SYMBIO STEEL

Guidelines to improve current synergies in the steel industry

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Table of content

Summary 5
1.Introduction 6
2. Consolidating Insights from WP2, WP3 and WP4 7
2.1 Insights from the impact assessment (WP3) 8
2.1.1 Fossil carbon replacement is the most mature and most transferable synergy 10
2.1.2 Slag, dust and sludge recycling is well evidenced but concentrated in a handful of projects 10
2.1.3 Evidence of energy efficiency and low-quality scrap recycling have been lacking in projects 11
2.2 Insights from dissemination (WP2) 12
2.2.1 Cross-sector dissemination channel is lacking 12
2.2.2 Engagement is still concentrated among specialists, broader industry and policy audiences remain to be reached 12
2.3 Insights from collaboration with stakeholders (WP4) 12
2.3.1 Stakeholders confirm IS as a top decarbonisation issue, alongside electrification and hydrogen 12
2.3.2 Industrial symbiosis is confirmed as a leading, but not yet universally understood, decarbonisation strategy 13
2.3.3 Slag, heat and off-gases are the most consistently identified underutilised resources 13
2.3.4 Barriers identified by stakeholders 13
2.3.5 Interviews add operational detail on established and emerging synergies 14
2.3.5 Insights from the implementation scenarios 14
3. Success Stories and Lessons from specific projects 16
3.1 REUSteel: two decades of RFCS by-product research 16
3.2 HARMONI: regulatory and standardisation barriers across SPIRE sectors 17
3.3 CORALIS: industrial symbiosis as a business case 18
3.4 SYMBA: AI enabled matching for bio-based symbiosis 19

3.5 INSET: capacity-building and skills for industrial symbiosis 19
3.6 SCALER and EPOS: earlier Horizon 2020 process-industry symbiosis toolkits 20
3.7 Academic evidence: steel slag flows 21
3.8 International perspectives 22
3.9 Corroboration from peer-reviewed literature produced by the Symbio-Steel consortium itself 23
3.10 A note of caution: decarbonization can erode established symbiosis, not only create new pathways 24
3.11 Implementation of roadmaps and standardisation initiatives: Hubs for Circularity, IS2H4C and RISERS 25
4. Challenges and Opportunities: A Consolidated View 27
5. Goals for Enhancing Industrial Symbiosis in the Steel Sector 30
5.1 Goal-setting approach and prioritisation criteria 30
5.2 Discussion of the goals 32
5.2.1 G1 extend EU end-of-waste criteria and clarify REACH 32
5.2.2 G2 durably funded IS facilitators 32
5.2.3 G3 a shared digital matching database for the steel sector 33
5.2.4 Goals G4-G11 33
6. Guidelines to Improve Current Synergies in the Steel Industry 34
6.1 Guidelines for steel producers and plant operators (G1, G3, G4, G6) 34
6.2 Guidelines for downstream users and symbiosis partners (G3, G5, G8, G11) 35
6.3 Guidelines for policymakers and standardisation bodies (G1, G7) 36
6.4 Guidelines for facilitators, researchers and the Symbio-Steel community (G2, G3, G6, G9, G10, G11) 37
7. Conclusions 39
List of Tables 41
Abbreviations and acronyms 42

Summary

Industrial symbiosis (IS) is a practical expression of the circular economy in which under-utilised resources, materials, energy, water, by-products, or expertise, generated by one company or sector are put to productive use by another, generating mutual economic, environmental and social benefits. The European steel industry, as one of the largest generators of solid, gaseous and liquid by-products among the energy-intensive industries, has been an early and active participant in symbiotic exchanges, both by supplying its by-products (e.g., slags, dusts, sludges, off-gases) to other value chains and by absorbing residues from other sectors (e.g., biomass, plastics, off-gases from ammonia or urea production) into its own processes. This deliverable is the concluding output of WP 5 "Towards the future: recommendations and guidelines" of the Symbio-Steel project. It summarises technical and non-technical findings produced in the project (key performance indicator assessment in WP3, demonstration and validation activities carried out in WP4, and the workshops, survey and stakeholder engagement carried out in WP2). It also includes findings from European and international research on IS relevant to the steel sector, including the RFCS dissemination project REUSteel, the Horizon 2020 projects HARMONI, CORALIS, SYMBA, INSET, SCALER and EPOS.

1.Introduction

The Symbio-Steel project aims to accelerate the adoption of IS solutions within the European steel sector by promoting cross-sectoral collaboration, resource efficiency, and circular economy strategies. Building on the objectives of the European Green Deal[1], the project focuses on identifying opportunities to transform steel industry by-products, residues, and energy streams into valuable resources for other industrial sectors. Through the monitoring and dissemination of outcomes from previous national and European projects, Symbio-Steel supports the development of sustainable industrial networks capable of reducing waste generation, lowering CO_2 emissions, and decreasing dependence on virgin raw materials.

The deliverable summarizes WP5 by combining results from T5.1 and T5.2 with the results of the rest of the project (WP2, WP3 and WP4) as well as lessons from parallel European and international initiatives, in order to define concrete, prioritised goals and practical guidelines for the sector.

The deliverable has three aims:

1. Identify the key insights, success stories, challenges and opportunities;
2. Summarize these into a small number of clear and achievable goals for further IS in the European steel industry;
3. Translate these goals into practical guidelines addressed to the different actors: steel producers, plant operators, downstream users, policymakers, standardisation bodies, facilitators and researchers who support IS networks.

[1] European Commission, Communication No. 640, 2019. The European Green Deal; (COM No. 640, 2019), Commission of European Communities, Brussels, Belgium, 2019

2. Consolidating Insights from WP2, WP3 and WP4

Extensive research on IS has been conducted during the Symbio-Steel project which is summarized here and used to obtain guidelines in this deliverable.

- WP3 *Impact assessment*: review best technical practices in projects and defined a set of eleven key performance indicators (KPIs). 82 funded projects (ECSC, RFCS, FP3-FP6, Horizon 2020, Horizon Europe and other fundings) were reviewed[2]. The KPIs covering energy efficiency, direct CO_2 emissions, virgin raw-material substitution, scrap and by-product recycling rates, replacement of fossil carbon materials, reuse of carbon from off-gases, and technology readiness level (TRL), were applied to more than 50 European and nationally funded projects relevant to IS in the steel and related sectors[3]. This provides a quantitative picture of where IS has already delivered measurable results, and where the evidence base remains lacking.
- WP2 *Communication and Dissemination activities*: has organized dedicated IS workshops and stakeholder survey reaching over 100 contacts across more than 50 organisations with 53 responses[4]. This qualitative evidence complements the quantitative KPI results and grounds the guidelines in priorities identified by practitioners themselves.
- WP4 *Enhancement of synergies in Energy Intensive Industries*: four synergies were identified in the project (S1 steelmaking slag valorisation in construction, cement and agricultural value chains; S2 SCCs supplied to EAF steelmaking; S3 steel process gases as feedstock for the chemical sector; S4 external recovery of steelworks heat and cross-sector energy integration) with recommendations of what an exchange needs in order to be implementable, and a minimum dataset with a staged procedure for cross sectorial industrial data exchange.

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[2] Symbio-Steel Deliverable 3.4, Technological solutions for steel-driven industrial symbiosis. Claudia Sergi, Matilde Breda. April 2026. Lead beneficiary: RINA-CSM
[3] Symbio-Steel Deliverable 3.2, Second report on Key Performance Indicators. Kieush, L.; Rieger, J. 29 September 2025. Lead beneficiary: K1-MET
[4] Symbio-Steel Deliverable 2.3, First Dissemination and communication report. Yu, H.; Nylund, E. 3 October 2025. Lead beneficiary: Swerim

2.1 Insights from the impact assessment (WP3)

In WP3 eleven KPIs were developed to allow for comparison of IS outcomes of past and ongoing RFCS, Horizon 2020, Horizon Europe as well as nationally funded projects, and applied them to 58 such projects, of which 22 provided sufficiently detailed data for KPI evaluation[3]. Table 1 summarises the KPI framework and indicates where each indicator is best evidenced to date.

Table 1. Summary of the WP3 KPIs[3]

KPI		What it measures	Where it is best evidenced
1	Energy efficiency	Reduction in specific energy consumption	Underrepresented, further project search needed
2	Direct CO_2 emissions reduction (Scope 1)	% or absolute reduction in process CO_2	Acasos[5], GREENEAF2[6], POLYNSPIRE[7], INITI-ATE[8], FISSAC[9]
3	Reduction in virgin raw material usage	% substitution of virgin inputs by secondary materials	SLASORB[10], SLACON[11], ALTERAMA[12], CORALIS[13], OnlyPlastic[14], BioReSteel[15]
4	Recycling of low-quality steel scrap	Uptake of degraded/mixed scrap grades	Underrepresented, further project search needed

[5] ACASOS (RFCS-CT-2007-00003) Alternate Carbon Sources for Sintering of Iron Ore, 2007-2010
[6] GREENEAF2 (RFSP-CT-2014-00003) Biochar for a Sustainable EAF Steel Production, 2014-2016
[7] POLYNSPIRE (H2020 820665) Demonstration of Innovative Technologies towards a more Efficient and Sustainable Plastic Recycling, 2018-2023
[8] INITI-ATE (H2020 958318) Innovative industrial transformation of the steel and chemical industries of Europe, 2020-2026
[9] FISSAC (H2020 642154) Fostering Industrial Symbiosis for a Sustainable Resource Intensive Industry across the Extended Construction Value Chain, 2015-2020
[10] SLASORB (RFSP-CT-2009-00028) Using slag as sorbent to remove phosphorus from wastewater 2009-2012
[11] SLACON (RFSR-CT-2012-00006) Control of slag quality for utilisation in the construction industry, 2012-2015
[12] ALTERAMA (RFCR-CT-2014-00006) Developing uses of alternative raw materials in cokemaking, 2014-2017
[13] CORALIS (Horizon 2020 GA 958337) Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis, 2022-2025 www.coralis-h2020.eu
[14] OnlyPlastic (RFCS 899415) EAF working with polymers derived from plastic residue in substitution of fossil fuel, 2020-2023
[15] BioReSteel (RFCS 101112383) Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling, 2023-2027

	KPI	What it measures	Where it is best evidenced
5	Slag recycling rate	% of slag recovered/reused vs. produced	SLAGFERTILISER[16], SLACON, CORALIS, Slagreus[17]
6	Dust and sludge recovery and reuse	% of dust/sludge streams recovered	CORALIS
7	Recycling rate of iron rich residues	% of iron-bearing residues recycled	CORALIS
8	Replacement rate of fossil carbon materials	% substitution of coal/coke by alternative carbon	Most widely evidenced KPI 14 projects: Flexinject[18], Acasos, GREENEAF[19]/2, INNOCARB[20], ALTERAMA[21], RIMFOAM[22], POLYNSPIRE, OnlyPlastic, RETROFEED[23], BioReSteel, FLEXCOKE[24], GreenHeatEAF[25], TACOS[26]
9	CO_2 capture rate from process/off-gases	% of process CO_2 captured/reused	Carbon4Minerals[27]

[16] SLAGFERTILISER (RFSR-CT-2011-00037) Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health, 2011-2014
[17] Slagreus (RFCS 847260) Reuse of slags from integrated steelmaking, 2019-2022
[18] Flexinject (RFSR-CT-2008-00001) Flexible injection of alternative carbon material into the blast furnace, 2008-2011
[19] GREENEAF (RFSR-CT-2009-00004) Sustainable EAF steel production, 2009-2012
[20] INNOCARB (RFSR-CT-2010-00001) Innovative carbon products for substituting coke on BF operation, 2010-2013
[21] ALTERAMA (RFCR-CT-2014-00006) Developing uses of alternative raw materials in cokemaking, 2014-2017
[22] RIMFOAM (RFSR-CT-2014-00008) Recycling of industrial and municipal waste as slag foaming agent in EAF, 2019-2023
[23] RETROFEED (H2020 869939) Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock, 2019-2023
[24] FLEXCOKE (RFSR-CT-2013-00001) Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions, 2013-2016
[25] GreenHeatEAF (HEU 101092328) Gradual integration of REnewable non-fossil ENergy sources and modular HEATing technologies in EAF for progressive CO2 decrease, 2023-2026
[26] TACOS (RFCS 847322) Towards A zero CO2 Sintering, 2019-2022
[27] Carbon4Minerals (HEU 101091870) Transforming CO_2 into added-value construction products, 2023-2027

	KPI	What it measures	Where it is best evidenced
10	Share of carbon in process gas transformed into products	% of gas phase C converted to product	Carbon4Minerals
11	TRL	Maturity of the demonstrated solution	Flexinject, POLYNSPIRE, BioReSteel

The following three insights stand out from and are directly relevant to the guidelines developed in this deliverable.

2.1.1 Fossil carbon replacement is the most mature and most transferable synergy

The replacement of fossil coal and coke by alternative carbon materials (e.g. biochar, waste plastics, refuse-derived fuel and other carbon rich industrial residues) is the most frequently and most successfully demonstrated KPI, evidenced across fourteen of the projects reviewed in WP3, from the early RFCS project Flexinject (2008-2011) through to the ongoing BioReSteel project (2023-2027)[3]. Replacement rates of up to 100 % have been demonstrated at pilot or industrial scale in electric arc furnace (EAF) operations (GREENEAF, GREENEAF2, RIMFOAM, OnlyPlastic), and substitution rates of 20-33 % have been shown to be compatible with unchanged coke and sinter quality in cokemaking and sintering (Acasos, INNOCARB, ALTERAMA, FLEXCOKE)[3]. This was highlighted in Deliverable 5.1, that alternative carbon sources are one of the most researched IS pathways[28].

2.1.2 Slag, dust and sludge recycling is well evidenced but concentrated in a handful of projects

KPIs III, V, VI and VII, covering the reduction of virgin raw-material use and the recovery of slag, dust, sludge and other iron-rich residues, include small number of large demonstration projects. E.g. CORALIS, which reported a 100 % slag recycling rate, complete recovery and reuse of dust and sludge, and a 100 % recycling rate for iron-rich residue streams within its Italian demonstration site. The RFCS projects SLAGFERTILISER and SLACON, which achieved slag recycling rates of 82.5-100 % in construction and agricultural applications respectively[3]. The concentration of strong evidence in a limited number of projects indicates that these results have not yet been widely replicated, shown as a barrier in Deliverable 5.2,

[28] Symbio-Steel Deliverable 5.1, Analysis of future challenges in industrial symbiosis due to next generation steelmaking. Morillon, A.; Algermissen, D. Final version, 30 January 2026. Lead beneficiary: FEhS

which found that even technically mature by-products such as ladle furnace (LF) slag remains underexploited outside a small number of well-resourced initiatives[29].

2.1.3 Evidence of energy efficiency and low-quality scrap recycling have been lacking in projects

WP3 explicitly flags KPI I (energy efficiency) and KPI IV (recycling of low-quality steel scrap) as under-represented in the project reviewed, concluding that "further project search should be done" for both[3]. Eight projects were screened in Deliverable 3.3 quantifying KPIs values for three of them[30].

GreenHeatEAF (Horizon Europe, 2023-2026) reported 100 % replacement of the EAF 5th-hole carbon stream with biochar under controlled industrial trials. However, for partial-substitution scenarios closer to routine operation the values reported were under 15 % of total fossil carbon, and 5-13 % in a sensitivity analysis context, illustrating how strongly KPI VIII values depend on which part of the process is being measured. TACOS (RFCS, 2019-2022) tested a range of biogenic and waste-derived carbon carriers, including pyrolysed eucalyptus flakes, in iron ore sintering pot trials, demonstrating fossil-carbon replacement of up to 60 % under optimised conditions. TACOS was framed by its own consortium as work toward zero-CO_2 sintering, yet the only KPI it could evidence quantitatively was fossil carbon replacement (KPI VIII) rather than energy efficiency (KPI I), illustrating KPI I evidence gap. Slagreus (RFCS, 2019-2022) achieved a slag recycling rate of up to 25 % for Fe-enriched BOF slag reused as a substitute for iron ore fines in sinter plants, a markedly lower figure than the near 100 % rates reported for CORALIS and SLACON, because Cr content restricted substitution and high concentrations of Cr and V excluded the calcium rich fraction from fertiliser and cement applications under current EU regulatory limits. This regulation constrained result shows that the waste versus by-product classification barrier identified throughout this report can restrict valorisation even where a technical reuse route exists and has been demonstrated.

Given that by 2030 scrap EAF production is projected to rise from around 47 % to 57 % in Europe, and that this will increasingly involve mixing direct reduced iron (DRI) or hot briquetted iron (HBI) with lower grade scrap[28], this is a significant gap that should be addressed. KPI evidence on how IS can support the efficient recycling of low-quality scrap streams will become more, not less, important over the remainder of the decade as transition to next generation steelmaking takes effect.

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[29] Symbio-Steel Deliverable 5.2, Identification of barriers to industrial symbiosis. Morillon, A.; Algermissen, D. Final version, 4 August 2026. Lead beneficiary: FEhS
[30] Symbio-Steel Deliverable 3.3, Final report on Key Performance Indicators. Kieush, L.; Rieger, J. Final version, 23 March 2026. Lead beneficiary: K1-MET.

2.2 Insights from dissemination (WP2)

WP2 has pursued communication and dissemination strategy combining conferences participating, workshops, newsletters, videos, stakeholder survey, webinar, project website and LinkedIn presence, etc., targeting steel industry stakeholders as well as relevant sectors. The following two insights from engagement actives are relevant to the guidelines developed in this deliverable.

2.2.1 Cross-sector dissemination channel is lacking

The strong engagement achieved in WP2 (over 50,000 LinkedIn impressions, over 1300 reactions, and over 2,100 website views within the project period) as well as active participation in or hosting different activities, such as the session on IS at the FEhS/ESTEP event in Duisburg in 2025, a joint webinar with Jernkontoret on characterisation, reuse and recycling of steel and alloy by-products, workshops on IS in ESTAD 2025, EMECR 2026 and EUROSLAG 2026, etc., indicate a real, unmet demand among industry and research audiences for exactly the kind of cross project synthesis that Symbio-Steel provides[4]. This corroborates the informational barrier findings of Deliverable 5.2, which identified poor information-sharing mechanisms and the absence of shared, sector specific databases as a persistent obstacle to IS uptake[29], and suggests that continued, well-resourced dissemination activity of this kind should itself be treated as an enabling intervention, not merely a reporting obligation.

2.2.2 Engagement is still concentrated among specialists, broader industry and policy audiences remain to be reached

While strong interest by researchers is shown during dissemination events during Symbio-Steel projects, combined with the HARMONI and INSET evidence, there is a pattern: technical knowledge of IS solutions is often available, but the audiences who most need to act on it (plant operational staff, SME by-product users, and regional/national policymakers) are not yet being reached at scale by any single initiative.

2.3 Insights from collaboration with stakeholders (WP4)

The following are insights from the survey conducted in WP2 who's results were interpreted in WP4.

2.3.1 Stakeholders confirm IS as a top decarbonisation issue, alongside electrification and hydrogen

A survey conducted within the project and disseminated from the ESTEP 2025 Spring Dissemination event onward asked stakeholders which technological innovations they expected to drive decarbonisation in steelmaking over the coming decade. Among 53 respondents (47 % working directly in iron and steelmaking), "electrification" (84 %), "circular economy" (70 %), "use of hydrogen as a reducing agent" (62 %) and "industrial

symbiosis" (56 %) were the most frequently cited answers[28]. This result, generated under WP2/WP4/T5.1 and reported in Deliverable 4.1[31], confirms that IS is viewed by the sector's own practitioners as being on a par with electrification and hydrogen as a decarbonisation lever not as a secondary or "nice to have" activity and provides a direct stakeholder mandate for the guidelines in this report.

2.3.2 Industrial symbiosis is confirmed as a leading, but not yet universally understood, decarbonisation strategy

Asked which technological innovations would drive steelmaking decarbonisation over the coming decade, respondents ranked electrification highest (84%), followed by circular economy (70%), use of hydrogen as a reducing agent (62%), industrial symbiosis (56%), carbon capture, storage and usage (40%), use of hydrogen in burners (24 %) and biofuels (22 %)[31]. At the same time a third of respondents (30%) had never encountered the concept of IS before taking the survey, despite 70% already being familiar with it. Notwithstanding the strong ranking IS receives among practitioners who already know the term, basic awareness remains necessary for a meaningful minority of the sector's wider workforce, reinforcing the skills and outreach goals.

2.3.3 Slag, heat and off-gases are the most consistently identified underutilised resources

Asked to identify underutilised resources in their own organisation, respondents most frequently cited EAF slag (62%), followed by heat (57%), BOF slag (51%), LF (49%), wastewater and off-gases (45% each) and sludge (34%)[31]. Almost 77 % of respondents believed these underutilised resources could be exploited within the steel sector, most often citing construction and buildings (78%) and fertiliser production (53%) as the most promising destination industries, followed by energy generation (50%) and agriculture and chemicals (47% each). This is directly consistent with the WP3 KPI evidence on slag, dust and iron-rich residue recovery, and with the construction and cement sector destinations identified for BF and EAF slag[3].

2.3.4 Barriers identified by stakeholders

Deliverable 4.1[31] respondents identified economic barriers as the single largest obstacle to both low-carbon technology adoption (80.56 %) and IS adoption specifically (63.89 %), followed by financial barriers (66.67 % and 52.78 % respectively) and regulatory barriers, which respondents rated as more constraining for IS (58.33 %) than for low-carbon technology adoption generally (55.56 %). Organisational barriers, such as coordination challenges and information confidentiality between companies, and logistics barriers, such as the absence of

[31] Symbio-Steel Deliverable 4.1, Stakeholders consultation report. Sergi, C.; Cirilli, F. April 2026. Lead beneficiary: RINA-CSM/RINA CONSULTING — Centro Sviluppo Materiali

nearby partners, were each cited by roughly two in five respondents as constraints on symbiosis specifically. Half of respondents did not believe current economic incentives were sufficient to encourage IS adoption in the steel industry. This stakeholder evidence adds to, the barriers discussed in Symbio-Steel Deliverable 5.2.

2.3.5 Interviews add operational detail on established and emerging synergies

Five in-dept interviews presented in Deliverable 4.1 add practical details to the survey findings. The BF/BOF steelmaker described symbioses in off-gas recovery, ammonium sulphate production, and zinc-residue marketing, but noted BOF slag "has no market in Italy" despite its value, citing economic sustainability and regulatory classification as key barriers. The Italian EAF steelmaker cited a long-running symbiosis supplying EAF slag to a motorway operator for bituminous products, plus exchanges of LF slag with cement producers and EAF dust for zinc recovery, but flagged waste classification and insufficient stream quantities as major barriers. The Spanish EAF steelmaker identified slags, process gases, waste heat, and metallic by-products as having the greatest symbiosis potential, pointing to digital twins and better monitoring as enablers for scaling spot agreements into broader exchange networks. Among technology providers, Envigas described biocarbon production from certified wood-pellet residues for EAF customers. Tenova highlighted its KT® injector for recycled-plastic injection in EAF, noting that Italian standard UNI 10667-17 classifies qualifying polymers as products rather than waste, easing authorisation. This reinforces core point: resolving waste/by-product classification is often the binding barrier on realising technically proven synergies.

2.3.5 Insights from the implementation scenarios

Deliverable 4.2[32] moves from documented technologies to exchanges that identifiable actors can plan, qualify, operate and verify. Each pathway is described as a complete chain (source, resource, conditioning, transport/infrastructure, receiver, substitution), and four scenarios are developed: S1 (slag valorisation) is supported by the largest number of project entries and the strongest stakeholder signal, S2 (SCCs for EAF steelmaking) has the broadest set of quantified industrial trial results, S3 (steel gases to chemicals) rests on modelled assessment cases with different system boundaries, and S4 (external heat recovery) rests mainly on stakeholder interest and public cases, without a quantified KPI result.

- Implementation needs more than a compatible by-product and receiver. Reviewing CORALIS, Hubs for Circularity, IS2H4C, RISERS and INITIATE, shows that six layers must be considered together: resource, technology, infrastructure, industrial and commercial conditions, governance and information, and impact and replication.

[32] Symbio-Steel Deliverable 4.2, Future IS Scenari. Breda M.; Mirabile D. October 2026. Lead beneficiary: RINA-CSM/RINA CONSULTING — Centro Sviluppo Materiali

- A common ranking of the scenarios is not yet possible. The available documents contain no complete site dataset, comparable delivered costs or common KPI boundaries for any scenario. Deliverable 4.2 therefore introduces no new recycling rates, CO_2 savings, heat exports or investment returns, and presents the scenarios as priorities for detailed site assessment, not as a ranking of environmental or economic performance.
- Data exchange is a functional part of implementation. A minimum dataset and a six-stage procedure (identification, controlled disclosure, technical reconciliation, joint qualification, operational exchange, verification and change control) are proposed, keeping measured evidence, modelled assessment, proposed arrangements and unresolved data requirements distinct. A structured file can serve as a starting point.
- Clusters add value only through an identifiable interaction. Material, energy and integrated multi-resource cluster configurations are described. Locating several bilateral exchanges in one region does not by itself create a combined benefit, and the same gas or heat cannot be credited in full to two uses (for example as chemical feedstock and as fuel).
- Historical availability of a by-product cannot be assumed. Long lived symbiosis assets should be evaluated against the source's expected process development (slag chemistry, gas availability, heat profile), with contracts and designs allowing requalification or alternative supply.

3.Success Stories and Lessons from specific projects

Symbio-Steel is one of several European and international initiatives working on IS in resource and energy intensive industries. This section reviews seven external projects with a close relationship to Symbio-Steel's own goals (REUSteel, HARMONI, CORALIS, SYMBA, INSET, SCALER and EPOS) together with recent peer reviewed evidence on steel slag flows, documented international experience, evidence that decarbonisation can disrupt as well as create IS, and further internal evidence drawn from the project's own KPI monitoring and deliverables, and draws out the lessons most relevant to the goals defined in this report.

3.1 REUSteel: two decades of RFCS by-product research

REUSteel "Dissemination of results of the European projects dealing with reuse and recycling of by-products in the steel sector"[33] is the closest precedent to Symbio-Steel itself, an RFCS dissemination project whose explicit aim was to identify, organise, combine and integrate the most relevant and promising outcomes from a large number of prior and running European projects on the reuse and recycling of steel by-products, to identify areas with promising results for future research, and to evaluate the reasons for success and failure in past projects on scientific, technical, economic and legislative grounds[33/34].

REUSteel's outputs are directly useful to Symbio-Steel's own WP5 in three ways. First, its review of slag reuse, and of by-product reuse in cement production and road construction, provides a technical baseline against which the WP3 KPI results can be compared[34/35]. Second, its explicit objective to identify "non-technological barriers to these innovations … and other actions which can support the elimination of such barriers"[33] identified some barrier categories used in Symbio-Steel Deliverable 5.2 (regulatory/legal, economic/market,

[33] . REUSteel (RFCS GA 839227) "Dissemination of results of the European projects dealing with reuse and recycling of by-products in the steel sector" 2019-2021 www.reusteel.eu
[34] Colla, V.; Branca, T.A.; et al. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. Metals/Matériaux, 2020. www.mdpi.com/657606
[35] REUSteel, Project overview. https://www.reusteel.eu

organisational/managerial, informational and social/cultural)[29], indicating that these barrier categories are stable and recurring across the sector rather than specific to the current policy moment. Third, a 2023 REUSteel paper[36] on future research and development needs for steelmaking by-products organises those needs around the same three part logic later adopted in Symbio-Steel Deliverable 5.1, verifying continued usability of by-products, adapting treatment methods, and exploring new valorisation pathways, which reinforces the robustness of that framing for the guidelines developed in this report[28/34].

3.2 HARMONI: regulatory and standardisation barriers across SPIRE sectors

HARMONI "Harmonised assessment of regulatory bottlenecks and standardisation needs for the process industry"[37] addressed non-technological barriers across all eight sectors of the SPIRE public private partnership (chemicals, steel, ceramics, cement, minerals, metals, water and engineering), with the explicit aim of identifying and prioritising regulatory and standardisation barriers common to these sectors and of building a collaboration network with EU regulatory authorities and standardisation bodies to address them[37/38].

Two HARMONI findings are particularly relevant to Symbio-Steel. First, HARMONI's cross sectoral methodology demonstrated that many of the barriers the steel sector stakeholders experience as sector specific (unclear end-of-waste criteria, slow or inconsistent standardisation, fragmented national implementation of EU directives) are shared with cement, minerals and chemicals industries, meaning that steel only advocacy is less likely to succeed than coordinated, cross-sectoral engagement with regulators and standardisation bodies of the kind HARMONI itself modelled[37]. Second, HARMONI's transferability analysis explicitly recommends structured attention to the "attitudes" and "motivation" of the people who must implement a transferred innovation, not just its technical and regulatory feasibility, as a precondition for successful technology or practice transfer between sectors and sites[38]. This is a direct precedent for the organisational and social barriers cited in Symbio-Steel

[36] Colla, V.; Branca, T.A.; Pietruck, R.; Wölfelschneider, S.; Morillon, A.; Algermissen, D.; Rosendahl, S.; Granbom, H.; Martini, U.; Snaet, D. Future Research and Developments on Reuse and Recycling of Steelmaking By-Products. Metals 2023, 13, 676. https://doi.org/10.3390/met13040676

[37] HARMONI (Horizon 2020 GA 768755), "Harmonised assessment of regulatory bottlenecks and standardisation needs for the process industry" 2017-2019 www.aspire2050.eu/harmoni

[38] HARMONI Deliverable 5.2, List of areas with high transferability potential. https://www.aspire2050.eu/sites/default/files/users/user740/harmoni_d5.2_areas_transferability_potential_fv.pdf

Deliverable 5.2[29], and supports treating regulatory engagement and human/organisational factors as complementary, not competing, priorities in the guidelines.

3.3 CORALIS: industrial symbiosis as a business case

CORALIS "Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis"[13] is the largest and most directly comparable demonstration project reviewed in this report. It combined new business and management strategies with technology-based enablers across three "lighthouse" demonstration areas: chemicals/minerals/water in Spain, steel/cast iron/aluminium in Italy, and farming/energy in Sweden, plus three other sites in Spain, Austria and Turkey intended to replicate the approach after the project's end[13].

CORALIS's relevance to Symbio-Steel is both quantitative and qualitative. Quantitatively, its results feed directly into the WP3 KPI framework: within its Italian (steel-centred) demonstration site, CORALIS reported a 100 % slag recycling rate, complete recovery and reuse of dust and sludge generated by rolling-mill operations, a 100 % recycling rate for iron-rich residue streams, and a 1.6 % reduction in virgin raw-material use[3]. At its Spanish site (Escombreras), industrial residues were reported to have replaced virgin raw materials in the recovery of hydrochloric acid and calcium carbonate, cutting CO_2 emissions by 96 % and energy use per tonne by 70 % at TRL 6[39]. Qualitatively, independent syntheses of CORALIS's experience across its six demonstration and follower sites converge on the same enabling factors: dedicated IS facilitators, active local authority support, streamlined permitting, and structured public private partnership arrangements were consistently associated with successful, durable symbiosis, while the project's closing assessment explicitly frames these managerial and governance factors as being at least as important as the underlying technology. This "facilitator" findings were flagged in Symbio-Steel Deliverable 5.2 as decisive for overcoming organisational barriers, based on the independent, large-scale demonstration evidence behind them. CORALIS also produced roadmaps for its regions, a Symbiosis Readiness Level scale, guidance on legal environments and on pricing exchanged products and services, and a digital monitoring tool, treating technical feasibility as only one stage of a staged implementation roadmap.

[39] European Commission, CORDIS, CORALIS, Periodic final reporting cordis.europa.eu/project/id/958337/reporting/de

3.4 SYMBA: AI enabled matching for bio-based symbiosis

SYMBA "Securing Local Supply Chains via the Development of New Methods to Assess the Circularity and Symbiosis of the Bio-based Industrial Ecosystem"[40] targets the bio-based sector rather than steel directly, but its methodology is highly transferable. SYMBA project was ongoing during the writing of this report, and final results were not available. The project aims to devise and validate a replicable IS methodology tailored to local and regional bio-based industrial ecosystems, to define criteria for selecting regional IS hubs, and to build an AI-supported database and matching platform that suggests candidate symbiosis processes, monitors circularity, and connects potential partners across agriculture, chemicals, plastics and textiles value chains.

The relevance of SYMBA's approach to the steel sctor is twofold. First, several of the biomass-derived waste streams SYMBA investigates (residues from potato and grain processing, sawdust, lignin) are the same categories of alternative carbon feedstock explored in the steel-sector RFCS projects reviewed in WP3 (Acasos, GreenEAF, GreenEAF2, INNOCARB, BioReSteel), so SYMBA's growing evidence base on biomass characterisation and logistics is a directly relevant knowledge source for steel-sector alternative carbon research going forward. Second, SYMBA's core proposition that a digital, AI-supported matching platform can substantially reduce the informational asymmetry between potential symbiosis partners, responds directly to the "informational and knowledge barriers" presented in Symbio-Steel Deliverable 5.2, and to the recommendation made there that shared, quality assured digital databases and AI-based matching tools should be developed for the steel sector[40/29].

3.5 INSET: capacity-building and skills for industrial symbiosis

INSET "Industrial Symbiosis for Enterprises and Training"[41] addresses a barrier category that neither REUSteel, HARMONI, CORALIS nor SYMBA targets directly: the shortage of people trained and confident enough to plan, broker and manage IS partnerships. INSET has produced a 100-hour certified training curriculum for "IS Planners and Managers", a collection of ten best practice case studies from diverse sectors, a networking handbook to help stakeholders identify potential synergy partners, and a mobile app consolidating these resources.

Two elements of INSET's experience are directly relevant to the steel sector. First, a series of INSET "roadshow" workshops held across Barcelona, Yecla (Murcia), Kaunas and northern Italy between September and November 2025 deliberately varied their target audience by location (mixed stakeholder groups (public authorities, companies, consultants) in Spain,

[40] SYMBA (Horizon Europe GA 101135562). 2024-2026 www.symbaproject.eu
[41] INSET (Erasmus+) 2023-2026 inset-symbiosis.eu

university students (the future workforce) in Lithuania, and business leaders in Italy) while keeping each session's objectives sharply focused. Participant feedback confirmed that this combination of a shared toolkit with locally tailored delivery was what made the training useful. This is a directly usable template for the workforce and skills guidance developed in this report. Second, INSET's own framing links its skills agenda explicitly to the same policy drivers as Symbio-Steel (Green Deal Industrial Plan and the need to reduce low-skilled activity in waste management in favour of higher-value symbiosis-brokering roles) reinforcing the WP2 stakeholder finding that "young people" and workforce/skills questions are a named target audience for Symbio-Steel's own dissemination strategy.

3.6 SCALER and EPOS: earlier Horizon 2020 process-industry symbiosis toolkits

SCALER "Scaling European Resources with industrial symbiosis"[42] and EPOS "Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis"[43] predate REUSteel, HARMONI and CORALIS but remain directly relevant, because both treated the steel sector as one of several process industries to be served by a shared IS toolkit rather than a single-sector programme. SCALER set out to assess around 1,000 potential industrial synergies, support 30 regions in transitioning to IS practices, and reach 500 industrial sites, producing best-practice guides, action plans and transferability assessments intended to speed up implementation across the whole European process industry. EPOS brought together five process sectors — steel, cement, chemicals, minerals and water — including ArcelorMittal within its French demonstration cluster, and delivered a "toolbox" of technological and organisational options for cross-sectoral symbiosis.

EPOS's Humber-region case study was a resource exchange between the petrochemical producer INEOS and the cement producer CEMEX, separating a high-calorific waste liquid fuel so its organic fraction could be used as a cement-kiln fuel, is instructive for the guidelines in this report even though the participating sites are not steelworks. The exchange was technically and economically viable (an estimated 1,200–1,400 tonnes of CO_2 saved per year, with payback within two to three years) but implementation depended on the material first being reclassified out of hazardous waste status through a new permit[44]. This is a second,

[42] SCALER (Horizon 2020 GA 768748), "Scaling European Resources with industrial symbiosis" 2017-2020 cordis.europa.eu
[43] EPOS (Horizon 2020 GA 679386), "Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis" 2016-2020 www.spire2030.eu/epos
[44] Society of Chemical Industry (SOCI). Industrial symbiosis comes to Hull with SPIRE Horizon 2020 project EPOS. https://www.soci.org/news/general-news/industrial-symbiosis-comes-to-hull

independent confirmation, alongside the Piemonti et al.[45] evidence, that waste/by-product reclassification, rather than technology or economics, is frequently binding on realising an already identified synergy, reinforcing the priority.

3.7 Academic evidence: steel slag flows

Beyond funded projects, peer-reviewed research provides an important complementary evidence base. A particularly relevant study by Piemonti, Conforti, Cominoli, Luciano, Plizzari and Sorlini (2023)[45] used a Mass Flow Analysis, combining regional and provincial waste declaration databases with questionnaire data from steelmaking and slag treatment/recovery companies, to map the actual fate of EAF and LF slag in the Province of Brescia, Italy. One of Europe's most concentrated steelmaking regions, with eleven steel mills producing around 1.1 million tonnes of slag per year.

The study's findings give unusually granular, quantitative support to the barrier analysis in Symbio-Steel Deliverable 5.2. Only 18 % of slag classified as "waste" in the province was destined for recovery in 2017, rising to 25 % in 2018, with the remainder sent to landfill despite well established, standards-compliant reuse routes in road construction and concrete production. Even the slag with the strongest technical case for reuse was rarely classified as a "by-product" rather than "waste". EAF slag achieved by-product status in only 10-20 % of cases depending on the year, and LF slag in effectively none, principally because producers found it difficult to demonstrate the "certainty of use" condition required under Article 5 of the EU Waste Framework Directive[46], and therefore preferred to route residues to dedicated waste treatment plants rather than pursue by-product status. The authors conclude that regional or national IS initiatives, supported by mass flow analysis planning tools, are needed to establish the demonstrable certainty of reuse that the by-product classification requires[45]. An empirical, regionally specific confirmation of the regulatory barrier findings and recommendations already set out in Symbio-Steel Deliverable 5.2.

A second, related insight from this study is that no single existing regional database (in their case, Lombardy's MUD waste declaration system) is sufficient on its own to monitor IS performance, because it captures only material classified as waste and not the 30-40 % of annual slag production already classified as by-product, and cannot distinguish between EAF and LF slag despite their very different reuse characteristics. Combining regulatory databases with sector consortium data and direct company questionnaires, as the authors did, was

[45] Piemonti, A.; Conforti, A.; Cominoli, L.; Luciano, A.; Plizzari, G.; Sorlini, S. 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
[46] Article 5 of the EU Waste Framework Directive (2008/98/EC)

necessary to obtain a reliable picture. This was a finding with direct implications for how Symbio-Steel's own recommended shared databases and monitoring tools should be designed.

3.8 International perspectives

Although the great majority of the sources reviewed in this report are European, IS is a global practice, and experience from outside Europe offers additional, sometimes contrasting, lessons for the goals defined in this report.

East Asian eco-industrial parks provide some of the longest running and most directly steel relevant international case studies. In the Caofeidian Industrial Zone in China, a designed program of material recycling and graded (cascading) energy use created an explicit symbiosis between the steel industry and seawater desalination, illustrating a steel utility pairing not prominent in the European case studies reviewed[47]. China's National Demonstration Eco-Industrial Parks program, launched from the Guangxi Guitang Group park in 2001 and now covering more than 200 approved parks, was itself explicitly modelled on earlier programs in the United Kingdom, Japan and South Korea, and empirical analysis of Chinese data found that designation as a National Demonstration Eco-Industrial Park increased local carbon emission efficiency by around 3.5 % on average, driven mainly by industrial structure upgrading and green technological innovation[48/49]. In South Korea, the Ulsan eco-industrial complex evolved from spontaneous, bilateral exchanges into a systematically expanded, policy-supported symbiosis network, and comparative analysis of the Ulsan case alongside sites in China and Japan concludes that top-down policy design and bottom-up spontaneous company action are not alternatives but complements, durable IS networks in East Asia combined both[50/51]. In Japan, quantitative assessment of the Kawasaki eco-town, which includes major steelmaking and related heavy industry facilities, demonstrated measurable material and energy flow

[47] Journal des Sciences Sociales (Facts Reports). Industrial symbiosis: practices in China's industrial parks. https://journals.openedition.org/factsreports/6635
[48] Trellis. Lessons from China's industrial symbiosis leadership. https://trellis.net/article/lessons-chinas-industrial-symbiosis-leadership
[49] Does Industrial Symbiosis Improve Carbon Emission Efficiency? Evidence from Chinese National Demonstration Eco-Industrial Parks. Sustainability 2024, 16, 828. https://www.mdpi.com/2071-1050/16/2/828
[50] Park, H.; Rene, E.; Choi, S.; Chiu, A. Strategies for sustainable development of industrial park in Ulsan, South Korea — From spontaneous evolution to systematic expansion of industrial symbiosis. Resources, Conservation and Recycling. https://www.sciencedirect.com/science/article/abs/pii/S0301479707000175
[51] Evolution of 'designed' industrial symbiosis networks in the Ulsan Eco-industrial Park: 'research and development into business' as the enabling framework. https://www.sciencedirect.com/science/article/abs/pii/S0959652612000832

benefits from combined urban and IS, reinforcing the case for planning IS jointly with municipal infrastructure rather than treating it as a purely company matter[51/52].

Taken together, this international evidence reinforces two points made elsewhere in this report, from a European perspective, that sustained policy support and dedicated facilitation matter as much as the underlying technology, and that IS benefits from being planned at a defined territorial scale, while also suggesting an opportunity not yet prominent in the European steel sector projects reviewed: closer integration between steelworks and municipal or utility infrastructure (water, district heating, waste management), of the kind achieved at Caofeidian and Kawasaki. This is reflected in the goals proposed in this report.

3.9 Corroboration from peer-reviewed literature produced by the Symbio-Steel consortium itself

Beyond the internal evidence reviewed, members of the Symbio-Steel consortium have also published an independent, peer-reviewed systematic literature review of IS in the steel sector, covering 49 studies published between 2019 and 2025 and identified through the Scopus and Web of Science databases[53]. Although produced under the same project, the paper is a separately peer-reviewed output, and its conclusions are important to mention here. First, it confirms, through a systematic literature search that regulatory, informational, economic, technological and organisational barriers recur consistently across the wider IS literature, not only in the steel sector, giving the barrier identified throughout this report additional external validity. Second, it identifies two emerging technical pathways not otherwise covered in this deliverable: mineral carbonation of BOF slag to produce stable silicates and carbonates, which one cited study found could sequester over 1,400 tonnes of CO_2 per year at pilot scale while producing a construction and agriculture grade product, and the INITIATE concept, in which steelworks off gases are used as feedstock for ammonia and urea production. A 2025 techno-economic assessment of INITIATE found the concept could reduce net CO_2 emissions by 1,365-1,546 kg CO_2 equivalent per tonne of steel (about double the reduction achieved by the

[52] van Berkel, R.; et al. Quantitative Assessment of Urban and Industrial Symbiosis in Kawasaki, Japan. Environmental Science & Technology. https://pubs.acs.org/doi/10.1021/es803319r
[53] Colla, V.; Branca, T.A.; Petrucciani, A.; Sergi, C.; Mirabile, D.; Cirilli, F.; Morillon, A.; Algermissen, D.; Wang, C.; Nylund, E.; Yu, H.; Jarnerud Örell, T.; Rieger, J.; Kieush, L.; Snaet, D. Recent achievements of Industrial Symbiosis in the steel sector based on the Symbio-Steel project: a review. Matériaux & Techniques 2026, 114, 103. https://doi.org/10.1051/mattech/2026002

reference case it was benchmarked against) using sorption-enhanced water gas shift technology for simultaneous carbon capture and hydrogen/nitrogen production[54/55].

A second, independently authored systematic review reaches a complementary conclusion from outside the Symbio-Steel consortium where it explicitly frames its contribution as moving beyond localised, discrete waste exchange case studies toward quantifying the benefits and barriers of IS at the scale of the whole steel supply chain, and it flags variable by-product quality, regulatory hurdles and high upfront infrastructure costs as the main obstacles to wider adoption[56]. That a second article published within weeks of Symbio-Steel article in early 2026 and using different search strategies, converge on the same barrier categories identified in Symbio-Steel Deliverable 5.2 is a further, external instance of the convergent evidence argument made in this deliverable.

3.10 A note of caution: decarbonization can erode established symbiosis, not only create new pathways

As previously noted, next-generation steelmaking routes will change the composition and volume of steel by-products. A 2025 study of the United Kingdom's cement and steel sectors adds a point that is not otherwise reflected in this deliverable or its predecessors: decarbonisation can eliminate an established symbiotic exchange altogether, not merely change its characteristics[57]. Ground granulated blast furnace slag (GGBS) is a by-product of the primary BF steelmaking route, and the exchange is the oldest and longest running example of IS in the sector. It is a low carbon substitute for a significant share of Portland cement in the UK. Using material flow analysis, life-cycle assessment and economic modelling, the study shows that as UK steelmakers complete the shift from primary BF production to secondary, EAF production in pursuit of their own net zero targets, domestic GGBS output is projected to fall sharply, since EAF steelmaking does not produce BF slag in comparable form or volume. Cement producers who have built their own decarbonisation plans around continued GGBS

[54] Zecca, N.; Lücking, L.; van Dijk, H.A.J.; Manzolini, G. Techno-Economic Assessment of Industrial Symbiosis Between Steel and Urea Plants: The INITIATE Process. Energy & Fuels 2025. https://doi.org/10.1021/acs.energyfuels.5c04026
[55] INITIATE (Horizon Europe), project reference cited in Colla et al. 2026 [38] and in Symbio-Steel Deliverable 3.2 [3] as an example KPI II project; see reference 39 for the associated techno-economic assessment.
[56] A critical review on industrial symbiosis applied to the steel manufacturing. Environmental Technology Reviews 2026, 15(1), 97–117. https://doi.org/10.1080/21622515.2025.2608249
[57] From symbiosis to scarcity: evaluating disruption associated with decarbonisation to circular waste materials between the UK cement and steel sectors. Resources, Conservation and Recycling, 2025. https://www.sciencedirect.com/science/article/abs/pii/S0921344925004379

availability therefore face a supply risk created directly by the decarbonisation of an upstream symbiosis partner.

This finding matters for the goals and guidelines in this deliverable in a way distinct from the KPI I/IV evidence gap discussed or the by-product characterisation goal. It is not only that new by-product streams need characterising as steelmaking technology changes, but that some of the steel sector's best established, highest volume symbioses may need to be actively decreased, with their downstream partners supported through the transition, rather than simply monitored and adapted. The UK cement-steel evidence suggests this assumption should not be taken for granted for every established exchange, and that downstream partner sectors warrant their own line of engagement among the goals set out in this deliverable.

3.11 Implementation of roadmaps and standardisation initiatives: Hubs for Circularity, IS2H4C and RISERS

Deliverable 4.2[32] reviewed recent implementation roadmaps to establish what must be in place before a technically demonstrated synergy becomes an operating exchange. Three of them add to the evidence above. The Processes4Planet topic on Hubs for Circularity (H4C) calls for systemic integration of mass and energy flows, industrial infrastructure and logistics, digital modelling and sensing for dynamic resource management, and IT infrastructure that protects commercially sensitive information. IS2H4C [58] combines IS implementation with digital collaboration and decision-support tools, including a platform for sharing resources, infrastructure and information within such hubs. RISERS is developing a roadmap for IS standardisation to facilitate resource sharing, identify gaps in sectoral standards, support market uptake and strengthen cross-sector interoperability. Both RISERS and IS2H4C are still developing their outputs, so the points below reflect their stated approach rather than final results.

Three lessons from the guidelines: First, a scenario cannot be defined only by a compatible by-product and receiver: physical infrastructure, geographical proximity, the temporal profile of the resource, continuous information exchange, confidentiality management and coordinated planning among several actors can each decide whether an exchange works, which reinforces the territorial and cluster perspective. Second, RISERS[59] shows that resource compatibility does not guarantee implementation unless there are mutually accepted approaches to resource classification, quality specification, characterisation, product acceptance, data communication and performance verification, which adds a standardisation

[58] IS2H4C (HEU 101138473) From Industrial Symbiosis to Hubs for Circularity, 2024-2028
[59] RISERS (HEU 101135539) A Roadmap for Industrial Symbiosis Standardisation for Efficient Resource Sharing, 2024-2026

dimension to the regulatory needs. Third, IS2H4C supports treating information requirements as a functional part of implementation rather than an administrative add-on, and considering networks rather than only bilateral exchanges.

4. Challenges and Opportunities: A Consolidated View

Sections 2 and 3 reviewed a wide range of evidence on the state of IS in the steel sector. This section consolidates that evidence into a single set of challenges and corresponding opportunities, organised under the same themes used in Symbio-Steel Deliverable 5.2, plus four additional themes (technology transition, territorial/infrastructure integration, decarbonisation driven exchange erosion and implementation readiness/evidence comparability) that emerged from Deliverable 4.2, Deliverable 5.1, from the international evidence reviewed, and from the UK cement-steel study. Table 2 summarises this consolidated view. The discussion below highlights the points where the evidence gathered for this deliverable adds most to the picture already established in 5.1 and 5.2.

Table 2. Challenges and corresponding opportunities for IS in the steel sector

Topic	Challenge	Corresponding opportunity
Regulatory Legal	Fragmented, national or single case end-of-waste decisions; difficulty demonstrating "certainty of use" under WFD Art. 5; unclear REACH interaction[29/45]	Extend EU end-of-waste criteria to prioritise slag streams; clarify REACH
Market Economic	Geographically confined (150-200 km) markets for slag products; long payback periods; SME financing gaps[29]	Green public procurement; co-funding/de-risking instruments; long term agreements
Organisational Informational	Business confidentiality creating an IS gap; discontinuous facilitation capacity; incomplete monitoring databases[29/45]	Dedicated, durably funded facilitators; shared digital/AI matching databases (e.g. SYMBA)[29/40]

Topic	Challenge	Corresponding opportunity
Technology Transition	Next-generation routes (H_2/DRI/EAF, smelter, CCUS-BF) will change slag basicity, mineralogy and volume; KPI I & IV evidence gaps[3/4]	Systematic characterisation, real time monitoring and predictive modelling embedded in R&I roadmaps
Skills Workforce	Shortage of trained IS planners or brokers; low value roles crowding out higher value symbiosis brokering[41]	Sector adapted training curricula and networking tools (e.g. INSET) [41]
Cross sector coordination	Barriers common to several SPIRE sectors are tackled sector by sector, diluting influence with regulators[37]	Coordinated, cross sectoral engagement with regulators and standardisation bodies (e.g. HARMONI) [37]
Territorial Infrastructure	European projects concentrate on intercompany exchanges; closer steelworks municipal/utility integration underexplored[47/51]	Explore steel utility symbiosis (water, district heat) alongside intercompany exchanges
Decarbonisation driven exchange decline	Shift from BF to EAF steelmaking will shrink or eliminate GGBS supply, threatening the established steel cement slag symbiosis[35/57]	Early supply risk monitoring and managed transition support for downstream partners (e.g. cement)
Implementation readiness and evidence comparability	Demonstrated technologies are not yet verified resource exchanges (quality variability, acceptance limits, delivered cost, responsibilities); KPI values use differing boundaries and denominators; thin evidence for heat and dust/sludge[32]	Staged qualification with a common minimum dataset and exchange procedure; report KPI boundary; follow-up scenarios for dust/sludge and heat

The following are challenges that need attention:

- **Regulatory fragmentation** is the most constantly cited barrier across every source reviewed. Every external project reviewed independently identifies the classification of secondary materials as waste versus by-product as the single most consequential

nontechnical barrier. The case for treating regulatory clarification as the single highest priority goal in this deliverable, rather than one among several equally weighted priorities.

- **Facilitators** are identified as decisive for overcoming organisational barriers.
- **Digital matching tools** are moving from concept to deployment in adjacent sectors, but not yet in steel. Such tools are being actively built for an adjacent sector using several of the same waste streams (biomass residues, plastics) which are already exploited by the steel sector. No equivalent tool yet exists specifically for steel sector by-products.
- **Decarbonisation transition** adds urgency, not just a new category of risk. Next-generation steelmaking routes will alter slag basicity, mineralogy, trace-element content and cooling behaviour, with consequences for downstream valorisation, and that this effect is amplified by evidence gap on KPI IV (recycling of low-quality scrap). Even well established, currently suitable slag types are under recovered today because of regulatory and market barriers, this indicates that those barriers must be resolved on a timescale that keeps pace with the technology transition, not on a slower, business as usual timescale.
- **Workforce and skill gap** runs across the whole system, not just at plant level. This is treated as a distinct goal rather than folded into the organisational or informational theme, because its primary lever (training and curriculum development) is different in kind from facilitation or database building.
- **Implementation readiness and evidence comparability** are a challenge in their own right. A technology demonstrated in a project does not establish that a suitable resource supply, receiving process, authorisation route and commercial arrangement coexist at a given location, and reported KPI values often differ in boundary conditions, which limits comparison between projects. Deliverable 4.2[32] responds with a minimum dataset, a staged qualification and data-exchange procedure and explicit reporting of boundaries. This is treated as a distinct theme because its remedy (qualification and data practice) differs in kind from regulatory reform, facilitation or training.

5. Goals for Enhancing Industrial Symbiosis in the Steel Sector

5.1 Goal-setting approach and prioritisation criteria

Building on the consolidated challenges and opportunities in Section 4, this section defines eleven clear, achievable goals for further enhancing IS in the European steel industry. Ten addressing how to build and strengthen symbiosis, and an eleventh goal addresses how to manage the risk that decarbonisation removes an established one, per the evidence reviewed. Each goal is deliberately stated as an outcome that a defined actor (or set of actors) can act on, rather than as a restatement of a challenge, so that it maps directly onto the practical guidelines.

Goals are prioritised against three criteria:

- Potential impact: the scale of the environmental, economic or resource efficiency benefit expected if the goal is achieved, drawing on the KPI evidence reviewed and the case studies.
- Feasibility: how readily the goal can be pursued given current technical maturity, institutional capacity and the timeframe of relevant EU policy processes. Goals that depend on lengthy legislative change are scored lower than those achievable through voluntary or project actions, even where their potential impact is high.
- Alignment: the strength of the goal's fit with the European Green Deal, the EU Circular Economy Action Plan, the Fit for 55 package, and the priorities stakeholders themselves identified in the WP2 survey.

Table 3 sets out the resulting ranking.

Table 3. Prioritised goals for enhancing IS in the steel sector, scored against potential impact, feasibility and alignment with EU sustainability objectives

	Goal	Impact	Feasibility	Alignment	Priority
G1	Extend EU end-of-waste criteria to prioritise steelmaking slag streams (EAF, LF) and clarify end-of-waste/REACH	High	Medium	High	1
G2	Establish or sustain durably funded, independent IS facilitators for the steel sector at regional/national level	High	High	High	2
G3	Develop a shared, digital, quality assured by-product and demand matching database for the steel sector, informed by SYMBA's methodology	High	Medium	High	3
G4	Include by-product/slag characterisation, monitoring and predictive modelling into next-generation steelmaking R&I so IS pathways keep pace with technology change	High	Medium	High	4
G5	Use green public procurement and long-term offtake agreements to stabilise demand for secondary steel sector materials	Medium-High	Medium	High	5
G6	Build steel sector specific IS training and networking resources for planners, brokers and plant staff, drawing on the INSET model	Medium	High	Medium-High	6
G7	Pursue coordinated, cross-SPIRE sector engagement with regulators and standardisation bodies rather than steel only advocacy	Medium	Medium	High	7
G8	Explore steel utility and steel municipal symbiosis (water, district heat, waste) alongside intercompany exchanges	Medium	Low-Medium	Medium	8

	Goal	Impact	Feasibility	Alignment	Priority
G9	Close the WP3-identified evidence gaps on energy efficiency (KPI I) and low-quality scrap recycling (KPI IV) through targeted follow-up research	Medium	Medium	High	9
G10	Sustain and broaden Symbio-Steel style cross project dissemination beyond the project's own duration	Medium	High	Medium	10
G11	Monitor and manage the decarbonisation driven supply risk to established secondary material exchanges, starting with GGBS supply to the cement sector	Medium-High	Medium	Medium	11

5.2 Discussion of the goals

5.2.1 G1 extend EU end-of-waste criteria and clarify REACH

This is ranked first because it is the single barrier identified independently across the largest number of sources reviewed in Symbio-Steel and because the Piemonti et al. evidence shows its practical consequence in unusually concrete terms: even in one of Europe's most concentrated and technically capable steelmaking regions, the majority of slag classified as waste was still sent to landfill rather than recovered, in large part because producers could not demonstrate the "certainty of use" condition needed for by-product status. The by-product route (Article 5) and the end-of-waste route (Article 6) of the Waste Framework Directive have different conditions, that compliance with a technical product specification does not by itself establish legal status (although a recognised specification can support the qualification of a secondary material, as the OnlyPlastic[14] case shows), and that a new IS outlet should not be assumed environmentally preferable merely because it creates an additional use for a residue, given the waste hierarchy (Article 4). Clarification under G1 should therefore address both routes and a documented path from a material's current status to its intended use. Feasibility is scored medium rather than high because EU end-of-waste criteria require Commission regulatory action (as already achieved for iron, steel and aluminium scrap under Regulation (EU) No 333/2011) and therefore a longer timeframe than project interventions; this makes G2 and G3 important complementary, faster achieving goals.

5.2.2 G2 durably funded IS facilitators

This is ranked second on the strength of the CORALIS demonstration evidence and is judged high on feasibility because it does not require new EU legislation, it can be pursued through

national or regional funding instruments, industry association initiatives, or continuation funding for structures (such as facilitator roles embedded in RFCS or Horizon Europe follow-up projects) that already exist in emerging forms. The main risk is discontinuity of funding once a project or programme ends. Which can be overcome by the facilitator's role to be resourced for the whole implementation period, and that each exchange has an operational owner and a coordinator who maintains the shared action register. Agreeing early who funds and maintains this function addresses the discontinuity risk.

5.2.3 G3 a shared digital matching database for the steel sector

This is ranked third because SYMBA has already demonstrated the technical and organisational feasibility of an AI supported matching platform for an adjacent sector, using several of the same waste streams already relevant to steel industry, meaning the steel sector does not need to develop this capability from scratch. Such a database can start from a minimum common dataset (stable identifiers, a shared data dictionary, stated units and version control, with numeric values, units and quality flags in separate fields) and a staged exchange procedure, and that a structured file can serve initially. Matching tools should record why a match was suggested and which evidence is still required, because digital matching cannot replace qualification where composition or operating constraints determine acceptance. Public summaries should be kept separate from partner-shared and restricted commercial data. This goal is ranked below G1 and G2 because a matching platform's benefits depend on the underlying regulatory clarity (G1) and facilitation capacity (G2) already being in place to convert matches into actual transactions.

5.2.4 Goals G4-G11

The remaining goals address the technology transition (G4, G9), market stabilisation (G5), skills (G6), cross sectoral regulatory engagement (G7), territorial/utility integration (G8), the continuation of cross project dissemination itself (G10), and the risk that decarbonisation removes an established exchange rather than only changing it (G11). These are discussed in detail through the stakeholder specific guidelines in the following section, which translate each goal into concrete actions for the actor(s) best placed to pursue it.

6. Guidelines to Improve Current Synergies in the Steel Industry

This section translates the goals defined in previous section into practical guidelines, organised by the actor best placed to act on them: steel producers, plant operators, downstream users, symbiosis partners, policymakers, standardisation bodies, and the facilitators, researchers and networks including Symbio-Steel's own successors that support IS. Each guideline references the goal(s) it serves.

6.1 Guidelines for steel producers and plant operators (G1, G3, G4, G6)

- **Document "certainty of use" systematically**. Where a by-product classification is being sought for a slag, dust or sludge stream, build and retain the documentation (offtake agreements, technical specifications, standards compliance records) needed to demonstrate the Article 5 Waste Framework Directive conditions from the outset of production, rather than retrospectively. The Piemonti et al. evidence shows this documentation gap, not technical unsuitability, is the main reason recoverable slag is landfilled[45].
- **Characterise by-product streams against next-generation process changes now**. Where a plant is planning or piloting a next-generation route (H_2-DRI-EAF, smelting reduction, CCUS-BF), commission slag/dust/sludge characterisation work in parallel with process development, not after commissioning, so that downstream users and treatment/recovery plants have advance notice of any change in basicity, mineralogy or trace-element content[28].
- **Register and update by-product data in shared/sector databases**. Participate in the sector specific digital matching database recommended under G3 once available (or in interim regional systems, such as sector consortium reporting alongside statutory waste declarations) so that classification, volume and quality data are visible to potential partners without compromising commercially sensitive process information[29/45].

- **Invest in workforce capacity for IS brokering**. Identify and train staff (or partner with external facilitators) to take on the IS planner role modelled by the INSET training curriculum, rather than treating by-product management purely as a compliance function[41].
- **Qualify resource-receiver pairs in stages and report results with their boundaries.** Before committing to an exchange, characterise a representative sample of the resource over the relevant production period, agree on acceptance limits and the reference practice with the receiver, and run integration trials long enough to address the identified technical risk (a short successful campaign does not demonstrate seasonal supply stability or long-term equipment wear). When reporting KPI values, state the stream, boundary and denominator (for example the share of total slag generation versus the share of one stream).
- **Retain the classification basis for each stream**. Record the legal basis (by-product under Article 5 or end-of-waste under Article 6 of the Waste Framework Directive), the intended use, required authorisations and the responsible authority, and re-evaluate after any change in material or application, including changes caused by new steelmaking routes.

6.2 Guidelines for downstream users and symbiosis partners (G3, G5, G8, G11)

- **Signal demand through long term offtake commitments**. Cement, construction, roadbuilding, agriculture and chemical sector partners should favour long term offtake agreements over one-off spot purchases of secondary materials where possible, since payback periods for valorisation infrastructure are frequently longer than conventional five-year industry thresholds and are a recognised barrier to investment[29].
- **Engage utilities and municipalities as potential symbiosis partners, not only industrial peers**. Following the international evidence reviewed, water utilities, district-heating operators and municipal waste management bodies should be included in regional IS mapping and matching exercises alongside cement, chemicals and construction partners[47/52].
- **Use green public procurement criteria where applicable**. Public and quasi-public downstream users (infrastructure agencies, public construction clients) should specify secondary, by-product-derived materials in tender criteria where technically equivalent to virgin materials, to help stabilise demand as recommended under G5[29].
- **Build decarbonisation driven supply risk into procurement planning**. Cement producers and other downstream users of well-established steel by-products,

particularly GGBS, should model the effect of their upstream partners' own decarbonisation timelines on future by-product availability, rather than treating current supply volumes as a stable baseline, and should engage steel producers early on transition planning and alternative supplementary cementitious materials, following the disruption risk documented for the UK cement steel relationship[57].

- **Agree on commercial terms that allocate risk explicitly**. Define quantity and quality commitments, sampling and dispute rules, and rejection, interruption and termination terms, and where dedicated infrastructure is needed, the consequences of early loss of source or receiver. Assess costs and benefits for each actor, since an exchange with an overall positive balance may remain unacceptable if one participant bears disproportionate cost or risk.
- **For heat network operators and industrial heat users, start with data**. Where external recovery of steelworks heat is considered, begin by collecting synchronous source and demand data (temperature, continuity, timing) and define backup or safe-interruption arrangements, since no quantified project evidence for steelworks heat export currently exists.

6.3 Guidelines for policymakers and standardisation bodies (G1, G7)

- **Clarify the end-of-waste and REACH interface in guidance**. Issue interpretive guidance on how REACH registration and evaluation obligations apply to residue-based materials once they achieve end-of-waste status, to reduce the legal uncertainty currently discouraging investment in novel valorisation products[29].
- **Coordinate steel sector regulatory engagement with the other SPIRE/Processes4Planet sectors**. Use existing cross sectoral structures (of the kind HARMONI built) rather than pursuing steel specific advocacy in isolation, since the underlying barriers (waste classification, standardisation gaps, permitting complexity) are shared with cement, minerals and chemicals industries[37].
- **Ensure continuity of facilitation and dissemination funding across projects**. Design national and EU funding instruments so that successful facilitator roles, databases and dissemination channels established under one project (RFCS, Horizon Europe) can be continued or handed over rather than lapsing at project ends, addressing the funding discontinuity risk identified in Deliverable 5.2 and echoed in the UK NISP experience it discusses.
- **Agree on commercial terms that allocate risk explicitly**. Define quantity and quality commitments, sampling and dispute rules, and rejection, interruption and termination terms, and where dedicated infrastructure is needed, the consequences of

early loss of source or receiver. Assess costs and benefits for each actor, since an exchange with an overall positive balance may remain unacceptable if one participant bears disproportionate cost or risk.

- **For heat network operators and industrial heat users, start with data**. Where external recovery of steelworks heat is considered, begin by collecting synchronous source and demand data (temperature, continuity, timing) and define backup or safe-interruption arrangements, since no quantified project evidence for steelworks heat export currently exists.

6.4 Guidelines for facilitators, researchers and the Symbio-Steel community (G2, G3, G6, G9, G10, G11)

- **Close the WP3-identified evidence gaps**. Commission or prioritise follow-up research specifically targeting KPI I (energy efficiency) and KPI IV (recycling of low-quality steel scrap), which WP3 found to be underrepresented across the 58 projects it reviewed, and which will become more consequential as EAF production using DRI/HBI and mixed scrap grows toward the projected ~57 % share of European output by 2030[3/28].
- **Design any future shared database around the limitations documented by Piemonti et al.** Ensure a steel sector matching or monitoring database captures by-product classified material (not only waste classified material), distinguishes between slag types with materially different reuse characteristics (e.g. EAF vs. LF slags), and uses multiple sources (regulatory declarations, sector consortium data, direct company reporting) rather than relying on a single regulatory dataset, since single source regional databases have been shown to under represent true recovery performance[45].
- **Adopt the INSET model of locally tailored, toolkit training**. When designing IS training or capacity building activities for the steel sector, follow INSET's approach of pairing a common toolkit (course materials, case studies, networking handbook) with audience specific delivery (plant operators, downstream SMEs, students, policymakers) rather than a single generic format[41].
- **Plan for continuity beyond the project's own duration**. Identify, before the project ends, which Symbio-Steel outputs (KPI framework, barriers, this guidelines document, the stakeholder network built through WP2) have standalone value and could be maintained by a successor initiative, or a follow on RFCS/Horizon Europe project, consistent with the continuity risk identified throughout this report[4/29].
- **Track exchange decrease risk alongside new synergy opportunity**. Extend the technology transition monitoring recommended under G4 to explicitly cover the risk that an existing, high-volume exchange (starting with GGBS supply to cement)

shrinks or disappears as steelmakers decarbonise, not only that by-product composition changes; the UK cement steel evidence indicates this risk is important[57].

- **Develop a follow-up scenario for dust, sludge and mill scale**. Prioritise element specific mass balances, treatment yields, residue destinations and external receiver data for this resource family and keep recovery of a target metal distinct from the fraction of total residue recycled when reporting KPI VI and VII.
- **Use a common data-exchange procedure and keep evidence classes apart**. Record exchanges with a minimum dataset and a staged procedure, keep measured evidence, modelled assessment, proposed arrangements and unresolved data requirements distinct, and maintain a gap register with named owners.

7. Conclusions

This deliverable has brought together the internal evidence generated across Symbio-Steel's project (KPI impact assessment of WP3, the stakeholder engagement and dissemination record of WP2, the stakeholder consultation reported in WP4) with the technology transition outlook of Deliverable 5.1, the barrier analysis of Deliverable 5.2.

Four conclusions recur:

- The technical foundations of IS in the steel sector are largely in place: fossil carbon replacement is now demonstrated at up to 100 % substitution in EAF operations, and slag, dust and sludge recovery routes are well characterised, even if concentrated in a limited number of projects. However, many headline values in projects (including 100 % figures) refer to specific streams, operating conditions or demonstration cases and not to shares of total generation, so they must be read with their boundaries and denominators.
- The barriers on wider deployment are overwhelmingly nontechnical, and the same handful of barriers (unclear waste/by-product classification, limited markets, discontinuous facilitation, and informational asymmetry between potential partners) are identified independently by every source reviewed in this report, from EU regulatory analysis to a single region mass flow study to 2026 systematic literature review.
- The technology transition described in Deliverable 5.1 does not remove these barriers. It adds urgency to resolving them, because the by-product streams IS depends on, are themselves changing in volume, composition and behaviour.
- Same transition can also subtract from the sector's symbiosis portfolio rather than only add to it. The projected decline in BF slag available to cement producers as UK steelmakers shift toward EAF production shows that even the oldest, best-established exchange reviewed in this deliverable is not immune to disruption.

Technological maturity does not by itself create an exchange. A synergy becomes operational only when a qualified resource-receiver relationship, a feasible transfer arrangement, an authorisation route, workable commercial terms and an agreed allocation of responsibilities exist together, and when the supporting data are traceable and keep measured evidence, modelled assessment and proposed arrangements apart. The evidence is currently strongest for slag valorisation and for SCCs in EAF steelmaking, weaker for conversion of steel gases and weakest for external heat recovery, with dust, sludge and mill scale the main pathway still to be developed as a scenario.

The eleven goals and accompanying guidelines are intended as a practical, prioritised response to this evidence, addressed to the specific actors best placed to act on each one. None of them requires starting from scratch as each build on a demonstrated precedent (CORALIS for facilitation, SYMBA for digital matching, INSET for skills, HARMONI for cross sectoral regulatory engagement, EPOS for cross sectoral permitting lessons) that the steel sector can adapt rather than reinvent. Realising this potential will require sustained commitment from steel producers, downstream users, policymakers, standardisation bodies and the research and facilitation community alike, continuing well beyond the formal duration of the Symbio-Steel project itself.

List of Tables

Page

Table 1. Summary of the WP3 KPIs2 **8**
Table 2. Challenges and corresponding opportunities for IS in the steel sector **27**
Table 3. Prioritised goals for enhancing IS in the steel sector, scored against potential impact, feasibility and alignment with EU sustainability objectives **31**

Abbreviations and acronyms

AI	Artificial Intelligence
BF:	Blast Furnace
BOF	Blast Oxygen Furnace
CCU	Carbon capture, utilization and storage
DRI	Direct reduced irion
EAF:	Electric Arc Furnace
ECSC	European Coal and Steel Community
EMECR	International Conference on Energy and Material Efficiency and CO_2 Reduction in the Steel Industry
ESTAD	European Steel Technology and Application Days
EU:	European Union
G1-G11	Goals 1 to 11
GGBS	Ground granulated blast furnace slag
H4C	Hubs for Circularity
HBI	Hot briquette iron
HEU	Horizon Europe funding program
IS:	Industrial symbiosis
LF	Ladle furnace
M:	Month
NISP	United Kingdom National Industrial Symbiosis Programme
PU:	Public
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFCS:	Research fund for coal and steel
S1-S4	Synergies 1 to 4
SCC	Secondary carbon carrier
SME	Small Medium Enterprise
SPRIRE	Sustainable Process Industry through Resource and Energy Efficiency
T:	Task
TRL	Technology readiness level
WFD	Waste Framework Directive
WP:	Work Package