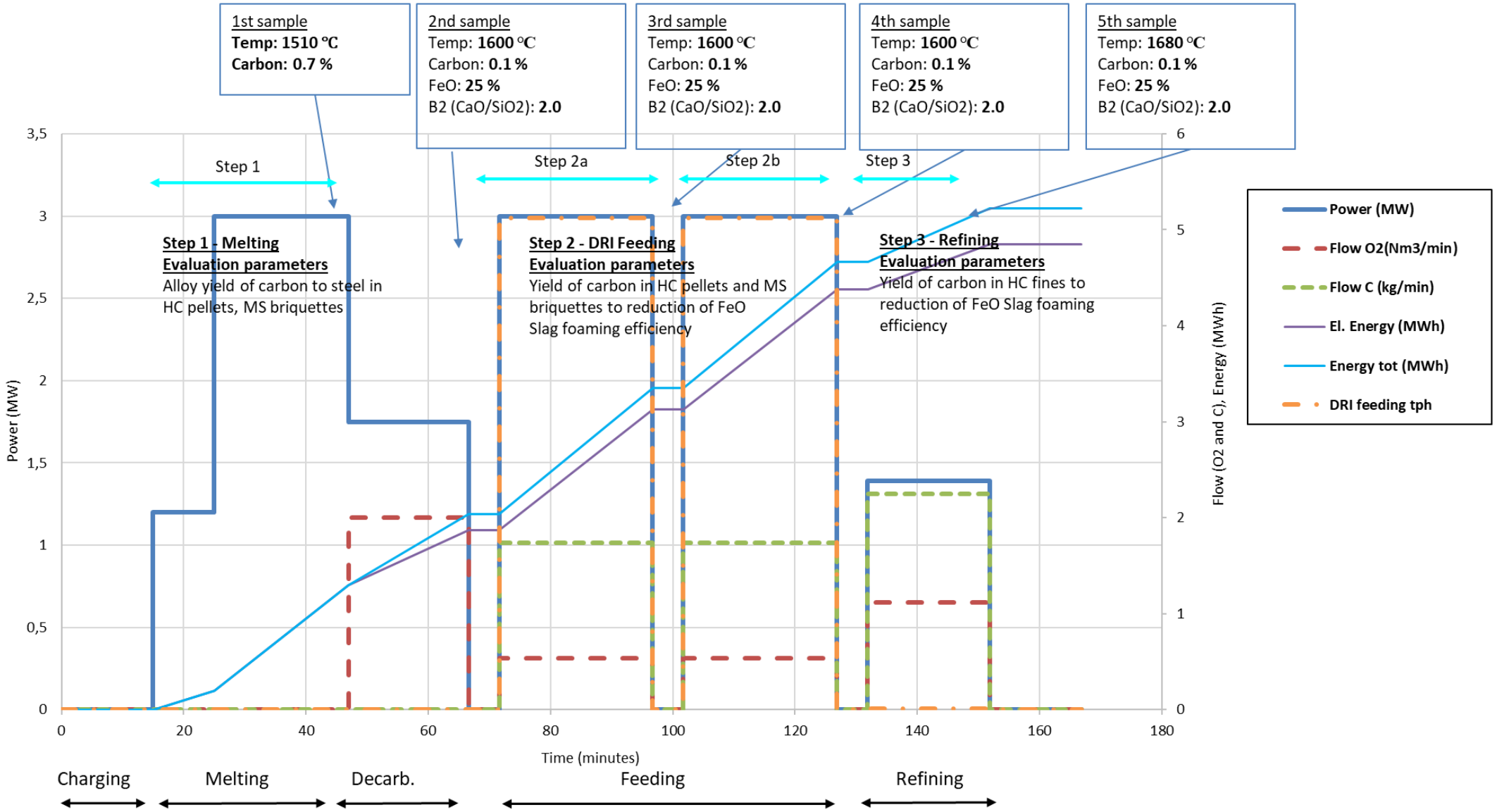
Pristine/pyrolyzed hydrochar fine



Biocarbon-containing mill scale

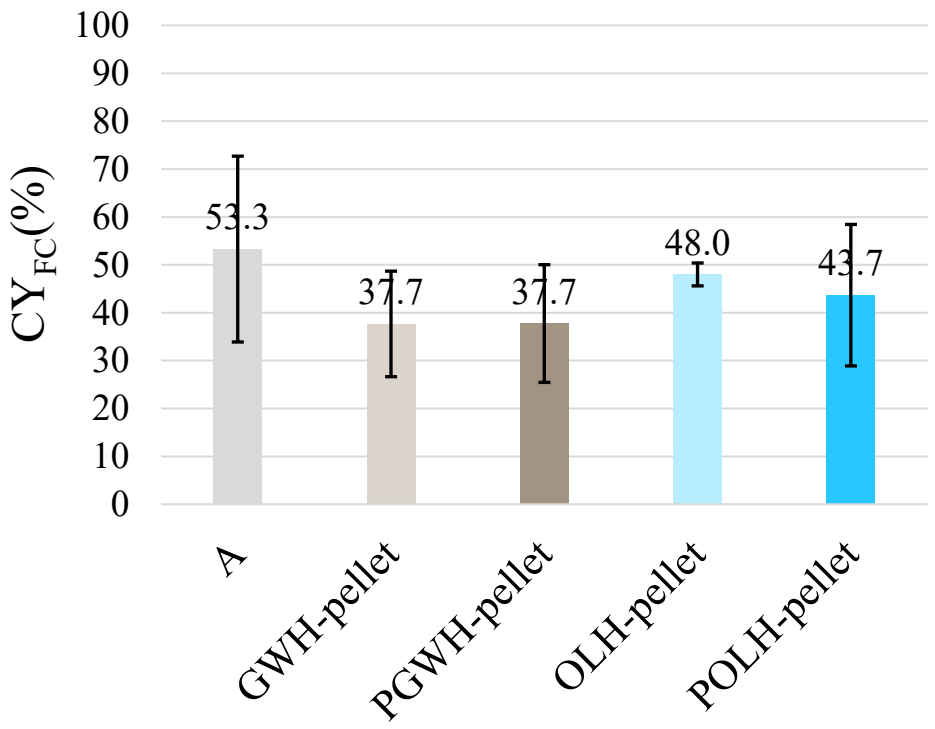
2 types of feedstock of green waste, olive pomace with 5 different forms of a) Pristine hydrochar pellet; b) Pyrolyzed hydrochar pellet; c) Pristine hydrochar fine; d) Pyrolyzed hydrochar fine; e) Hydrochar containing mill scale briquettes.

Testing program



Carburization [Stage1]

$$CY_{FC}\% = \frac{W_{Me} \cdot [(\%C)_{Me,1} - (\%C)_{scrap}]}{W_{CM} \cdot (\%C)_{CM,FC}} \cdot 100\%$$



CM	FC (wt-%)	Addition during trial (kg/t-steel)	Amount required to replace 1 kg A (kg)*
A	78.3	15	1
GWH-pellet	22.7	64	4.9
PGWH-pellet	**49.8**	**28**	2.2
OLH-pellet	23.4	64	3.7
POLH-pellet	**64.1**	**28**	1.5

*Calculated based on= (FC_A*CY_A)/(FC_i*CY_i)

- Difference in CY due to differences in density and carbon structure
- POLH is the best carburizing agent, followed by PGWH, OLH, and GWH

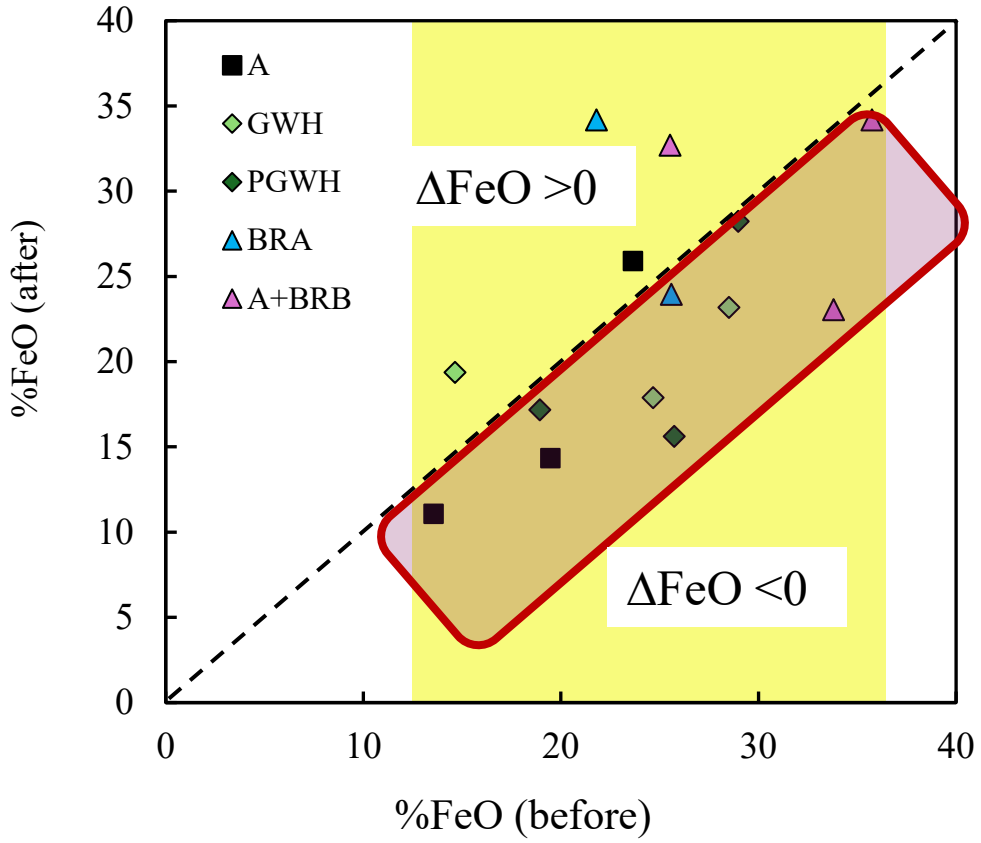
DRI feeding [Stage 2]-Reduction

$$\Delta FeO = (\%FeO)_{after} - (\%FeO)_{before}$$

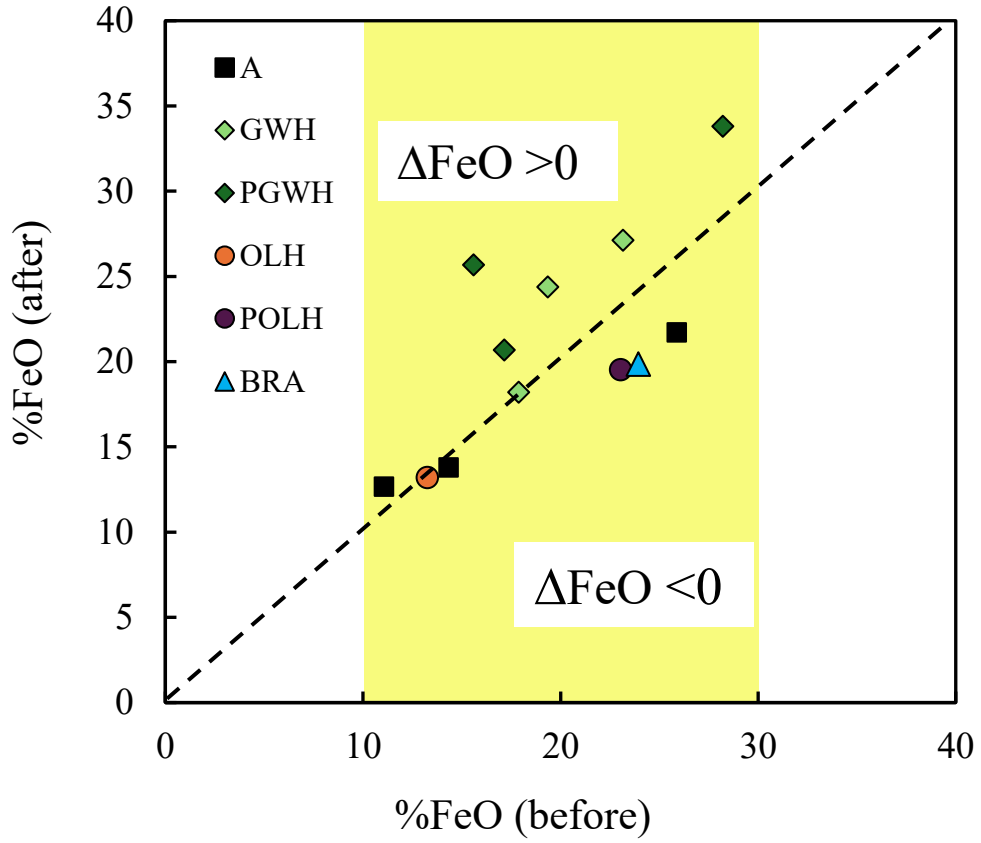
*BRA=POLH+MS

*BRB=OLH+POLH+MS

Stage 2a



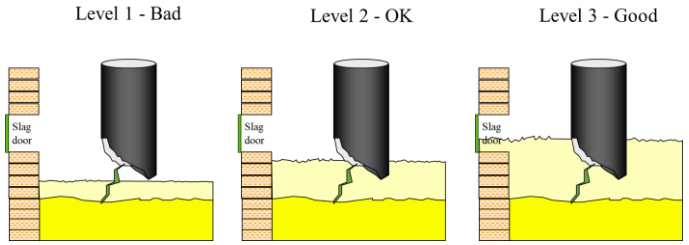
Stage 2b



Addition amount (kg)	A	GWH	PGWH	OLH	POLH	BRA	A+BRB
Per ton steel*	11	15-19	15-16	7-9	8	83-85	A: 3, BRB: 28-30
Per ton DRI	18	25-31	26	13-17	13	148-150	A: 4, BRB: 48-51

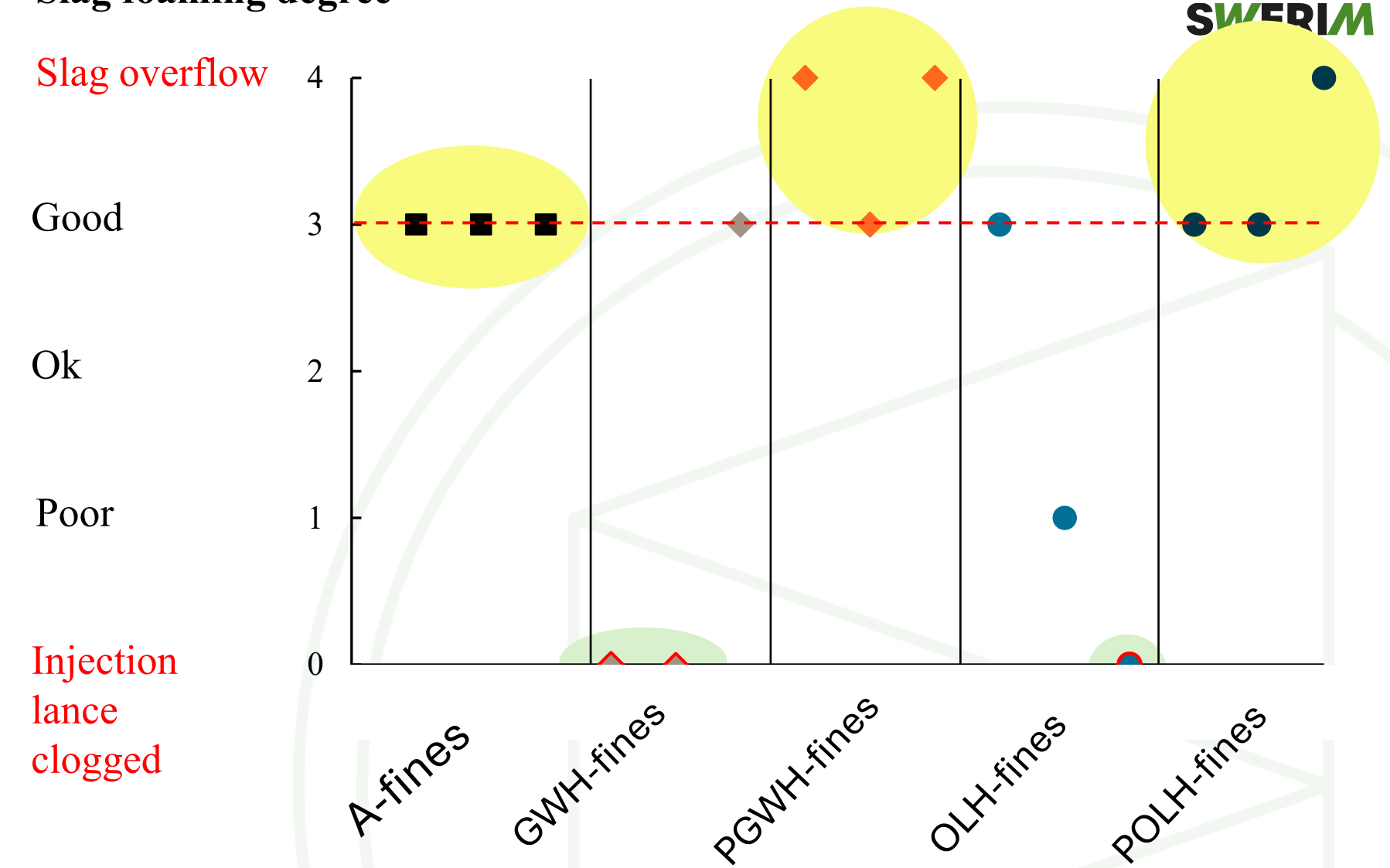
*Addition amounts normalized to 7150 kg steel (3106 kg scrap+4044 kg steel from DRI).

Slag foaming [Stage 3]





Slag foaming observation from the slag door!



	A-fines	GWH-fines	PGWH-fines	OLH-fines	POLH-fines
Injection amount (kg/t-steel)	6-7	15-25	9-11	14-24	8-12

Concluding remarks

Various hydrochar-based materials were successfully tested in Swerim's pilot-scale EAF as carburizing agents, reductants, and slag foaming agents.

Phosphorus successfully extracted from hydrochar using diluted mineral acid; >95% phosphorus removal achieved at the lab scale; investigation on the production of a heavy-metal-free phosphorus fertilizer is in progress, thus towards the industrial symbiosis by covering steelmaking and fertilizer production.

Industiral trials on using hydrochar in EAFs are under planning at FENO, ORI Martin and Celsa, which will be carried out in autumn and forwards; meanwhile, LCA and TEA analysis are on going to evaluate the sustainability of the BioReSteel concept!

Thanks for your attention!

SWERIM

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chuan.wang @swerim.se

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Slag as the supply chain interface

– BIOCARBON MEETS SCRAP AND DRI

Erland Nylund[1,2,3], Johan Martinsson[3], Amanda Vickström[2], Jim Allansson[3]

[1)] Presenter [2)] Swerim AB, Business area Metallurgy
[3)] Luleå University of Technology, Department of Engineering Sciences and Mathematics

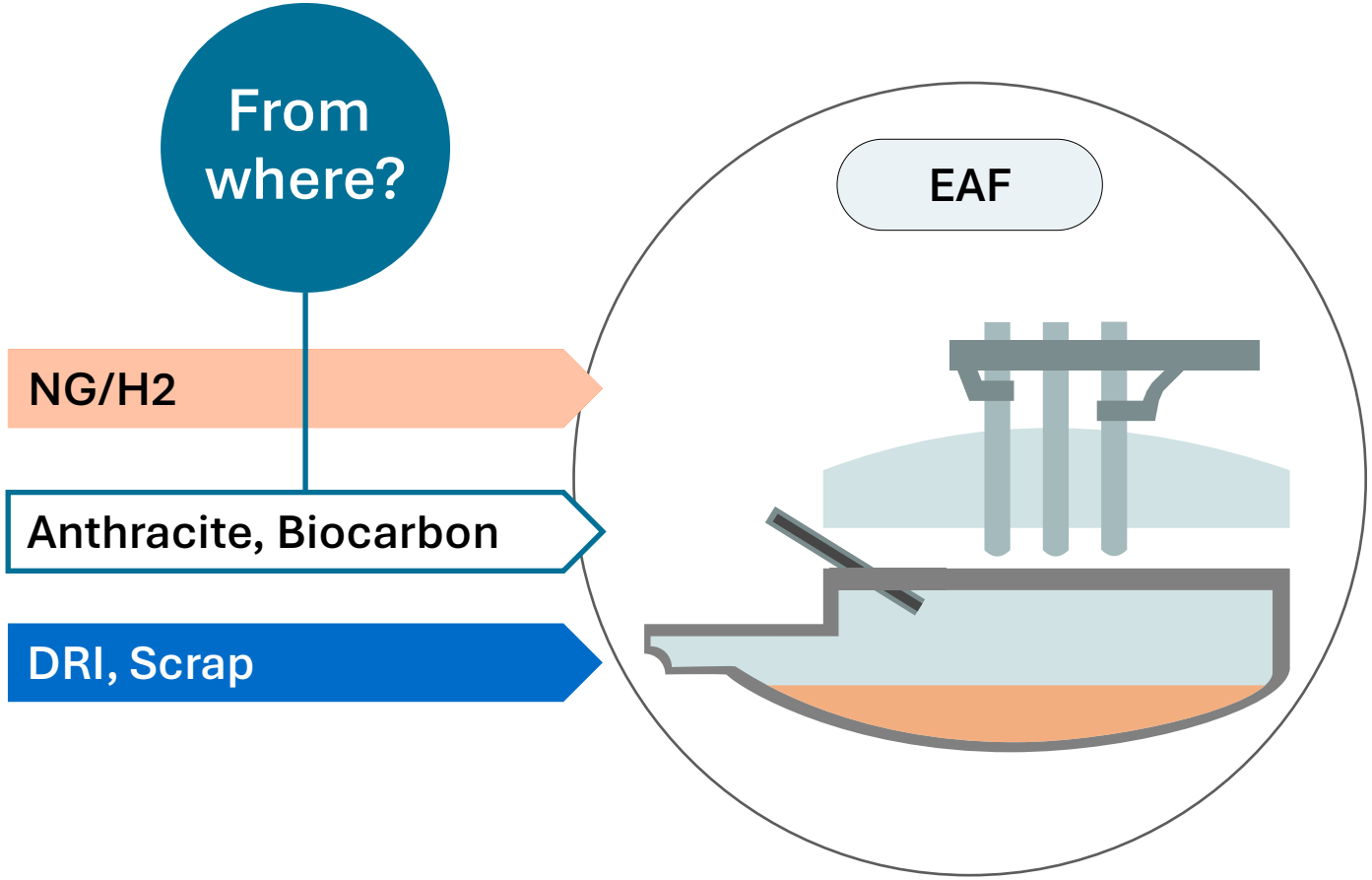
Defossilisation and carbon

Why fossil-free steelmaking needs carbon

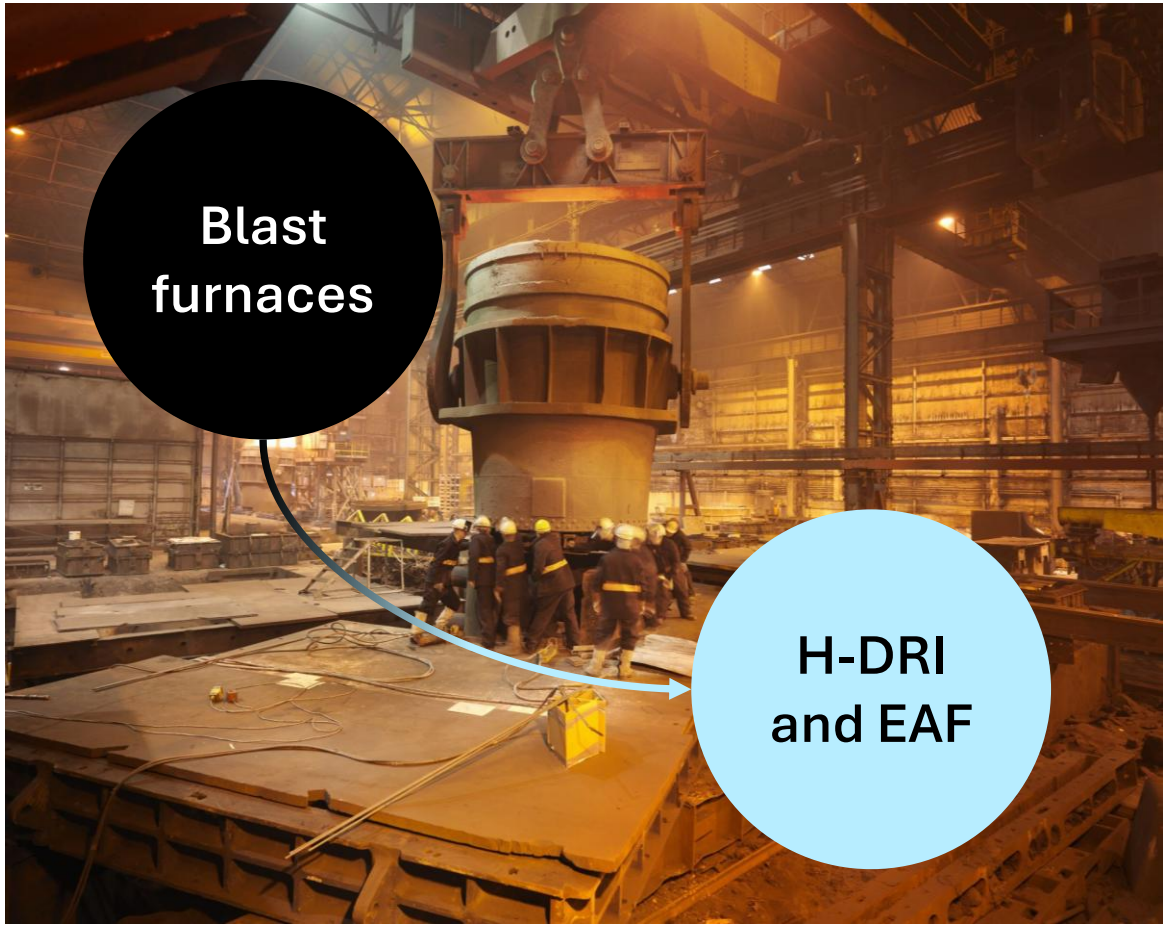
More than 90% of carbon intensity removed as Blast Furnace is phased out

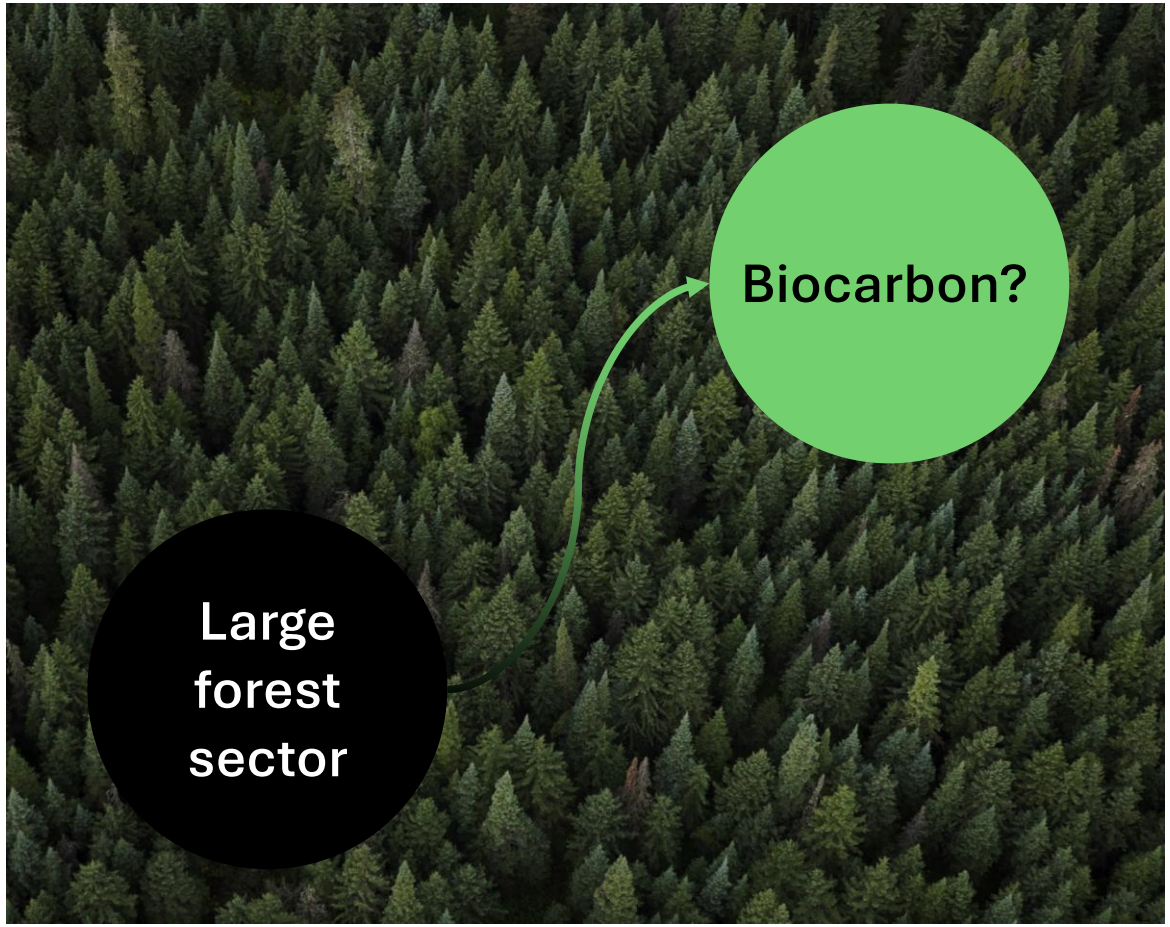
Carbon needed for:

- Carburisation
- Slag foaming
- Oxide reduction – production yield and efficiency



Sweden – forests and iron





Biocarbon limitations

HÅBIMET PROJECTS

Social, Policy and Technical aspects

> Why don't we have a mature market for metallurgical biocarbon?

- Price of biomass and production
- Quality – C_{fix} and P-content
- Supply security
- Fire safety



PROJECT CONSORTIUM

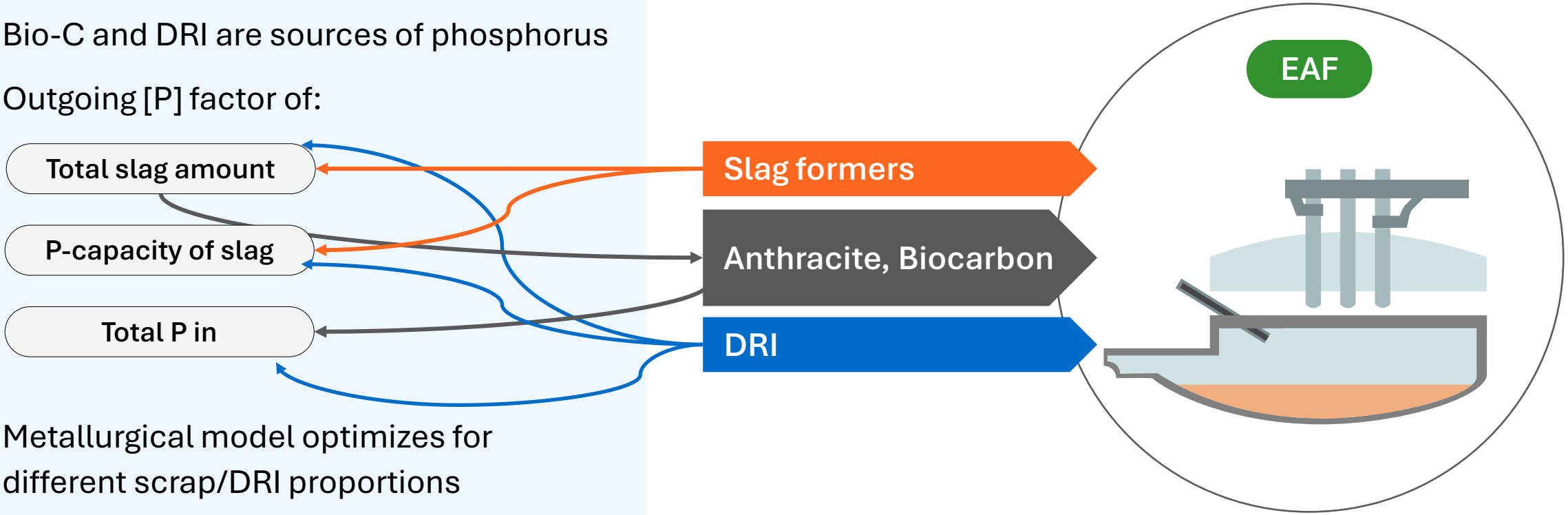
albaeco · Energiforsk · envigas · Höganäs · Luleå Tekniska Universitet · SLU Swedish University of Agricultural Sciences · Vargön Alloys AB

FUNDING

FORMAS · Swedish Energy Agency · Swedish Metals & Minerals · VINNOVA

Technical limitation – phosphorus

- Limit to [P]
- Bio-C and DRI are sources of phosphorus
- Outgoing [P] factor of:



- Metallurgical model optimizes for different scrap/DRI proportions

Key projects

Hydrogen Direct Reduction of Iron, Electric Arc Furnaces

SSAB

- Ca 4 Mton BF capacity → 4.25 Mton EAF
- Designed for DRI input

LKAB

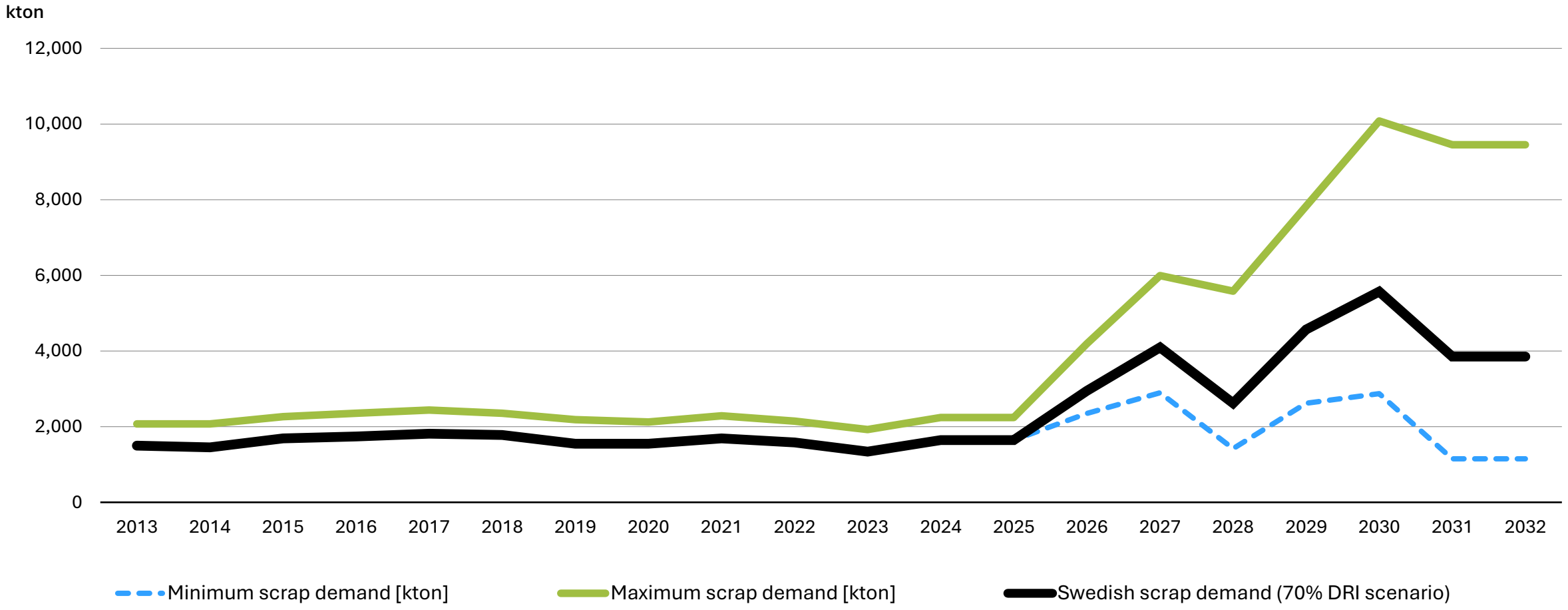
- 1.5 Mton H-DRI plant demonstration
- First phase ca 4 Mton H-DRI capacity

Stegra – greenfield startup

- Integrated H-DRI – EAF steel plant
- Phase 1: 2.5 Mton capacity
- Phase 2: 5 Mton capacity
- 2-5 Mton H-DRI capacity

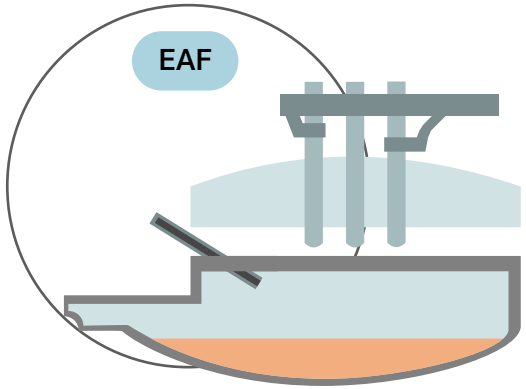
Projections of scrap demand in Sweden

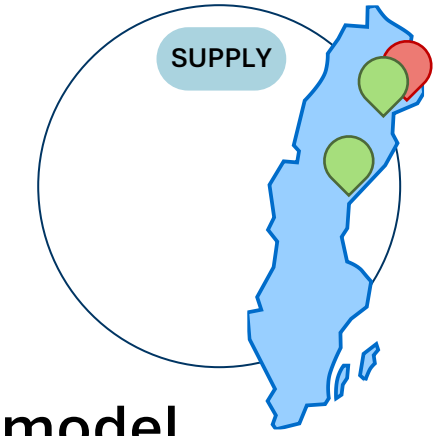
Spread of Swedish scrap demand 2013–2032



Metallurgical and system modelling

Studying the industry that does not exist yet



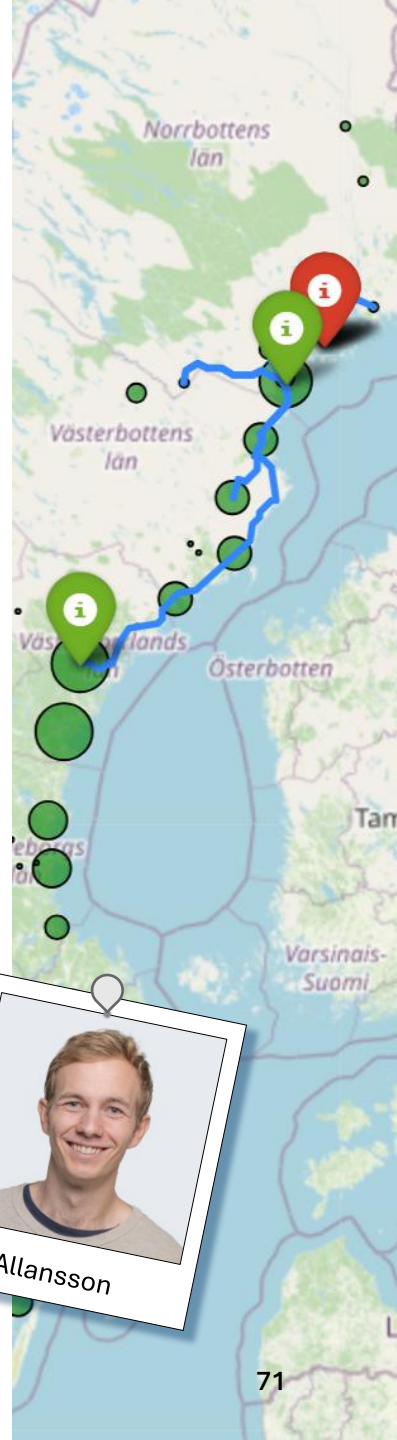


Metallurgical model

- Mass and energy balance for EAF steel mill
- Impact of different raw material choices

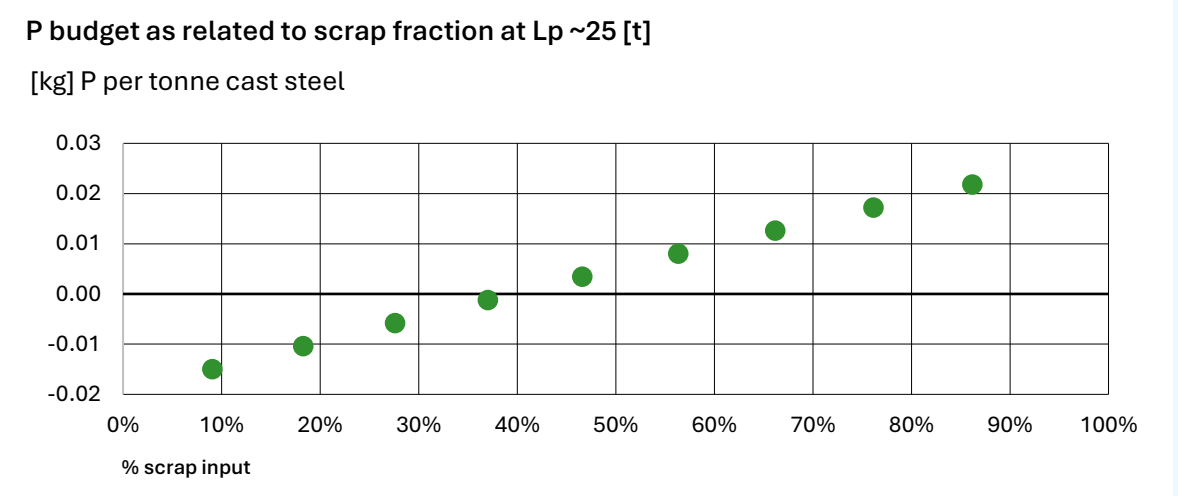
Biomass supply model

- Where are biomass sources located?
- Where to locate pyrolysis
- Cost-optimisation of supply chain

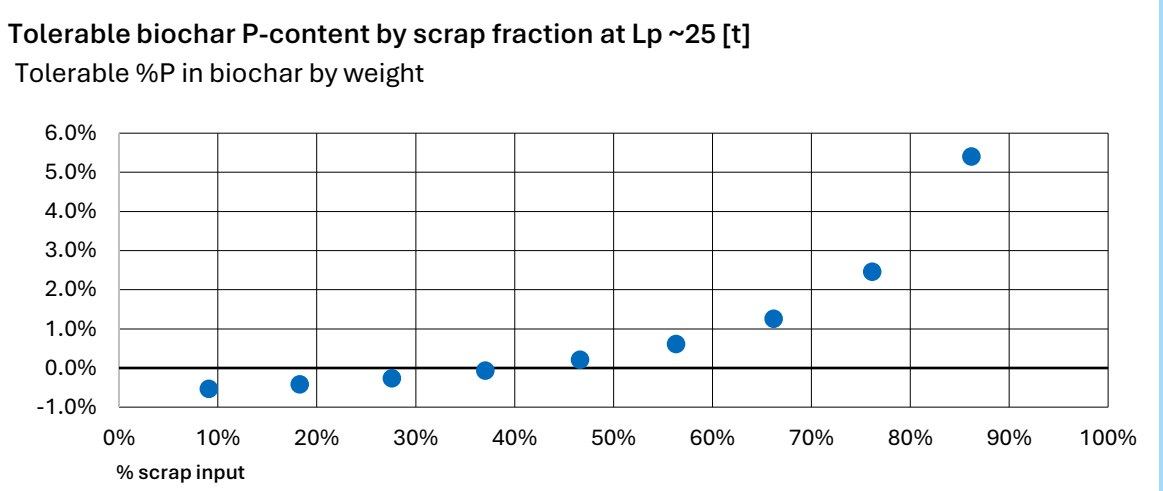


P-budget dynamics

- C-demand and DRI share of iron input is positively correlated.
- P-budget and DRI share of inputs is negatively correlated (at low assumed Lps).



Combined, these have an exponential impact on the tolerable concentration of phosphorus in biocarbon.



Findings – summary

Where phosphorus comes from

- Hydrogen Direct Reduced Iron
- Biocarbon
- Low-quality scrap

Phosphorus budget

Choice of iron source and slag system determines C demand and maximum P in carbon addition.

Phosphorus budget is a **system property.**

Scrap vs DRI

DRI a certain degree of self-mitigation.

Overall – more scrap gives a larger P-budget.

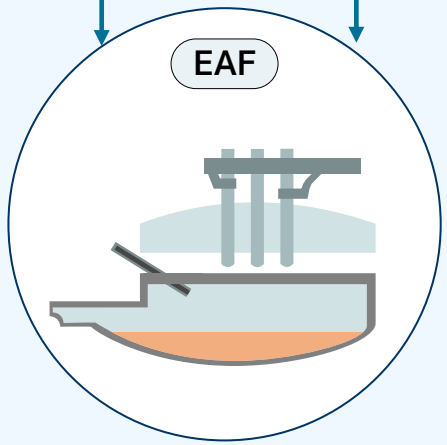
Even 100% DRI allows for more P than anticipated.

Linking models

Metallurgical model

Fossil, Bio-C ratio

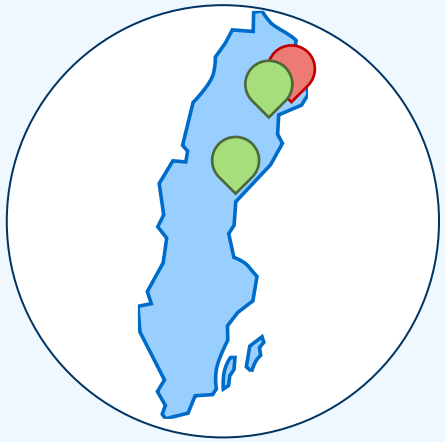
DRI, scrap ratio



Bio C quality (P-budget)

Bio C quantity demand

Biomass supply model



Cost-optimised supply

Biomass sourcing

Integration preferences

Insights on biochar logistics

Cost drivers biocarbon

- Biomass price
- Possibility for bulk transport
- Efficient integrations for pyrolysis process

Cost drivers iron

- Total iron/steel demand
- (high quality) scrap availability
- Hydrogen price§

Implications

- Cheap bio-wastes like sludge have an attraction
- Bulk transportability key factor
- Both sensitive to energy market fluctuations

Conclusions

- Forecasting current production to defossilised operations is flawed
- Slag system optimisation can give raw material flexibility
- Scrap-DRI supply and operational preference has considerable impact of bio-C supply chains
- Aiming for ”worst acceptable” quality can have great impact on Bio-C affordability



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Forskning och Innovation i Norrbotten för Avancerad grön Stålframställning och Tillverkning

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On industrial symbiosis enablers: the importance of facing and solving technical and policy issues

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XIII European Slag Conference, Special Session on Industrial Symbiosis
Luleå-Sweden
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SYMBIO STEEL

Role of the facilitator

The facilitator in an industrial symbiosis system is:

- a **system integrator** → connects actors and resources
- a **knowledge intermediary** → reduces information barriers
- a **trust builder** → enables collaboration
- a **process manager** → supports implementation
- a **catalyst for circular economy** → accelerates innovation and uptake



Project funded by the Research Fund for Coal and Steel (RFCS) G.A. 101156509

Role of the managerial facilitator

- ❑ Create the right consortium
- ❑ Contact with local entities
- ❑ Authorisation process for building new plants (o part of them)
- ❑ Authorisation process for experimental testing
- ❑ Transport of materials in EU
- ❑ Exchange of materials between partners (analysis of regulatory framework and permitting procedures)

Ability to build trust among actors. **Trust** represents a critical enabler of industrial symbiosis, as it mitigates reluctance to share sensitive information and fosters long-term collaborative relationships

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Role of the technical facilitator

- ❑ Create the right consortium
- ❑ Experimental testing at laboratory and/or pilot plant scale
- ❑ Support in the definition of the process conditions
- ❑ Technical meeting in the consortium to discuss bottleneck and next steps

Knowledge-oriented actor, responsible for collecting, translating, and disseminating information among network participants. Knowledge enables organisations to understand each other's processes, resource flows, and constraints, and to identify viable synergies.

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Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis

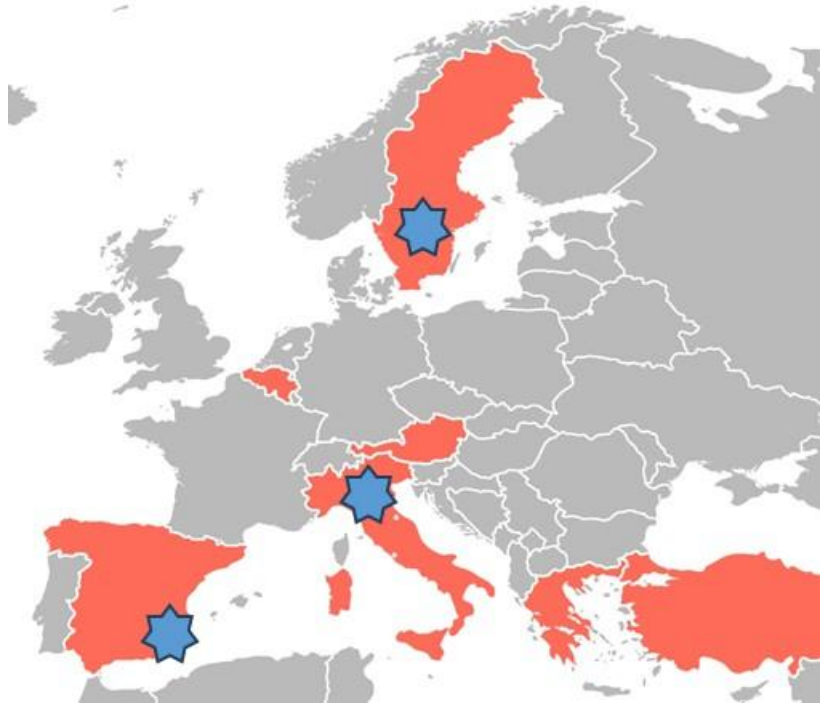
CORALIS

Industrial Symbiosis
in Energy Intensive Industries

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958337.

CORALIS in a nutshell

The main objective of CORALIS is **to create pathways for the decarbonisation** of resource 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.



Topic: CE-SPIRE-01-2020 Tapping into the potential of Industrial Symbiosis.
Grant Agreement no. 958337
29 partners
Period: 1st October 2020 - 31st March 2025

https://www.coralis-h2020.eu/

Fertiberia Demo case



Circular Economy:

- HCl as by-product of KNO_3
- Ca recovered from wastewater for $CaNO_3$
- $CaSO_4$ recovered from wastewater for Ammonia Nitrate and for Ammonia Sulphate

Symbiosis:

- CO_2 from ***Vertex*** (by-product), for sulphate carbonation
- H_2SO_4 from ***Aedmesa*** (by-product), for Ca recovery
- Glycerol from ***Masol*** and ***Repsol*** (by-product), for wastewater treatment
- Phosphate from ***Phosphea*** (rejected product), for wastewater treatment
- Wastewater common problem resolved as Ca is recovered
- Renewable energy plant study for the ***Desalination*** plant, ***QSr*** and the whole Cluster

Frovi Demo case





Objective	Results
Establish an operational industrial symbiosis demonstrator	•10-hectare greenhouse •Operational since May 2024. •8000 tons of tomatoes per year. •> 100 good jobs
Launch a full-scale greenhouse utilizing waste heat	•10 MW waste heat connection •≈85% of heat needs •Low-grade (45°) waste heat.
CO_2 -recycling from flue gases	Bad idea: •Way too costly •80-90% loss
Validate a business model	•Contracted grower tenant •120 m€ financing
Provide data and insights	•Open to research throughout
Showcase as a lighthouse	•Lots of visits and attention

Initial Motivation for Brescia Demo Case

Brescia regional industrial symbiosis initiative was motivated by Confindustria Brescia's strong desire to support local business in significantly reducing the amount of materials disposed in the provincial landfills.



Challenges were:

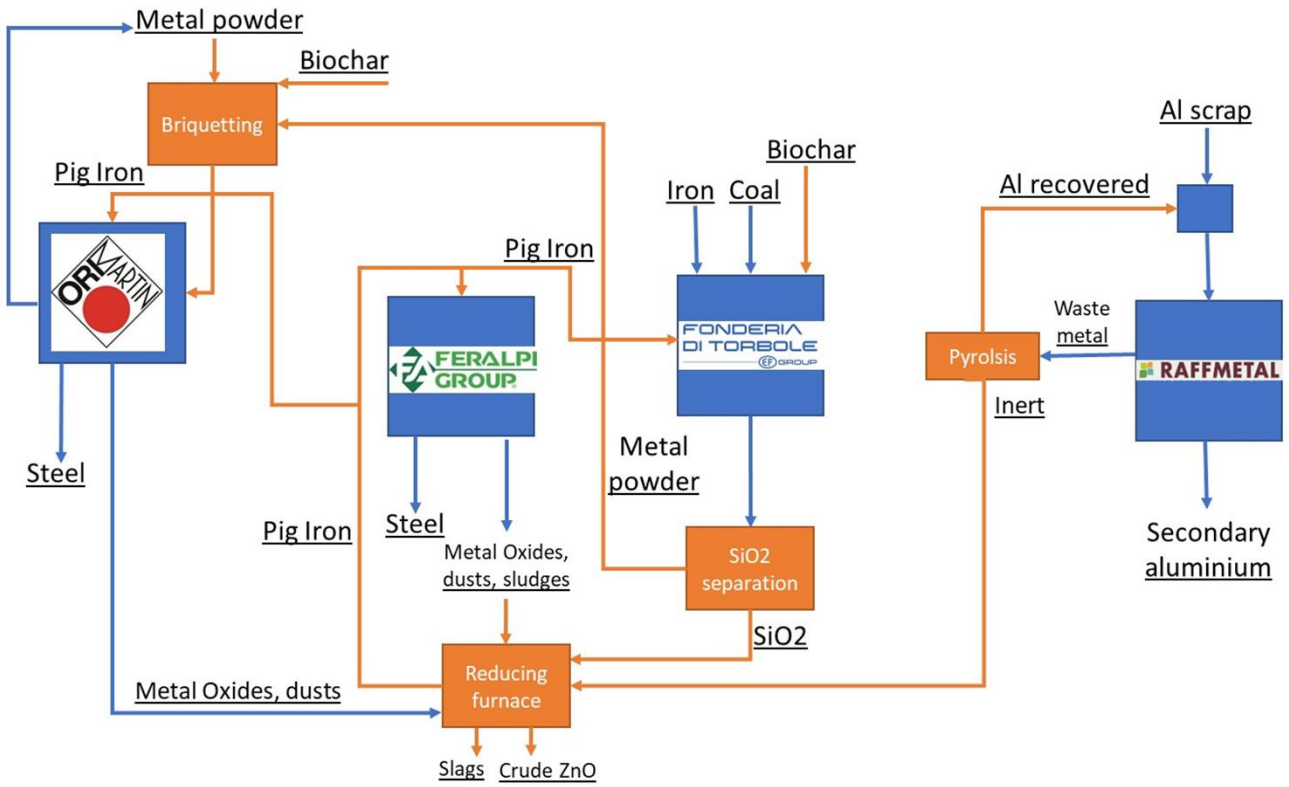
1. to collect metal wastes for their **reintroduction in the value chain** of metals production
2. to **realise synergies** at regional level for waste landfilling prevention,
3. to **reduce cost** connected to both discharge and raw materials
4. to acquire **deeper understanding** on Industrial Symbiosis performance and conditioning factors from the technical, economic and managerial perspective,
5. to find an efficient **solution to avoind the landfilling** of wastes

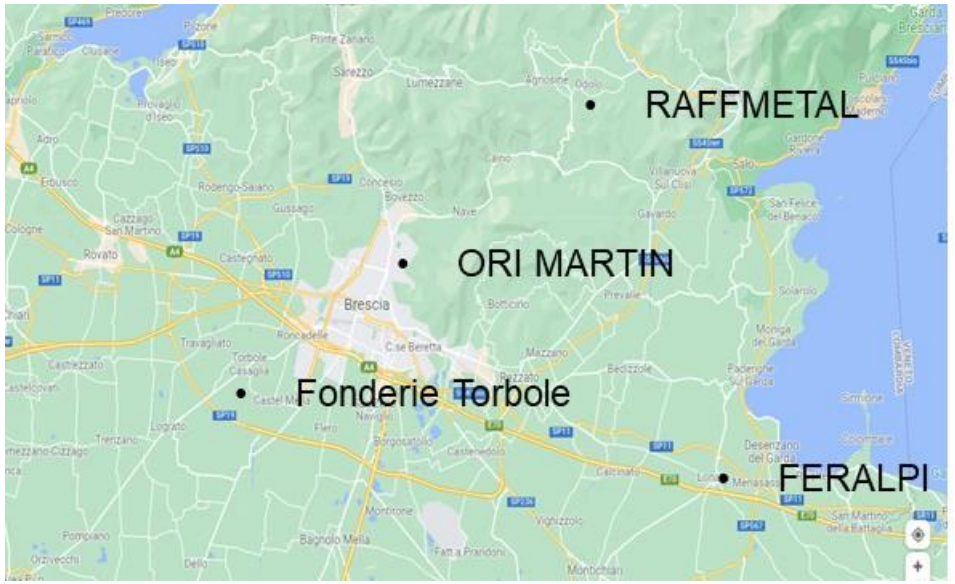






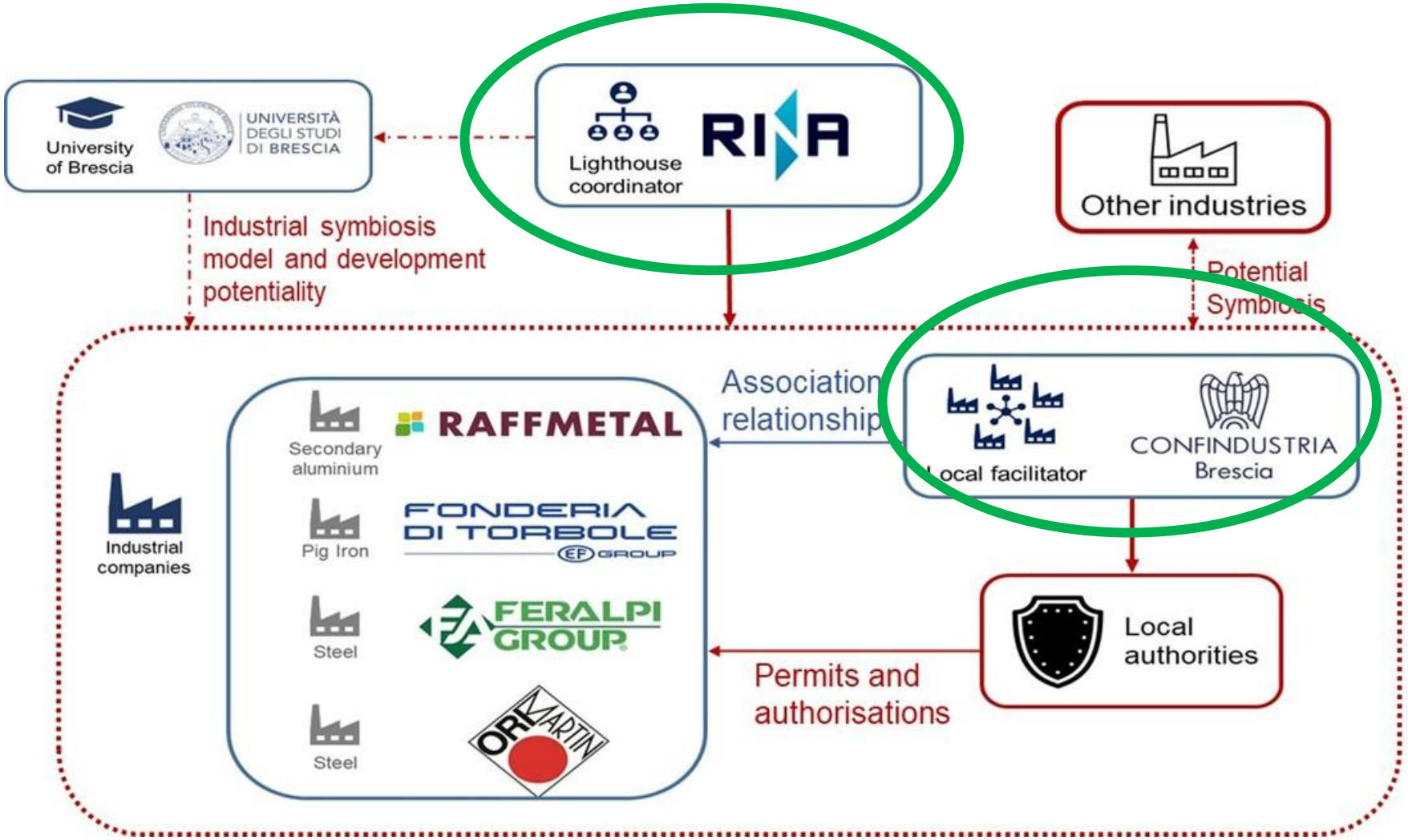
BRESCIA Demo case





Brescia democase, as industrial partners, includes 2 steelworks, 1 cast iron producer, 1 aluminum producer and a facilitators both Rina Consulting – Centro Sviluppo Materiali SpA and Confindustria Brescia.

Industrial Symbiosis Management & Facilitator Role



Technical challenges are complex logistics, ingrained existing methods of dealing with waste, lack of know-how and a high degree of uncertainty about the outcome. Each non-technical challenge has been faced with Confindustria Brescia.

Technical and policy issues of the industrial symbiosis

Technical issues refer to **practical and operational barriers**:

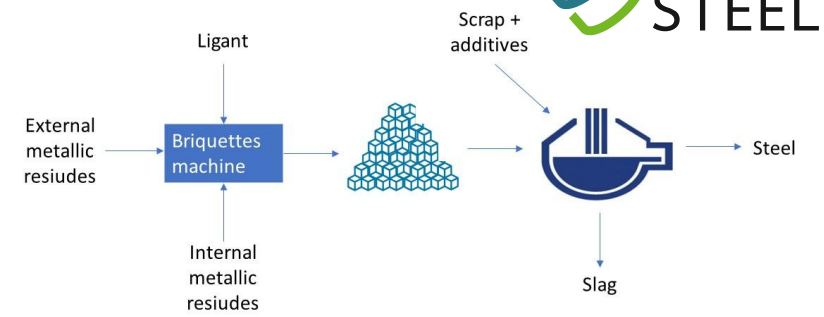
- Compatibility of material flows (quality, purity, variability)
- Need for pre-treatment or processing technologies
- Logistical constraints (transport, storage)
- Lack of standardization or data availability

Policy issues relate to **regulatory and institutional constraints**:

- Waste classification vs. by-product status
- End-of-Waste criteria
- Permitting procedures and administrative burdens
- Lack of incentives for reuse/recovery
- Misalignment between environmental regulations and industrial practice

R&D and validation

The reuse of selected iron residues (not directly usable in the EAF) has lightly reduced the raw materials inlet for metal production. New product have been prepared, such as ferro-alloy and calcium alluminate.



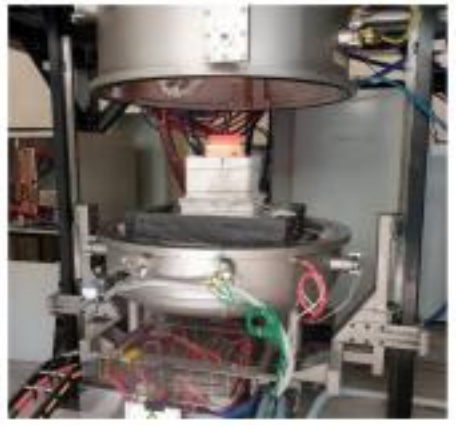


Metal oxide reduction



Ferroalloy production





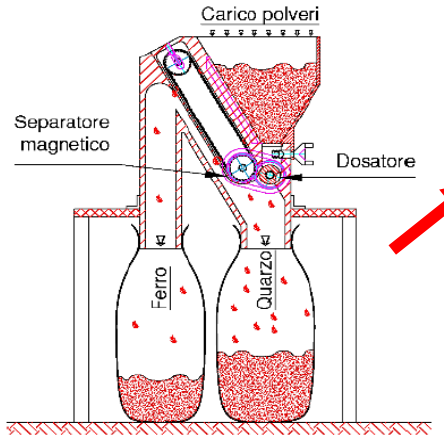




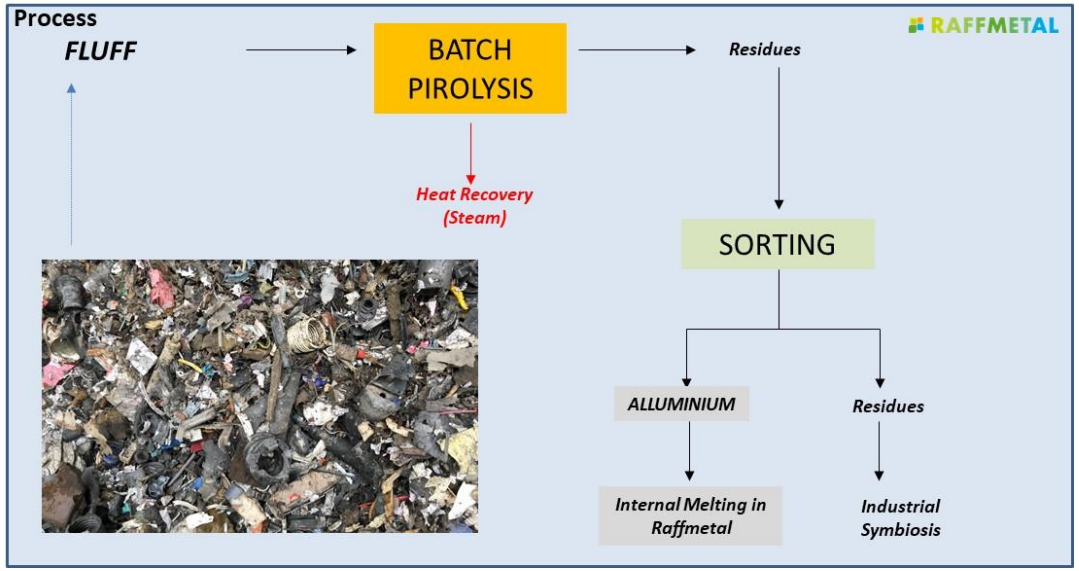
Iron recovery

R&D and validation

A suitable separation technology based on density and magnetic properties has been designed by Torbole. This technology aims to obtain two different streams, metal and silica that can be respectively reused by partners of the IS demo-case.



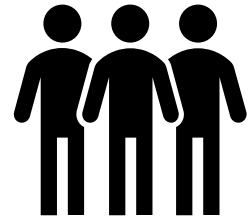




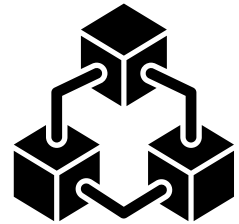
The pyrolysis of Raffmetal organic wastes, a complete novelty, has been deeply analysed and good and worst have been identified.

Conclusion - facilitator

The main characteristics of industrial symbiosis **facilitators** highlight their role as complex, **multi-dimensional actors** that orchestrate collaboration under conditions of uncertainty, enabling the emergence and development of resource-efficient and circular industrial networks



The transition from potential to operational symbiotic exchanges relies on the **systematic identification and resolution of both technical constraints**—such as material compatibility, process integration, and logistics—**and policy barriers**, including regulatory misalignments, permitting challenges, and the absence of supportive frameworks. Addressing these dimensions is essential to unlock scalable and resilient symbiotic networks.



Conclusion - BRESCIA Demo case

The Brescia lighthouse of the CORALIS project provides a clear empirical **demonstration of the critical role of technical and policy enablers** in industrial symbiosis implementation.

From a **technical perspective**, the development and validation of dedicated technologies—such as briquetting units, separation systems, pyrolysis processes, and reducing furnaces—were essential to enable the transformation of heterogeneous industrial residues into secondary raw materials. However, challenges related to material quality, process compatibility, and industrial-scale deployment significantly constrained the full operationalization of the symbiotic network.

Concurrently, **policy-related barriers**, particularly in relation to waste classification, permitting procedures, and regulatory constraints on material exchange, limited the scalability of symbiotic solutions and often confined their implementation to pilot or micro-scale.

The Brescia case therefore highlights that industrial symbiosis is inherently dependent on the joint resolution of technological and regulatory bottlenecks, confirming that these dimensions are not merely constraints but fundamental enablers for the **transition toward circular and decarbonised industrial systems**.



Any questions?

Thank you for your attention!

XIII European Slag Conference, Special Session on Industrial Symbiosis

Open access article on Recent achievements of Industrial Symbiosis in the steel sector

Website: www.symbiosteel.eu

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