Analysis of future challenges in industrial symbiosis due to next generation steelmaking

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Table of content

Summary

The steel industry is undergoing a profound transformation driven by ambitious climate targets, regulatory pressure, and Europe's commitment to deep decarbonization. As conventional, carbon-intensive steelmaking routes are progressively replaced or supplemented by low-carbon technologies, the established frameworks of industrial symbiosis face significant disruption. Industrial symbiosis—long embedded in steelmaking through the valorisation of by-products such as slags, dusts, and sludges or mutual beneficial transactions of other wastes, energy, water, logistics, capacity, expertise, equipment and materials among different sectors—must evolve to remain effective under changing technological and material conditions.

Next-generation steelmaking routes, including hydrogen-based direct reduced iron combined with electric arc furnaces, enhanced scrap-based EAF production, novel smelting reduction processes, and blast furnaces integrated with carbon capture, utilization, and storage, fundamentally alter energy inputs, reductants, and process thermodynamics. These changes directly affect material flows, particularly the formation, composition, and quantity of steelmaking slags, which represent the largest by-product stream. Variations in gangue input, fluxing practices, and operating atmospheres are expected to influence slag basicity, mineralogy, trace element content, and cooling behaviour, with consequences for downstream processing and reuse pathways.

A central challenge for future industrial symbiosis lies in managing increased variability and uncertainty in by-product streams. Fluctuations in chemical and physical properties can compromise the suitability of by-products for established applications such as construction materials, cement production, or metal recovery. Ensuring quality consistency will require systematic characterization, advanced monitoring, and predictive modelling. In parallel, new or modified treatment and conditioning technologies may be needed to address issues such as residual carbon, trace metal content, or altered particle characteristics, while remaining energy- and cost-efficient.

Stakeholder feedback collected within the Symbio-Steel project highlights electrification, circular economy strategies, hydrogen use, and industrial symbiosis as key drivers of steel decarbonization in the coming decade. This underscores the strategic importance of targeted research on industrial symbiosis. Future research must focus on verifying the continued usability of by-products, adapting treatment processes to new material properties, and exploring novel valorisation routes. By proactively addressing these challenges, industrial symbiosis can continue to deliver environmental and economic benefits and support a resilient, low-carbon, and resource-efficient steel industry.

1.Introduction

The steel industry is in a transformation phase driven by climate targets, regulatory pressures, and the European commitment to decarbonization. Traditional steelmaking routes, long associated with high energy consumption and carbon emissions, are increasingly being replaced or complemented by next-generation low-carbon technologies. As Industrial Symbiosis (IS) has always been part of the steelmaking process it is critical to ensure a good continuation during the transformation, fostering the efficient use of resources, energy, and by-products across industrial systems. This report, *"Analysis of Future Challenges in IS Due to Next Generation Steelmaking,"* examines how the evolution of steelmaking processes will affect IS.

The transition toward decarbonized steelmaking—through technologies such as hydrogen-based reduction, electrification, increased scrap utilization, and carbon capture—will significantly alter material and energy flows within and beyond steel plants. These changes can present new challenges for existing IS networks, which have traditionally relied on stable by-product streams and well-established inter-industry exchanges. As production processes evolve, uncertainties related to by-product availability, quality, and infrastructure compatibility are expected to intensify. Consequently, the steel industry will need to foresee and adapt IS frameworks capable of responding to the demand while maintaining environmental and economic benefits.

Looking ahead to the next decade, targeted research and innovation will be essential to support the integration of IS into next-generation steelmaking ecosystems. This report analyses the future challenges and research needs associated with this transition, with the aim of developing comprehensive and forward-looking guidelines aligned with the anticipated needs of the steel industry. By addressing these challenges proactively, IS can play a pivotal role in enabling a resilient, low-carbon, and resource-efficient steel industry.

2. Emerging Steelmaking Technologies

The main next-generation steelmaking routes currently being developed and implemented across Europe include hydrogen-based direct reduced iron (H based-DRI) coupled with electric arc furnaces (EAF), enhanced scrap-based EAF production, new smelting reduction concepts, and blast furnace (BF) routes integrated with carbon capture, utilization, and storage (CCUS). These technological pathways differ in terms of reductants, energy inputs, operating temperatures, and raw material quality requirements, leading to fundamental changes in process thermodynamics and reaction mechanisms. As a result, they introduce new boundary conditions for process integration, resource efficiency, and emissions reduction within steel production systems.

A summary of emerging technologies was described in the InSGeP project and published as Deliverable 2.1 "*Data about future steel production figures and corresponding slag production" March 2024 (1).*

- **H based-DRI** is an ironmaking route that produces iron without BF using iron ore pellets, lump ore, fines or combinations of thereof as feedstock. Iron oxides are reduced using gaseous reductants such as natural gas or hydrogen to form DRI, which is subsequently melted in downstream units—such as EAFs, open slag bath furnaces, or smelters.
    - DRI is a solid metallic iron produced directly from iron ore in a DR furnace. DRI is a porous pellet or lump that can be discharged either hot (HDRI) or cold (CDRI), because of its high porosity and large surface area, it is relatively reactive and most commonly used on-site or nearby in EAF steelmaking (2).
    - Hot briquetted Iron (HBI) is produced from DRI, not directly from iron ore. After reduction in the same DR furnace, the hot DRI is mechanically compacted (briquetted) at high temperature into dense briquettes. This significantly increases bulk density and reduces surface area making HBI much safer and more stable for long-distance shipping (2).

- **DRI/HBI-EAF** route are proven technologies with TRL between 7 and 9 around the world, however it's not currently used in Europe, but few DRI plants are being constructed or planned to be constructed. The DRI/HBI can replace some or all of the scrap in an EAF.
- **Smelter, submerged arc furnace and open slag bath furnace** routes are being investigated in Europe as alternatives to scrap-DR-EAF. The DR method uses high quality iron ores with low levels of impurities which limits the types of ores that can be used. To utilize lower quality ores novel technologies are being developed, adding a melting stage to melt the DRI before charging it in a BOF, instead of an EAF. This electric melting stage is able to eliminate high amounts of gangue from the low-quality iron ore, resulting in hot metal similar to BF. These technologies are around TRL 7.
- **Hydrogen plasma smelting reduction** is a process in which iron ore is reduced and melted using hydrogen in a plasma state rather than through conventional coke-based methods. However, this process needs high quality iron ore (~62% of metal) (3). The technology is estimated at TRL ~6-7.
- **Iron ore electrolysis** uses electricity to convert iron oxides directly into metallic iron, avoiding the carbon-intensive steps of conventional BFs or hydrogen-based direct reduction. In processes such as molten oxide electrolysis (MOE), iron ore is placed in a high-temperature electrolyte and an electric current drives the reduction, producing oxygen at the anode and iron at the cathode (4). The technology is estimated at TRL ~4.

A summary of the current recycling paths for industrial by-products was investigated in an RFCS ReuSteel project, grant agreement number 839227 (5). Specifically current slag utilization paths were also summarized in the InSGeP project and published as Deliverable 2.2 "*Data about slag produced*" *March 2024 (6).*

Currently steel industry by-products are being used as raw materials in other industries, while by-products from other industries are replacing raw materials in the steel industry, this will not change with the emerging technologies as the steel industry has always had a very strong commitment to circular economy and goal of zero waste.

- Slag is used in external applications such as: road construction, civil engineering, aggregates, bituminous mixtures, mortar, slag sand, cement, concrete, asphalt, or liming material/fertiliser, resulting in IS (5)(6).
- Dust and sludge are either recycled internally or externally to recover Zn and Pb, resulting in IS. BOF dusts and sludges are used by the cement industry (7).
- Alternative reducing agents and carbon substitutions in the steelmaking process from other sectors is another example of IS (8).

As the technology and steelmaking will change in Europe to accelerate decarbonisation, it is crucial to continue the research into IS for by-products being used by the steel-industry from other sectors and for the by-products being produced by the steel-industry.

From the perspectives of materials and IS, these emerging steelmaking technologies are expected to substantially modify slag formation mechanisms, chemical composition, and amounts, since slag is the most important by-product in terms of quantity. Changes in gangue input, fluxing practices, reduction atmospheres, and furnace operation may affect key slag properties such as basicity, mineralogical phases, trace element content, and cooling behaviour as well as the resulting specific amount. These alterations have direct implications for downstream slag processing, quality consistency, and suitability for existing or novel valorisation pathways.

A technology-specific understanding of these effects is therefore essential to evaluate future challenges for slag-based IS and to identify research needs that support the integration of next-generation steelmaking routes into circular and low-carbon industrial ecosystems.

Some research on by-products from decarbonized steelmaking started with projects on national, but also European levels. The ongoing research project *InSGeP*, funded by RFCS under the grant agreement number 101112665, investigates possible characteristics of DRI based slag from EAF, Smelter and HPSR to validate possible applications and also necessary treatment methods, to keep the existing applications. A recently finished national project *SAVE CO2 (9)*, funded by the German Federal Ministry of Research, Technology and Space, led to an initial understanding of smelter slag and which slag formers are necessary, on the one hand, to carry out the metallurgical process and, on the other hand, to produce a material that meets the physical and environmental requirements of the cement industry for a comparable material to granulated blast furnace slag (GBFS), up to TRL 7. Several other national projects in different countries focus on DRI based EAF slag, often to create a GBFS like material, due to the expected higher revenue, compared to earthworks, and to continue the well-known cooperation with the cement industry as long-term partner. Just one publicly known project to date has gone beyond the laboratory and technical scale and built a water granulation plant for scrap-based EAF slag, *WAGEOS (10)*. Important aspects here are integration into the existing steelworks process, suitability for cement production, and environmental properties, which currently prevent the use of this slag in many EU countries.

3. Future Challenges for Industrial Symbiosis

One of the primary technical challenges for IS in the context of next-generation steelmaking is the variability and uncertainty of by-product streams. Emerging technologies such as hydrogen-based DRI–EAF, smelting reduction, and CCUS-enabled BFs alter the chemical and physical characteristics of slags, dusts, and sludges. Variations in feedstock composition, reductants, fluxes, and operating parameters can lead to fluctuations in elemental composition, mineral phases, particle size distribution, and moisture content. Such variability directly impacts the suitability of by-products for downstream applications, including construction materials, cement production, or chemical feedstocks. Ensuring consistent quality is therefore a technical priority, requiring systematic characterization, real-time monitoring, and predictive modelling to support reliable IS exchanges and synergies.

New slag compositions or residual streams may require treatment or conditioning to meet application standards. For example, high residual carbon in slags or the presence of trace metals in dust may necessitate thermal, chemical, or mechanical processing before their reuse. Research is needed to identify optimal treatment methods that are both scalable and energy-efficient, while preserving the potential for circular use. Beside slag, also other by-products from steelmaking are reused externally, like dust and sludges, to recover iron and zinc. The increasing capacities of EAF in combination with ratios of DRI/HBI and scrap of approximately 50/50 will lead to new challenges for the zinc and iron recovering industries in terms of technology and economics. Developing adaptable processing techniques will allow IS networks to remain flexible under changing steelmaking conditions and maintain high-value utilization of by-products.

4. Research Priorities

A survey was conducted as part of the Symbio-Steel project to gather knowledge and opinions of relevant stakeholders about the transformation. The question "Which key technological innovations do you think will drive decarbonization in steelmaking in the coming decade?" was asked and the answers are presented in **Figure 1** from 49 participants (46 % directly from iron and steelmaking). From the responses the most relevant technologies are "electrification" (83%), "circular economy" (69%), "use of hydrogen as reducing agent" (61%) and "industrial symbiosis" (57%). Showing a strong need for IS research to continue with the collaboration that has already been developed over decades but also finding new paths to work with other industries.

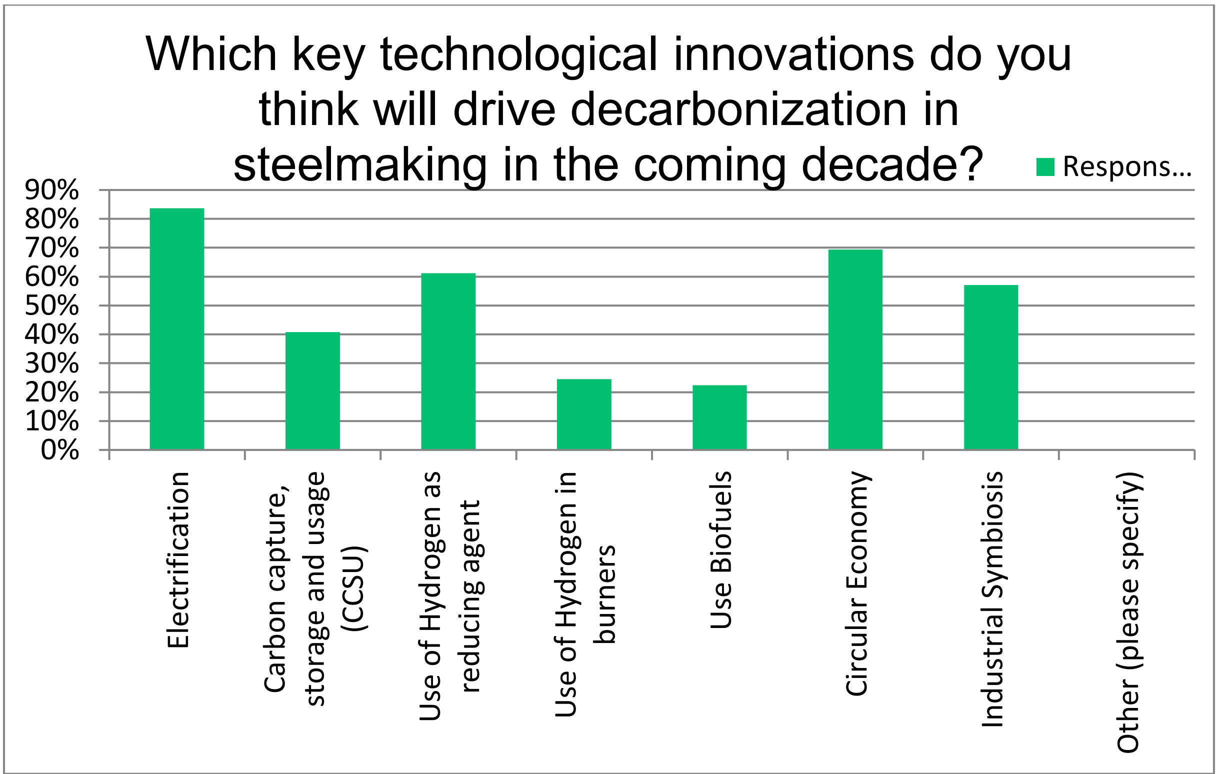

Figure 1: Answer to survey about: Which key technological innovations do you think will drive decarbonization in steelmaking in the coming decade?

The most important changes with respect to IS will come from closing BF and sinter plants while increasing the amount of EAF that will be in operation in Europe or other new steelmaking technologies e.g. smelters, which will result in utilization of DRI/HBI and lower quality scrap to produce metals. Currently about ~47% of steel produced in Europe comes from EAF, however by 2030 it is projected to increase to ~57% (11). This will result in different quality of by-products that will be produced and will need research to make sure that current reutilization paths are adequate or if not, how the by-products must be modified. As part of the previous ReuSteel project, an article was published in 2023 summarizing the future research needs of currently produced by-products as well as some needs due to the decarbonization of the steel industry (12).

Table 1 shows some of the research that will be needed in the context of IS due to the decarbonization of the steel industry.

Table 1: IS research needs due to the transformation of the steel industry.

Research Focus	Description and Objectives	Relevance to IS
Slag	Study chemical composition, mineralogy, and generation rates under next-generation steelmaking conditions; develop treatment or conditioning methods if needed; explore new valorisation pathways.	Ensures continued usability in established applications and enables development of novel IS pathways.
Dust	Characterize dust streams from filters and dedusting systems, including heavy metals and other contaminants; develop stabilization, recycling, or recovery methods other than sinter plant.	Facilitates safe reuse (internal recycling) or external recycling systems for dust or dust and other by-products. Valorisation of dust in metal recovery, supporting circular material flows.
Sludge	Investigate the composition and treatment of process sludges, including residues from wastewater treatment or gas cleaning; assess dewatering, chemical stabilization, or reuse options.	Facilitate safe reuse or valorisation, e.g. similar to dust.
Gas and energy by-products	Optimize capture, cleaning, and valorisation of off-gases from H-DRI, smelting reduction, or CCUS-enabled BF processes; evaluate potential for cross-sector energy use.	Supports energy efficiency and low-carbon integration in IS networks. Support energy recovery.
Water and chemical by-products	Research treatment, recycling, and reuse of process water, cooling water, and residual chemicals; ensure compliance with environmental standards.	Promotes circular water and chemical management across industrial clusters.
Material input variability	Study effects of alternative ores, scrap fractions, and fluxing agents on process stability, by-product characteristics, and product quality.	Ensures compatibility of outputs with existing and novel IS pathways.

It is important that the research into by-products has three components to it:

1. verification that after transformation the by-products can continue to be used in an established way;
2. by-products need to be treated to correspond to the requirements;
3. new paths need to be investigated.

An example is given in **Table 2** based on slag as it represents about 90 % (by mass) of by-products coming from the steel industry representing the biggest potential for IS (4).

Table 2: Research needs based on slag

Research Focus	Description and Objectives	Relevance to IS
Verification of By-Product Usability	Study the chemical, physical, and mechanical properties of by-products from next-generation steelmaking to confirm they meet the requirements of existing applications (e.g., construction, cement, road materials).	Ensures that established IS pathways remain functional despite changes in process conditions and slag composition.
Treatment and conditioning	Develop methods to adjust by-products that no longer meet specifications, including chemical stabilization, thermal processing, or particle size modification.	Maintains compatibility with industrial processes and preserves the value of by-products for symbiotic exchange.
Exploration of new valorisation pathways	Investigate novel applications for altered by-products, such as advanced construction materials, mineral recovery, or alternative chemical feedstocks, using pilot-scale testing and predictive modelling.	Expands IS opportunities, enabling resilient and adaptive networks aligned with circular economy objectives.

5.Conclusions

The decarbonization of the steel industry represents not only a technological transition but also a systemic transformation of material and energy flows that have been optimized over decades. IS has historically been an integral component of steelmaking, enabling the productive use of by-products and fostering strong interdependencies between the steel sector and adjacent industries. As next-generation steelmaking technologies gain prominence, preserving and strengthening these symbiotic relationships becomes both more challenging and more critical.

Emerging production routes such as hydrogen-based DRI-EAF, increased scrap utilization, smelting reduction, and CCUS-enabled blast furnaces introduce new boundary conditions for industrial symbiosis. While these technologies are essential for achieving deep emissions reductions, they disrupt the stability of by-product streams in terms of quantity, composition, and quality. Slag formation mechanisms, in particular, are expected to change substantially due to altered reductants, fluxing strategies, and operating conditions. Given that slags account for approximately 90% of steel industry by-products by mass (4), even modest changes can have far-reaching implications for established valorisation pathways and downstream industries.

One of the most pressing future challenges is the increased variability of by-products. IS relies on predictability and trust between partners, which are difficult to maintain when material properties fluctuate. Addressing this issue will require a shift from static quality concepts toward more dynamic and data-driven approaches. Advanced characterization techniques, real-time monitoring, and predictive process models will be essential tools for anticipating by-product properties and ensuring their reliable integration into external value chains. Without such measures, there is a risk that valuable secondary resources may be downgraded, landfilled, or underutilized, undermining both economic and environmental objectives.

In parallel, the transformation of steelmaking will place new demands on by-product treatment and processing technologies. Higher residual carbon contents, changes in mineralogy, or increased concentrations of trace elements may necessitate additional conditioning steps before reuse. This is particularly relevant not only for slags, but also for dusts and sludges that are currently used for iron and zinc recovery. The growing share of EAF production combined with mixed DRI and scrap inputs is expected to challenge existing recovery routes in terms of both technology and economics. Developing flexible, scalable, and energy-efficient treatment solutions will therefore be a cornerstone of future IS activities.

The results of stakeholder consultations clearly demonstrate that IS is recognized as a key enabler of steel decarbonization, alongside electrification, hydrogen use, and CE strategies. However, maintaining IS under transformed production conditions cannot be taken for granted. It requires targeted research efforts structured around three complementary objectives: first, verifying whether traditional by-product applications remain feasible after process transformation; second, adapting or developing treatment methods to meet evolving quality requirements; and third, exploring new valorisation pathways that align with future material properties and market needs.

Looking ahead, IS should be viewed not merely as a by-product management strategy, but as a dynamic system that co-evolves with steelmaking technologies. Proactive coordination between steel producers, downstream users, technology developers, and policymakers will be essential to ensure that symbiotic networks remain robust during the transition. By embedding IS into the design and deployment of next-generation steelmaking routes, the steel industry can safeguard resource efficiency, reduce environmental impacts beyond direct emissions, and reinforce its role as a cornerstone of a circular, low-carbon industrial ecosystem.

In conclusion, the transformation of steelmaking presents significant challenges for IS, but also offers an opportunity to rethink and modernize long-standing inter-industry collaborations. With focused research, adaptive technologies, and forward-looking frameworks, IS can continue to play a pivotal role in enabling a sustainable and competitive steel industry in the decades to come.

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List of Figures

List of Tables

List of acronyms and abbreviations

BF:	Blast Furnace
CDRI	Cold Direct Reduced Iron
CE:	Circular Economy
CCUS:	Carbon Capture, Utilization, and Storage
D:	Deliverable
DRI:	Direct Reduced Iron
EAF:	Electric Arc Furnace
EU:	European Union
GBFS:	Granulated Blast Furnace Slag
HBI:	Hot Briquetted Iron
HDRI	Hot Reduced Iron
H based-DRI	Hydrogen-Direct Reduced Iron
HPSR:	Hydrogen Plasma Smelting Reduction
IS:	Industrial symbiosis
M:	Month
PU:	Public
RFCS:	Research fund for coal and steel
T:	Task
WP:	Work Package