Future IS Scenarios Report

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Table of contents

Table of contents 2
1. Introduction 10
1.1 Background and context 10
1.2 Purpose and scope of Deliverable D4.2 11
1.3 Position of D4.2 within the Symbio-Steel project 12
1.4 Links with previous and parallel Symbio-Steel activities 13
1.4.1 WP3 KPI framework — D3.1, D3.2 and D3.3 13
1.4.2 Technological evidence base — D3.4 14
1.4.3 Stakeholder evidence — D4.1 14
1.4.4 Future steelmaking challenges — D5.1 14
1.4.5 Non-technical implementation barriers — D5.2 14
1.5 Structure of the document 15
2. Methodology for the Development of Future Industrial Symbiosis Scenarios 16
2.1 Overall methodological framework 16
2.2 Review of recent Industrial Symbiosis implementation approaches and roadmaps 16
2.2.1 CORALIS 17
2.2.2 Hubs for Circularity 17
2.2.3 IS2H4C 17
2.2.4 RISERS 18
2.2.5 Steel–chemical symbiosis: INITIATE 18
2.2.6 Methodological roadmaps and earlier steel-sector synthesis 18
2.2.7 Implications for the D4.2 methodology 19
2.3 Identification and classification of resource flows 19
2.3.1 Secondary resources supplied to the steel sector 20
2.3.2 Solid by-products and residues originating from steelmaking 21
2.3.3 Gaseous carbon streams 21
2.3.4 Waste heat and other energy streams 21

2.4 Common pathway architecture 22
2.5 Actor and partnership configuration 22
2.6 Screening of candidate pathways 23
2.7 System boundaries and quantitative reference conditions 24
2.8 Evidence hierarchy and data-quality management 24
2.9 Integration of the WP3 KPI framework 25
2.10 Integration of stakeholder evidence, barriers and enabling conditions 26
2.11 Common data structure for Industrial Symbiosis scenarios 26
2.12 Treatment of data gaps and uncertainty 27
2.13 Output of the methodology: screening results and selected scenarios 27
3. Steel-Driven Industrial Symbiosis Landscape, Pathway Classification and Implementation Gaps 30
3.1 Overview of steel-driven Industrial Symbiosis pathways 30
3.2 Secondary Carbon Carriers and secondary resources supplied to steelmaking 31
3.3 Slags and mineral residue pathways 32
3.4 Dust, sludge, mill scale and metal-recovery pathways 33
3.5 Process gas and CO_2 utilisation pathways 34
3.6 Waste heat, water, refractories and other resource pathways 35
3.7 Receiving sectors and cross-sectoral connections 35
3.8 Main implementation gaps 36
3.8.1 Technical and resource-quality gaps 36
3.8.2 Infrastructure, logistics and geographical gaps 36
3.8.3 Regulatory and legal gaps 37
3.8.4 Economic and market gaps 37
3.8.5 Organisational and governance gaps 37
3.8.6 Information and data-exchange gaps 37
3.8.7 Social and market-acceptance aspects 37
3.9 Priority pathways for detailed scenario development 38
4. Development of Selected Future Industrial Symbiosis Implementation Scenarios 39
4.1 Common scenario-development structure 39

4.2 Scenario S1 — Steelmaking slag valorisation in construction, cement and agricultural value chains 39
4.2.1 Scenario rationale and objective 39
4.2.2 Source and resource stream 40
4.2.3 Resource characteristics and requirements 40
4.2.4 Conditioning and technical integration 40
4.2.5 Transport, infrastructure and geographical configuration 40
4.2.6 Receiver and substitution function 41
4.2.7 Actors and partnership configuration 41
4.2.8 Data-exchange requirements 41
4.2.9 Relevant WP3 KPIs and available quantitative evidence 41
4.2.10 Implementation barriers and enabling conditions 42
4.2.11 Replication potential and remaining data gaps 42
4.3 Scenario S2 — Secondary Carbon Carriers supplied to EAF steelmaking 42
4.3.1 Scenario rationale and objective 42
4.3.2 Source and resource stream 42
4.3.3 Resource characteristics and requirements 43
4.3.4 Conditioning and technical integration 43
4.3.5 Transport, infrastructure and geographical configuration 43
4.3.6 Receiver and substitution function 43
4.3.7 Actors and partnership configuration 44
4.3.8 Data-exchange requirements 44
4.3.9 Relevant WP3 KPIs and available quantitative evidence 44
4.3.10 Implementation barriers and enabling conditions 44
4.3.11 Replication potential and remaining data gaps 45
4.4 Scenario S3 — Steel process gases as feedstock for the chemical sector 45
4.4.1 Scenario rationale and objective 45
4.4.2 Source and resource stream 45
4.4.3 Resource characteristics and requirements 45
4.4.4 Conditioning and technical integration 45

4.4.5 Transport, infrastructure and geographical configuration 46
4.4.6 Receiver and substitution function 46
4.4.7 Actors and partnership configuration 46
4.4.8 Data-exchange requirements 46
4.4.9 Relevant WP3 KPIs and available quantitative evidence 47
4.4.10 Implementation barriers and enabling conditions 47
4.4.11 Replication potential and remaining data gaps 47
4.5 Scenario S4 — Steel waste-heat recovery and cross-sector energy integration 47
4.5.1 Scenario rationale and objective 47
4.5.2 Source and resource stream 48
4.5.3 Resource characteristics and requirements 48
4.5.4 Conditioning and technical integration 48
4.5.5 Transport, infrastructure and geographical configuration 48
4.5.6 Receiver and substitution function 48
4.5.7 Actors and partnership configuration 49
4.5.8 Data-exchange requirements 49
4.5.9 Relevant WP3 KPIs and available quantitative evidence 49
4.5.10 Implementation barriers and enabling conditions 49
4.5.11 Replication potential and remaining data gaps 49
5. Quantitative Benchmarks and WP3-Linked Impact Assessment 50
5.1 Assessment approach and reference conditions 50
5.2 Application of the WP3 KPI framework to the selected scenarios 50
5.3 Scenario S1 — Quantitative benchmarks and applicable KPIs 52
5.4 Scenario S2 — Quantitative benchmarks and applicable KPIs 54
5.5 Scenario S3 — Quantitative benchmarks and applicable KPIs 55
5.6 Scenario S4 — Quantitative benchmarks and applicable KPIs 57
5.7 Data quality, assumptions and limitations 58
6. Cross-Scenario Assessment 59
6.1 Cross-scenario assessment framework 59

6.2 Technological maturity and scale-up requirements 59
6.3 Resource availability, quality and receiver compatibility 59
6.4 Resource-efficiency and environmental performance 59
6.5 WP3 KPI synthesis 60
6.6 Economic and market conditions 60
6.7 Infrastructure, logistics and geographical conditions 60
6.8 Regulatory and legal conditions 60
6.9 Organisational, governance and contractual conditions 61
6.10 Information and data-exchange requirements 61
6.11 Stakeholder and social dimensions 61
6.12 Replication potential 61
6.13 Cross-scenario comparison matrix 62
7. Cross-Sectoral Cluster Configurations and Replication Potential 63
7.1 From bilateral exchanges to Industrial Symbiosis clusters 63
7.2 Actors and stakeholder roles in cross-sector configurations 63
7.3 Steel-centred Industrial Symbiosis cluster configurations 64
7.3.1 Material-resource cluster configuration 64
7.3.2 Energy-based cluster configuration 64
7.3.3 Integrated multi-resource cluster configuration 64
7.4 Geographical proximity and spatial clustering 64
7.5 Governance and Industrial Symbiosis facilitation 65
7.6 Shared infrastructure and services 65
7.7 Replication across European industrial regions 65
7.8 Transferability across steelmaking routes and industrial contexts 65
8. Cross-Industrial Planning and Data-Exchange Framework 66
8.1 Role of data exchange in Industrial Symbiosis implementation 66
8.2 Minimum dataset for cross-industrial resource exchange 66
8.3 Data-exchange procedure 67
8.4 Cross-industrial planning interfaces 68

8.5 Data interoperability, confidentiality, ownership and governance 69
8.6 Roles and responsibilities of participating actors 69
8.7 Digital tools, databases and Industrial Symbiosis matching approaches 69
8.8 Consistency with the WP3 impact-assessment framework 70
9. Implementation Guidance and Roadmap 71
9.1 General implementation requirements 71
9.2 Actor engagement and partnership development 71
9.3 Technology qualification and process integration 71
9.4 Logistics, infrastructure and supply-chain requirements 71
9.5 Regulatory, permitting and end-of-waste considerations 72
9.6 Commercial conditions and long-term off-take arrangements 72
9.7 Monitoring and KPI-based performance verification 73
9.8 Governance, facilitation and stakeholder coordination 73
9.9 European partnerships, networks and cross-sector cooperation 73
9.10 Funding and financial enabling mechanisms 74
9.11 Implementation roadmap 74
9.11.1 Short-term actions 74
9.11.2 Medium-term actions 74
9.11.3 Longer-term actions 75
9.11.4 Research and innovation needs 75
9.11.5 Demonstration, scale-up and replication needs 75
10. Conclusions 76
10.1 Main findings 76
10.2 Priority Industrial Symbiosis opportunities 76
10.3 Remaining gaps and uncertainties 76
10.4 Key enabling conditions for implementation 77
10.5 Implications for future steel-driven Industrial Symbiosis and European R&I 77
11. References 78
12. Appendices 80

12.1 Appendix A — Detailed Scenario Assessment Sheets 80
12.2 Appendix B — Quantitative Input Data, Reference Conditions and Calculation Basis 83
12.3 Appendix C — Cross-Industrial Data-Exchange Template 87
12.4 Appendix D — Pathway Screening and Cross-Scenario Assessment Matrix 89
12.5 Appendix E — Actor and Stakeholder Mapping 91
13. List of tables 93
14. List of abbreviations and acronyms 94

Executive Summary

This deliverable aims to translate the technological, quantitative and stakeholder evidence generated within Symbio-Steel into four transferable Industrial Symbiosis implementation scenarios: slag valorisation in mineral value chains, Secondary Carbon Carriers supplied to EAF steelmaking, steel process gases used as chemical feedstock, and cross-sector recovery of steelmaking waste heat.

The assessment shows that implementation depends not only on technical feasibility, but also on resource variability, receiver specifications, infrastructure, regulatory status, commercial arrangements, governance and traceable data exchange.

S1 and S3 are supported by evidence across technology, quantitative performance and stakeholder relevance; S2 has the broadest industrial-trial evidence; and S4 is strategically relevant but remains mainly qualitative because no WP3 KPI I value is available. Project-specific numerical results are retained with their original boundaries and are not extrapolated to unspecified installations.

The report therefore provides pathway qualification procedures, actor roles, minimum datasets, KPI requirements, replication conditions and a staged implementation roadmap rather than site-specific engineering designs.

The principal remaining needs are site-level mass and energy balances, time-resolved resource and demand profiles, receiver acceptance criteria, delivered-cost data, legal qualification routes and clearly assigned data ownership and validation responsibilities.

1. Introduction

1.1 Background and context

Industrial Symbiosis (IS) is a practical approach to circular resource management in which underutilised resources of one industrial actor or sector — by-products, residues, secondary raw materials, energy, water, infrastructure, logistics capacity, equipment and expertise — are put to productive use by another. In energy- and resource-intensive industries, IS can reduce primary-resource demand, increase material recovery, improve energy efficiency and strengthen cross-sectoral cooperation. Deliverable D1.2 of Symbio-Steel presents these exchanges as an alternative to linear supply chains and highlights their contribution to resource efficiency and to a lower dependence on primary and critical materials[1].

The steel industry already takes part in many symbiotic exchanges. Steelmaking generates solid, gaseous and thermal streams that can be valorised internally or in external value chains, including slags, dusts, sludges, mill scale, process gases, spent refractories, waste heat and water. Conversely, steel production can receive secondary resources from outside the sector, such as biogenic and non-biogenic Secondary Carbon Carriers (SCCs) and other secondary raw materials. Deliverable D3.4 organised the technological evidence from 82 funded projects according to these upstream and downstream resource families[2].

The transition to low-carbon steelmaking makes this system perspective more important. D5.1 shows that hydrogen-based direct reduction, a larger share of Electric Arc Furnace (EAF) production, higher scrap use, novel smelting-reduction processes and Carbon Capture, Utilisation and Storage (CCUS) can change the quantity, composition, mineralogy and physical characteristics of steelmaking by-products[3]. Established valorisation routes may therefore need requalification, and new routes will require improved characterisation, monitoring and conditioning.

Against this background, the RFCS Accompanying Measures Project Symbio-Steel — *Fostering Industrial Symbiosis solutions for the steel sector by results monitoring and dissemination from national and EU funded projects coupled to definition of cross-sectorial synergy scenarios* (Grant Agreement No. 101156509) — consolidates the knowledge generated by national and

[1] Colla, V., Petrucciani, A. (2025). Comprehensive overview of the project. Deliverable D1.2, Symbio-Steel project, RFCS Grant Agreement No. 101156509, March 2025.

[2] Sergi, C., Breda, M. (2026). Technological solutions for steel-driven industrial symbiosis. Deliverable D3.4, Symbio-Steel project, RFCS Grant Agreement No. 101156509, April 2026.

[3] Morillon, A., Algermissen, D. (2026). Analysis of future challenges in industrial symbiosis due to next generation steelmaking. Deliverable D5.1, Symbio-Steel project, RFCS Grant Agreement No. 101156509, final version 30 January 2026.

European research and supports the definition of cross-sectoral IS scenarios. The project has a duration of 24 months[4], from 1 October 2024 to 30 September 2026.

Within Symbio-Steel, Work Package 4 (WP4), *Enhancement of synergies in Energy Intensive Industries*, moves from technology and stakeholder evidence towards implementation. Its objectives are to identify gaps and potential for novel initiatives engaging multiple industrial sectors, to connect stakeholders with relevant infrastructure, to promote the effective use of knowledge, research and technical infrastructure, to analyse funding instruments that favour IS, and to develop implementation scenarios involving actors and partnerships in Energy Intensive Industries (EIIs)[4].

1.2 Purpose and scope of Deliverable D4.2

D4.2 is the output of Task 4.2, Develop implementation scenarios and connect to actors and partnerships outside steel. The task requires guidelines for implementing IS pathways, starting from recent implementation roadmaps and IS scenarios; the identification of the main links to other industries and the corresponding stakeholders; and procedures for consistent data exchange, cross-industrial planning and impact assessment linked to the WP3 KPI framework[4]. WP3 has already established what is technically available: D3.4 catalogues the technologies, resource streams, treatment routes and receiving sectors reported by 82 funded projects[2], and D3.1–D3.3 define and quantify their performance where data allow[5,6,7]. What remains open is the step from a documented technology to an exchange that identifiable actors can plan, qualify, operate and verify. D4.2 addresses this gap. It translates the available technological, quantitative and stakeholder evidence into implementation-oriented IS scenarios and states explicitly the conditions, actors and data required to connect the steel sector with other industrial or civil value chains.

For the purposes of this deliverable, an implementation scenario is described through the complete pathway connecting the origin of an underutilised resource to its productive use in a receiving process:

[4] Symbio-Steel Consortium (2023). Fostering Industrial Symbiosis solutions for the steel sector by results monitoring and dissemination from national and EU funded projects coupled to definition of cross-sectorial synergy scenarios. RFCS-2023 Proposal, Proposal ID 101156509.

[5] Kieush, L., Rieger, J. (2024). Report on Key Performance Indicators. Deliverable D3.1, Symbio-Steel project, RFCS Grant Agreement No. 101156509, 20 December 2024.

[6] Kieush, L., Rieger, J. (2025). Second report on Key Performance Indicators. Deliverable D3.2, Symbio-Steel project, RFCS Grant Agreement No. 101156509, 29 September 2025.

[7] Kieush, L., Rieger, J. (2026). Final report on Key Performance Indicators. Deliverable D3.3, Symbio-Steel project, RFCS Grant Agreement No. 101156509, 23 March 2026.

Source → Resource → Conditioning → Transport / Infrastructure → Receiver → Substitution

Each pathway is complemented by the relevant actors, the applicable WP3 Key Performance Indicators (KPIs), data-exchange requirements, barriers, enabling conditions and replication conditions. The scope of D4.2 comprises:

- classification of steel-driven IS pathways and their receiving sectors;
- review of recent IS implementation approaches and roadmaps;
- selection and development of representative future implementation scenarios;
- identification of actors and stakeholder roles for each scenario;
- assessment of technical and non-technical implementation conditions;
- application of the WP3 KPIs (where supported by evidence);
- definition of a minimum dataset and a procedure for cross-industrial planning and data exchange;
- replication conditions and an implementation roadmap.

D4.2 is built exclusively on evidence already generated within Symbio-Steel and on public sources. No new data were collected from partners or industrial sites for this deliverable. Thus, the scenarios are transferable configurations rather than engineering designs for specific installations. Reported project results and WP3 KPI values are used with their original boundaries; where the evidence does not support a defensible value, no number is introduced and the missing information is recorded as a data gap. In this way, the limits of the evidence base become an explicit list of the data that future implementation studies must provide.

1.3 Position of D4.2 within the Symbio-Steel project

D4.2 is positioned at the interface between evidence collection and impact assessment in WP3, stakeholder and synergy development in WP4, and future-oriented recommendations in WP5.

WP3 provides the quantitative and technological basis. D3.1 established eleven KPIs covering energy efficiency, direct (Scope 1) CO_2 emission reduction, virgin raw-material reduction, recycling of low-quality scrap, slag recycling, dust and sludge recovery, recycling of iron-rich residues, replacement of fossil carbon materials, reuse of CO_2 from off-gases, transformation of process-gas carbon (CO/CO_2) into products, and Technology Readiness Level (TRL)[5]. D3.2 and D3.3 applied these indicators to funded projects[6,7], and D3.4 consolidated technologies, resource streams, treatment routes and receiving sectors[2].

WP4 adds the stakeholder and implementation dimension. Task 4.1 consulted actors inside and outside the steel sector on existing IS connections, gaps, boundary conditions and

opportunities for collaboration[8]. Task 4.2 uses this evidence to define scenarios together with the actors, infrastructure, information flows and impact-assessment requirements associated with them.

WP5 provides the forward-looking perspective. D5.1 assesses how next-generation steelmaking may affect IS[3], and D5.2 classifies the non-technical barriers into regulatory and legal, economic and market, organisational and managerial, informational and knowledge-related, and social and cultural categories[9].

This positioning follows the methodology outlined in D1.2, which foresees implementation scenarios based on recent IS publications, initial data patterns for cross-industrial cooperation, the use of the WP3 KPI categories and the identification of industries, suppliers and stakeholders beyond steel[1]. D4.2 is therefore the stage at which technological evidence, quantitative indicators, stakeholder requirements and future constraints are integrated at scenario level. Its results also provide input to the WP5 guidelines for improving current synergies (D5.3)[4].

1.4 Links with previous and parallel Symbio-Steel activities

1.4.1 WP3 KPI framework — D3.1, D3.2 and D3.3

D3.1 defined the common KPI framework used in Symbio-Steel (Table 1.1). The indicators are applied selectively: one or more KPIs are chosen according to the focus of the assessed activity[5]. D3.2 and D3.3 then connected the framework with quantitative evidence from RFCS, Horizon 2020, Horizon Europe and other funded initiatives[6,7]. D4.2 uses this framework rather than an independent indicator system and associates each scenario only with the KPIs that are technically relevant and supported by evidence. Where the operational definition in D3.1 differs from a shortened label used elsewhere, the D3.1 definition prevails (Section 5.2).

Table 1.1 WP3 Key Performance Indicators[5].

KPI	Indicator
I	Energy efficiency (share of recovered heat reused by other industries)
II	Direct CO_2 emissions (Scope 1) reduction
III	Reduction in virgin raw material usage
IV	Enhanced recycling of low-quality steel scrap
V	Slag recycling rate

[8] Sergi, C., Cirilli, F. (2026). Stakeholders consultation report. Deliverable D4.1, Symbio-Steel project, RFCS Grant Agreement No. 101156509, April 2026. SEN dissemination level.

[9] Morillon, A., Algermissen, D. (2026). Identification of barriers to industrial symbiosis. Deliverable D5.2, Symbio-Steel project, RFCS Grant Agreement No. 101156509, final version 3 August 2026.

VI	Dust and sludge recovery and reuse
VII	Recycling rate of iron-rich residue streams
VIII	Replacement rate of fossil carbon materials
IX	Reuse rate of CO_2 from process/off-gases
X	Share of carbon in process gas (CO/CO_2) transformed into products
XI	Technology Readiness Level

1.4.2 Technological evidence base — D3.4

D3.4 is the main technological evidence base for D4.2[2]. It reviewed 82 funded projects, covering ECSC, RFCS, Framework Programme, Horizon 2020/Horizon Europe and other funded initiatives, and reorganised their results by resource stream. The upstream families are biogenic SCCs, non-biogenic SCCs, and scrap and other secondary raw materials. The downstream families are BF, BOF, EAF and ladle slags; dusts; sludges and mill scale; process and off-gases; spent refractories; and waste heat, wastewater and other streams. D3.4 therefore provides the resource–treatment–receiver relationships that form the technical backbone of the D4.2 scenarios. The number of D3.4 project entries per resource family is used in the screening (Section 2.13).

1.4.3 Stakeholder evidence — D4.1

D4.1 complements the technological evidence with stakeholder information from a 27-question survey, which received 53 responses, and from targeted interviews[8]. Because the number of respondents varies between questions, every percentage quoted in D4.2 is given with its base (n). D4.1 has a sensitive dissemination level, whereas D4.2 is public: only aggregated findings are used, and no company-specific, interview-specific or personal information is reproduced. Survey results are treated as evidence of stakeholder perception and priorities, not as measurements of resource quantities or contracted demand.

1.4.4 Future steelmaking challenges — D5.1

D5.1 considers hydrogen-based DRI–EAF routes, scrap-based EAF production, novel smelting-reduction technologies and BF configurations with CCUS[3]. These changes modify reductant and energy requirements and affect by-product generation, composition and quality. D5.1 identifies the growing variability and uncertainty of by-product streams as a central issue and highlights characterisation, monitoring, predictive modelling and conditioning as prerequisites for maintaining or adapting symbiotic pathways. D4.2 uses these findings to assess the future robustness and replication potential of each scenario.

1.4.5 Non-technical implementation barriers — D5.2

D5.2 identifies five interacting categories of non-technical barriers: regulatory and legal, economic and market, organisational and managerial, informational and knowledge-related,

and social and cultural[9]. It shows that technically feasible pathways may still be constrained by the legal status of secondary resources, limited or volatile markets, investment conditions, trust and confidentiality, insufficient information exchange and the downstream acceptance of residue-derived products. D4.2 incorporates these dimensions into screening and cross-scenario assessment, so that technical feasibility is always evaluated together with the conditions needed for implementation.

1.5 Structure of the document

Following the present introduction, Chapter 2 describes the methodology: the review of implementation approaches, the classification of resource flows, the pathway architecture, the screening criteria, the evidence rules and the application of the WP3 KPIs. Chapter 3 presents the steel-driven IS landscape, the receiving sectors and the main implementation gaps. Chapter 4 develops the selected scenarios according to a common structure. Chapter 5 presents the quantitative benchmarks and the WP3-linked assessment, retaining the original boundaries of each value. Chapter 6 compares the scenarios across technical, environmental, economic, regulatory, organisational and replication criteria. Chapter 7 examines cluster configurations and replication across European regions. Chapter 8 defines the cross-industrial planning and data-exchange framework. Chapter 9 provides implementation guidance and a roadmap, and Chapter 10 summarises the findings, remaining gaps and enabling conditions. Appendices A–E contain the scenario assessment sheets, the quantitative evidence register, the data-exchange template, the pathway screening matrix and the actor map.

2. Methodology for the Development of Future Industrial Symbiosis Scenarios

2.1 Overall methodological framework

The methodology converts the technological, quantitative and stakeholder evidence of Symbio-Steel into implementation-oriented IS scenarios. It responds directly to the requirements of Task 4.2[4] and follows the approach foreseen in D1.2[1]. The sequence is:

Evidence base → Review of IS implementation approaches → Classification of resource pathways → Screening → Selected scenarios → WP3 KPI and implementation assessment → Clusters, data requirements and replication → Implementation guidance

The evidence base comprises four components:

- the WP3 KPI framework and its quantitative application (D3.1–D3.3)[5,6,7];
- technologies, resource streams, conditioning routes and receiving sectors (D3.4)[2];
- stakeholder priorities, boundary conditions and barriers (D4.1)[8];
- future steelmaking conditions and non-technical barriers (D5.1, D5.2)[3,9].

Public external sources complement this base, in particular for implementation roadmaps, replication approaches, cross-sector planning methods and documented cases. Two rules apply throughout. First, pathways are not required to be quantified to the same depth: the level of quantification follows the availability, traceability and comparability of the data. Second, where robust evidence is missing, a pathway is described through its substitution function, applicable KPIs, implementation requirements and data gaps, never through unsupported numerical assumptions.

2.2 Review of recent Industrial Symbiosis implementation approaches and roadmaps

Task 4.2 explicitly requires the collection of recent IS implementation roadmaps and scenarios[4]. The review focuses on European initiatives that address the transition from a

technically feasible synergy to implementation, scale-up or replication. It extracts the elements relevant to scenario development: pathway qualification, stakeholder coordination, infrastructure, business and regulatory conditions, data exchange, monitoring and replication.

2.2.1 CORALIS

The Horizon 2020 project CORALIS combined industrial IS demonstrations with cross-cutting technical, economic and regulatory assessment. Its public outputs include a roadmap for implementing IS in follower cases, analyses of cross-sectoral replication, guidance on legal environments, approaches to pricing exchanged products and services, an assessment of data-exchange channels, KPIs and a Symbiosis Readiness Level scale. According to the CORDIS reporting, strategic roadmaps were developed for three follower regions, together with a digital monitoring tool[10]. The self-assessment and planning framework published by Knoebl et al. likewise treats IS implementation as a staged roadmap[11]. Consequently, technical feasibility is only one stage: implementation also requires viable source–receiver relationships, techno-economic assessment, engineering and infrastructure definition, regulatory clarification, monitoring and data exchange, a business model and a replication plan.

2.2.2 Hubs for Circularity

The Processes4Planet topic on Hubs for Circularity (H4C) requires systemic integration of mass and energy flows, industrial infrastructure and logistics; the exploitation of cross-sectoral synergies; digital modelling and sensing for dynamic resource management; and IT infrastructure that protects commercially sensitive information[12]. Therefore, a scenario cannot be defined only by a compatible by-product and receiver. It may also depend on physical infrastructure, geographical proximity, transport or pipelines, the temporal profile of the resource, continuous information exchange, confidentiality management and coordinated planning among several actors.

2.2.3 IS2H4C

IS2H4C combines IS implementation with digital collaboration and decision-support tools, including a platform for sharing resources, infrastructure and information within Hubs for

[10] European Commission, CORDIS (2026). CORALIS — Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis. Grant Agreement No. 958337. Project results and public deliverables. DOI: 10.3030/958337.

[11] Knoebl, M., Ventura, L., Lindorfer, J., Martín Jimenez, I. (2025). "Industrial matchmaking: A self-assessment and planning framework and a roadmap approach for industrial symbiosis". Energy Research & Social Science, 127, 104185. DOI: 10.1016/j.erss.2025.104185.

[12] European Commission, CORDIS (2023). Hubs for circularity for near zero emissions regions applying industrial symbiosis and cooperative approach to heavy industrialized clusters and surrounding ecosystems (Processes4Planet partnership). Horizon Europe Topic HORIZON-CL4-2023-TWIN-TRANSITION-01-37.

Circularity[13]. It supports three principles adopted in D4.2: scenarios should consider integration into wider networks, not only bilateral exchanges; information requirements are a functional part of implementation, not an administrative add-on; and replication requires explicit identification of the conditions under which an exchange can be transferred to another site or region.

2.2.4 RISERS

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[14]. It 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. Therefore, D4.2 includes receiver specifications, data quality and regulatory conditions among its screening criteria.

2.2.5 Steel–chemical symbiosis: INITIATE

INITIATE uses residual steel gases as feedstock for ammonia and urea production, targets demonstration in an industrial environment at TRL 7 and includes a commercial implementation roadmap[15]. Its quantitative targets are specific to its own system boundary and are not transferred to other gas scenarios. INITIATE illustrates the source–receiver logic adopted in D4.2: steel residual stream → conditioning → cross-sector transfer → chemical conversion → marketable product.

2.2.6 Methodological roadmaps and earlier steel-sector synthesis

Two further sources shape the structure of D4.2. The methodological roadmap of Krzeminski et al. places mapping, feasibility assessment, opportunity selection and implementation in a connected sequence[16]; D4.2 follows the same progression from landscape (Chapter 3) to scenarios (Chapter 4), assessment (Chapters 5–6) and roadmap (Chapter 9). The RFCS project REUSteel, whose analysis of EU-funded research on the reuse and recycling of steel by-products is the methodological starting point of Symbio-Steel[4], produced a research and

[13] European Commission, CORDIS (2026). IS2H4C — Sustainable Circular Economy Transition: From Industrial Symbiosis to Hubs for Circularity. Grant Agreement No. 101138473. DOI: 10.3030/101138473. CORDIS.
[14] European Commission, CORDIS (2026). RISERS — A Roadmap for Industrial Symbiosis Standardisation for Efficient Resource Sharing. Grant Agreement No. 101135539. DOI: 10.3030/101135539.
[15] European Commission, CORDIS. INITIATE — Innovative industrial transformation of the steel and chemical industries of Europe. Grant Agreement No. 958318. Project record and Periodic Reporting for period 3, covering 1 November 2023–30 April 2025, last updated 11 November 2025.
[16] Krzeminski, P., et al. (2026). From theory to practice: a methodological roadmap for mapping, assessing, and implementing industrial symbiosis. Cleaner Engineering and Technology, 31, 101159.

development roadmap with a horizon to 2030[17]. D4.2 extends that perspective from by-product reuse to cross-sectoral implementation.

2.2.7 Implications for the D4.2 methodology

The reviewed approaches consistently show that implementation requires six layers to be considered together:

- Resource layer — quantity, composition, physical and thermal state, and variability of the resource;
- Technology layer — treatment, conditioning, process integration and maturity;
- Infrastructure layer — storage, transport, pipelines, heat networks and other physical interfaces;
- Industrial and commercial layer — receiver specifications, substitution function, market demand and contracts;
- Governance and information layer — responsibilities, data sharing, monitoring, confidentiality and facilitation;
- Impact and replication layer — resource-efficiency and environmental performance, KPIs, scale-up and transferability.

These layers are built into the pathway architecture (Section 2.4), the screening criteria (Section 2.6) and the scenario structure (Section 2.13).

2.3 Identification and classification of resource flows

Scenario generation starts from the resources that can support cross-sector exchanges. The classification follows D3.4[2] and, consistently with D5.2[9], distinguishes two directions:

- resources supplied to steelmaking, where the steel plant receives an external secondary resource;
- resources originating from steelmaking, where the steel plant is the source for internal reuse or for another industrial or civil sector.

Table 2.1 summarises the resource families, their main pathways in D3.4 and the number of D3.4 project entries addressing each family. A project can address more than one family, so the entries do not add up to 82.

[17] REUSteel Consortium. Road map for future research and development directions. Deliverable D5.1, REUSteel, Grant Agreement No. 839227.

Table 2.1 Resource families and D3.4 project entries[2].

Resource family	Main pathways reported in D3.4	D3.4 entries
Resources supplied to steelmaking		
Biogenic SCCs	Biochar, torrefied biomass and hydrochar for EAF charging and injection, BF injection, sintering and cokemaking	12
Non-biogenic SCCs	Recycled polymers, tyres and shredder residues for EAF injection or charging and BF injection	8
Scrap and other secondary raw materials	Scrap cleaning and de-coating, sensor-based scrap characterisation, steel fibres from end-of-life tyres	4
Resources originating from steelmaking		
Slags (BF, BOF, EAF, ladle)	Construction and road building, cement and binders, fertilisers and liming, phosphorus removal, metal recovery, thermal energy storage, refractories, carbonation	26
Dusts	Zn recovery by pyro- and hydrometallurgical routes; Fe-rich fractions and DRI for recycling	22
Sludges and mill scale	Briquetting and recycling to BF or EAF, Zn separation	11
Process and off-gases, CO_2	Ethanol, methanol, polyols, formic acid, dimethyl ether and urea; CO_2 capture and mineralisation	11
Spent refractories	Recycling in the EAF, reuse and remanufacturing	3
Waste heat and water	Heat recovery from off-gases, thermal energy storage, industrial water reuse	3

2.3.1 Secondary resources supplied to the steel sector

D3.4 identifies fixed carbon, moisture, volatile matter, ash, particle size and density, surface characteristics, calorific value, availability, cost and harmful elements as the parameters that govern SCC suitability[2]. Conditioning depends on both the material and its metallurgical function: thermal treatment can raise fixed carbon and lower moisture and volatiles in biogenic materials, agglomeration can improve charging and handling, and for injected SCCs density, dispersion and penetration into the slag or bath become decisive. A carbon-bearing stream is therefore not treated as an implementable SCC solely because it contains carbon; the whole

chain from generation through qualification to the intended function must be demonstrated. Several SCC entries concern EAF charging or injection, which is directly relevant to the expansion of EAF-based production discussed in D5.1[3].

2.3.2 Solid by-products and residues originating from steelmaking

Slags, dusts, sludges and mill scale, and spent refractories are kept separate because their chemistry, conditioning and receivers differ. BF, BOF, EAF and ladle slags have different metallurgical origins; D3.4 reports pathways ranging from internal recycling to construction, cement, fertilisers and liming, phosphorus removal, thermal energy storage, refractories, metal recovery and carbonation[2]. Slag is the largest family in D3.4, with 26 entries. Dusts, sludges and mill scale form the second largest group; their valorisation is driven by the recovery of iron and non-ferrous metals and by the management of fine particles, moisture and elements such as Zn and Pb, through pyrometallurgical, hydrometallurgical and combined treatments, briquetting, injection and recirculation. Spent refractories can be reused internally or recovered externally, depending on their chemistry and contamination.

2.3.3 Gaseous carbon streams

Process and off-gases form a distinct family because implementation requires continuous gas handling, purification and dedicated conversion or transport infrastructure. D3.4 reports CO_2 capture and mineralisation, the conversion of CO- and H_2-containing gases, and the production of ethanol, methanol, ammonia and urea, dimethyl ether, formic acid and polymer precursors[2]. These entries come mainly from Horizon 2020 and Horizon Europe projects and other recent initiatives. Gas scenarios are particularly sensitive to flow rate, pressure, temperature and temporal variability; CO, CO_2, H_2 and inert-gas concentrations; contaminants and gas cleaning; the energy required for separation and conversion; the availability of additional H_2; and the continuity of the receiving process.

2.3.4 Waste heat and other energy streams

Waste heat is treated separately because its value depends on temperature level and temporal availability. Potential uses include internal recovery, steam or power generation, direct industrial use, drying, thermal energy storage, export to neighbouring processes and district heating[2]. Heat recovery is addressed explicitly in only a few D3.4 entries, whereas stakeholders rate it highly: 57% of the respondents to the relevant D4.1 survey question (n = 47) identified heat as an underutilised resource[8]. This value reflects perception, not the fraction of technically recoverable heat. Waste-heat scenarios therefore require explicit matching between the source temperature and time profile and the receiver's demand, and they rely more on public cases and stakeholder evidence than on quantified project results.

2.4 Common pathway architecture

Each scenario is represented through the same chain — Source → Resource → Conditioning → Transport / Infrastructure → Receiver → Substitution — which allows heterogeneous exchanges to be compared. Table 2.2 defines each element.

Table 2.2 Elements of the common pathway architecture.

Element	Definition	Examples
Source	Industrial process or upstream actor from which the resource becomes available	EAF producing slag; integrated plant producing process gases; biomass processor supplying biochar
Resource	Material or energy stream exchanged, described by flow, composition, contaminants, moisture, particle size, density, temperature, calorific value and variability	EAF slag; BOF gas; hydrochar; low-temperature heat
Conditioning	Operations between generation and acceptance by the receiver; only steps supported by the reviewed evidence are included	Crushing and classification; ageing; metal separation; drying; grinding; briquetting; pyrolysis or torrefaction; gas cleaning; heat exchange
Transport / infrastructure	Physical connection between source and receiver; always assessed explicitly, never assumed negligible	Road or rail logistics and storage for solids; pipelines for gases; heat networks
Receiver	Process or actor able to use the conditioned resource	EAF; cement plant; road construction; chemical plant; non-ferrous smelter; district heating
Substitution	Conventional input or service displaced; links the exchange to the WP3 KPIs	Virgin minerals; fossil coal or coke; primary metals; fossil chemical feedstock; natural gas or conventional heat

2.5 Actor and partnership configuration

Task 4.2 requires the identification of links with other industries and their stakeholders[4]. Each scenario is therefore accompanied by a functional actor map based on seven roles: resource provider (source operator); conditioning or technology provider; logistics or infrastructure operator; receiver or off-taker; testing, certification or technical-support organisation; public or competent authority; and IS facilitator or cluster coordinator. D5.2 shows that independent

facilitators support partner matching, trust building, mediation and resource mapping, and that discontinued coordination can stop promising exchanges[9].

Not every scenario needs all seven roles; the taxonomy ensures that every responsibility required for implementation is assigned. Actors are identified by function. Organisations that took part in earlier funded projects are cited as examples of the required expertise, not as committed participants (Appendix E).

2.6 Screening of candidate pathways

D3.4 contains far more pathways than can be developed in detail, so candidate pathways are screened against nine evidence-based criteria (Table 2.3). No weighted numerical score is used, because the evidence provides neither common scales nor agreed weights. For each criterion, the strength or limitation of the available evidence is recorded instead.

Table 2.3 Screening criteria.

Criterion	Key questions	Main evidence
1. Technological maturity	Demonstrated scale, reported TRL (KPI XI), degree of integration, remaining scale-up needs	D3.2–D3.4
2. Resource availability and variability	Quantity, continuity, temporal variability, consistency of properties; no availability is assumed without a traceable source	D3.4, D5.1
3. Resource–receiver compatibility	Chemical and mineralogical composition, harmful elements, moisture, size, density, thermal state, process performance	D3.4
4. Infrastructure, logistics and geography	Transport, storage, pipelines or networks, source–receiver proximity, site integration	D3.4, D5.2
5. Substitution and resource efficiency	Input substituted, quantifiability, applicable WP3 KPI	D3.1–D3.3
6. Regulatory and legal conditions	Legal status (waste, by-product, end-of-waste), product requirements, permitting	D5.2
7. Economic and market conditions	Reported CAPEX/OPEX, treatment and avoided costs, value of substituted input, demand, off-take	D3.4, D5.2
8. Organisational and information conditions	Number of actors, continuity of cooperation, data ownership, confidentiality, monitoring	D4.1, D5.2

9. Replication potential	Compatible receiver, proximity, infrastructure, comparable resource quality, standards, scale	D3.4, D5.1, D5.2

Stakeholder relevance, derived from the aggregated D4.1 results, is used as a cross-cutting check on criteria 2, 3 and 8. D5.2 confirms that logistics can become decisive for bulky, low-value streams, that the legal classification of secondary materials is a recurrent barrier, and that confidentiality and information asymmetry limit deployment[9]. Where economic data are not available, economic feasibility is discussed qualitatively and the missing information is identified. D4.2 identifies the regulatory issues to be resolved before implementation but does not replace case-specific legal analysis.

2.7 System boundaries and quantitative reference conditions

The scenarios involve solids, gases and heat, so no single reference basis is imposed. For each scenario the boundary normally begins where the resource becomes available at the source and ends with its use in the receiving process, including conditioning, storage, transport, inter-site infrastructure and any conversion required before final use. Processes outside the evidence base are not added implicitly.

Quantitative results keep the reference basis of the original source wherever possible — for example kg of secondary material per tonne of steel, percentage substitution of a conventional input, recycling or recovery rate, GJ per tonne of resource, MWh per year, kg CO_2-eq per tonne of steel, or the percentage of process-gas carbon converted into product. SI units are used or converted transparently. Values from different projects are compared only when their definitions and boundaries are compatible: a 100% substitution of one EAF carbon stream, for example, is not read as a 100% replacement of the furnace's total fossil carbon unless the source defines the indicator in that way.

2.8 Evidence hierarchy and data-quality management

Evidence is managed according to two complementary principles: project consistency and source provenance. Symbio-Steel deliverables (D1.2, D3.1–D3.4, D4.1, D5.1 and D5.2) constitute the authoritative internal evidence base for the development of D4.2. Where a quantitative value can be traced to an underlying primary project deliverable, official report or dataset, the primary source is used to verify its numerical value, boundary and evidence status. Peer-reviewed literature is used where it provides methodological or quantitative information not covered by project documentation, while other documented technical sources are used only where their scope and reference conditions are clear. Where conflicting numerical

information is identified, the discrepancy is reported explicitly rather than resolved through an unreported assumption.

Each quantitative datum carries one of four statuses, which are used consistently in Chapter 5 and Appendix B:

- Reported (R) — value stated in a source and not calculated in D4.2. Where relevant, R is further qualified according to the nature of the source value, for example as measured, source-calculated, modelled, targeted or expected;
- Calculated (C) — value derived in D4.2 exclusively from reported input data, with the calculation and reference basis explicitly stated;
- Explicit analytical assumption — parameter introduced only for a clearly labelled illustrative or sensitivity calculation; assumptions are never presented as reported or observed industrial performance;
- Data gap (G) — parameter for which no defensible value is available; no numerical value is assigned.

Where a source reports a value as calculated but does not provide sufficient information to reconstruct the underlying arithmetic or mass balance, D4.2 retains the value as R (source-calculated) and does not infer the calculation method.

2.9 Integration of the WP3 KPI framework

The eleven WP3 KPIs are not all applicable to every scenario[5]. Table 2.4 gives the indicative mapping between pathway families and KPIs; the operational definitions and boundary conditions are given in Table 5.1.

Table 2.4 Pathway families and potentially applicable WP3 KPIs.

Pathway family	Potentially applicable KPIs
Waste-heat recovery	KPI I (recovered heat reused by other industries); KPI XI
SCC substitution in steelmaking	KPI VIII; KPI III where a primary input is displaced; KPI II where a consistent direct-emissions comparison exists; KPI XI
Slag valorisation	KPI V; KPI III; KPI XI
Dust, sludge and iron-rich residue recovery	KPI VI; KPI VII; KPI III; KPI XI
Process-gas and CO_2 utilisation	KPI IX (reuse of CO_2 from off-gases); KPI X; KPI II where the boundary allows; KPI XI
Scrap upgrading	KPI IV; KPI III; KPI XI

The mapping identifies which KPIs are conceptually relevant to each pathway; it does not establish that the data needed to calculate them are available. For every scenario, the assessment must therefore state the indicator definition, numerator, denominator, unit, system boundary, reference period, baseline or counterfactual, evidence status and responsible data owner. KPI X requires a defined carbon-bearing gas input and a quantified carbon flow to the product; KPI IX requires the quantity of CO_2 actually reused, which differs from the quantity captured. If either the numerator or denominator of an indicator is missing, the KPI is recorded as relevant but not calculated.

2.10 Integration of stakeholder evidence, barriers and enabling conditions

The implementation assessment combines the WP3 technology evidence with the stakeholder and non-technical evidence of WP4 and WP5. In the D4.1 survey, economic barriers were the most frequently selected obstacle to the adoption of IS (63.9% of respondents, n = 36), followed by financial (58.3%), regulatory (58%), organisational (47%) and logistics barriers (41%); technological barriers were selected by 22% of respondents[8]. Almost half of the respondents reported regulatory or policy-related difficulties (47%, n = 36), while D4.1 reports that approximately half of the respondents considered current economic incentives insufficient to encourage IS practices. These results are treated as stakeholder perceptions and implementation signals rather than as quantitative evidence of the feasibility of a specific pathway.

This profile is consistent with the D5.2 classification of non-technical barriers[9]. D4.2 therefore assesses every scenario against the five D5.2 categories and considers the enabling conditions identified in D5.2: long-term off-take arrangements, stable markets for secondary resources, suitable regulatory classification, independent IS facilitation, quality-assured resource databases, and information sharing that respects confidentiality. D5.2 specifically recommends long-term off-take agreements for industrial by-products and shared quality-assured data systems to reduce discontinuity and information risks[9]. No enabling condition is assumed to apply universally; its relevance is assessed scenario by scenario.

2.11 Common data structure for Industrial Symbiosis scenarios

Task 4.2 requires procedures for consistent data exchange and cross-industrial planning[4]. D4.2 adopts a minimum dataset organised in five groups:

- Source data — source process, generation point, quantity or flow rate, temporal availability;

- Resource-quality data — composition, contaminants, physical form, moisture, particle size or density and thermal state where relevant;
- Conditioning and logistics data — required treatment, expected output, storage conditions, transport mode and distance, infrastructure requirements;
- Receiver data — receiving process, demand where available, quality limits, operating constraints, conventional input substituted;
- Data-governance information — data source, reference conditions, measurement or calculation basis, data owner, confidentiality restrictions, validation responsibility.

This section defines the data structure used for scenario development. The exchange procedure, validation responsibilities and template are developed in Chapter 8 and Appendix C, to avoid duplication between methodology and implementation guidance.

2.12 Treatment of data gaps and uncertainty

Public project documentation often lacks annual flow rates, complete chemical variability, source–receiver distances, receiver capacities, detailed CAPEX/OPEX, contract conditions and time-resolved heat or gas profiles. D4.2 applies five rules:

- no missing industrial parameter is replaced by an assumed "typical" value;
- stakeholder percentages are not interpreted as physical resource quantities;
- project-specific performance remains project-specific evidence;
- values with different boundaries are not combined without reconciliation;
- where quantification is not defensible, a qualitative or semi-quantitative assessment is retained and the gap is recorded.

Missing data are therefore reported as a limitation of the evidence and translated into the data requirements listed in Appendix B and the data-exchange procedure of Chapter 8.

2.13 Output of the methodology: screening results and selected scenarios

Applying the criteria to the D3.4 resource families, together with the WP3 KPI evidence and the D4.1 stakeholder results, gives the evidence profile summarised in Table 2.5. Stakeholder percentages are shares of respondents to each survey question and express perception, not resource quantities.

Table 2.5 Evidence profile of candidate pathway families.

Pathway family	D3.4 entries[2]	Projects with quantified WP3 KPIs[6,7]	Stakeholder signal, D4.1[8]	Outcome
Slags	26	SLACON, SLAGFERTILISER, SLASORB, CORALIS; Slagreus (D3.3)	Underutilised: EAF slag 62%, BOF slag 51%, ladle slag 49% (n = 47). Construction as receiving sector 78% (n = 32)	S1
SCCs (biogenic and non-biogenic)	12 + 8 (18 distinct)	EAF: GREENEAF, GREENEAF2, OnlyPlastic, RIMFOAM, BioReSteel; GreenHeatEAF (D3.3). Further BF, sintering and cokemaking projects	Underutilised: biomass 28%, polymers and plastics 21% (n = 47)	S2
Process gases and CO_2	11	INITIATE; Carbon4Minerals	Underutilised: off-gases 45% (n = 47). Chemicals as receiving sector 47% (n = 32)	S3
Waste heat	2	None for KPI I	Underutilised: heat 57% (n = 47). Energy as receiving sector 50% (n = 32)	S4
Dusts, sludges and mill scale	22 + 11 (24 distinct)	CORALIS (KPI VI, VII)	Underutilised: sludge 34%, ferrous dust 28% (n = 47). Seen as raw-material substitutes: dust 43%, sludge 41% (n = 37)	Landscape and clusters
Scrap	4	–	Underutilised: ferrous scrap 30% (n = 47)	Landscape
Spent refractories	3	–	Underutilised: 21% (n = 47)	Landscape
Water	1	–	Underutilised: wastewater 45% (n = 47)	Landscape

The selection favours pathways that combine a documented resource–receiver relationship, quantified project evidence and stakeholder relevance, while covering four contrasting implementation configurations: qualification of a mineral product for an external receiver (S1), supply of a secondary input to steelmaking (S2), gas conversion with coupled carbon and energy balances (S3), and thermal matching with shared infrastructure (S4). S1 and S3 are supported on all three evidence dimensions. S2 has the broadest quantified evidence, with a moderate stakeholder signal. S4 is supported mainly by stakeholder evidence and public cases:

its technical documentation in D3.4 is limited and no KPI I value is available, so its assessment in Chapters 4 and 5 is explicitly qualitative. Dust, sludge and mill-scale recovery has a broad technical base but limited WP3 quantification; it is retained in the landscape and cluster analysis in Chapters 3 and 7 rather than developed as a detailed scenario. This selection is a portfolio decision based on evidence coverage and implementation diversity, not a ranking of commercial attractiveness.

The selected scenarios do not represent all pathways identified in Symbio-Steel; the wider set remains part of the landscape presented in Chapter 3 and Appendix D. Each scenario is developed in Chapter 4 according to a common eleven-part structure:

1. Scenario rationale and objective
2. Source and resource stream
3. Resource characteristics and requirements
4. Conditioning and technical integration
5. Transport, infrastructure and geographical configuration
6. Receiver and substitution function
7. Actors and partnership configuration
8. Data-exchange requirements
9. Relevant WP3 KPIs and available quantitative evidence
10. Implementation barriers and enabling conditions
11. Replication potential and remaining data gaps

This structure links each requirement of Task 4.2 — actors, links to other industries, data exchange and impact assessment — to a specific part of every scenario. A pathway advances from evidence review to site-specific implementation only when five minimum conditions are satisfied: a traceable resource supply is defined; the receiver has issued an acceptance specification; the conditioning and transfer chain is technically feasible; the legal route and responsible actors are identified; and the data required for the selected KPI and economic counterfactual are available. Where one or more conditions are missing, the pathway remains a candidate for qualification rather than an implementation-ready scenario.

3. Steel-Driven Industrial Symbiosis Landscape, Pathway Classification and Implementation Gaps

3.1 Overview of steel-driven Industrial Symbiosis pathways

The technological portfolio reviewed in D3.4 supports two complementary directions of Industrial Symbiosis (IS): the supply of secondary resources to steelmaking and the use of steelworks residues and energy streams in external value chains. Within the D4.2 classification, almost all (79 over 82 reviewed projects) are assigned to at least one resource family (Table 2.1)[18]. The implementation potential of these exchanges depends on the complete source–receiver relationship. Because a project may address more than one resource family, category counts are non-additive. Demonstrating a treatment technology establishes a necessary technical capability but does not by itself establish that a suitable resource supply, receiving process and commercial arrangement coexist at a particular location[2,9,19].

Consequently, the landscape is classified by resource family, conditioning requirement, receiving sector and substitution function. Internal recirculation is retained where it affects the quantity or quality available for external exchange; an exclusively internal recycling operation is not counted as a new cross-sector connection. Equally, material already sold to

[18] The remaining three projects do not provide a pathway that can be classified within the resource families used in this report.

[19] 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., and Snaet, D. (2026). Recent achievements of Industrial Symbiosis in the steel sector based on the Symbio-Steel project: a review. Matériaux & Techniques, 114, 103. https://doi.org/10.1051/mattech/2026002.

an established user is not treated as unutilised. An alternative destination must be assessed against its actual current use, including any loss of an existing recycling or energy-recovery service.

Table 3.1 links the resource families to their principal implementation questions. The categories describe possible exchanges rather than a forecast of market uptake. D5.1 further indicates that a change in steelmaking route can modify the composition and availability of these resources, requiring periodic reassessment of both established and proposed connections[3].

Table 3.1 Resource families and cross-sector connections.

Resource family	Principal connection	Substitution function	Decisive qualification issue
Biogenic and non-biogenic SCCs	Biomass processing or waste treatment to steel	Selected carbonaceous process inputs	Carbon function, contaminants and feeding behaviour
Slags and mineral residues	Steel to construction, cement, agriculture and other mineral users	Aggregates, raw components, qualified binder constituents, liming materials	Mineralogy, stability, leaching and end-use performance
Dust, sludge and mill scale	Steel to metal recovery, with possible return of recovered iron	Primary metal-bearing inputs	Element partitioning, impurities and treatment residues
Process gases and separated CO_2	Steel to chemicals and mineral products	Chemical feedstocks, associated hydrogen production, carbonated products	Gas quality, conversion requirements and displaced internal fuel use
Residual heat	Steel to neighbouring industry or heat networks	Delivered thermal service	Temperature, simultaneous demand and continuity
Water and spent refractories	Steel to water users or refractory and mineral processors	Freshwater or qualified mineral inputs	Contamination, segregation and fitness for the receiving duty

3.2 Secondary Carbon Carriers and secondary resources supplied to steelmaking

Secondary Carbon Carriers (SCCs) connect steel production with biomass-processing, recycling and waste-treatment activities. D3.4 distinguishes biogenic materials, including biochar, torrefied biomass and hydrochar, from non-biogenic materials such as selected plastics, tyre-derived fractions and shredder residues[2]. Their assessment must preserve this distinction because carbon origin, ash chemistry, volatile release and physical behaviour differ substantially. Recycled fossil carbon can reduce demand for newly extracted carbonaceous

materials; this does not make its carbon biogenic or establish an equivalent reduction in direct CO_2 emissions.

SCCs form one of the best-documented families in the Symbio-Steel evidence base: 18 distinct projects in D3.4, of which seven concern EAF charging or injection. The WP3 KPI dataset provides quantified fossil-carbon replacement (KPI VIII) for five EAF projects — GREENEAF, GREENEAF2, RIMFOAM, OnlyPlastic and BioReSteel — and for several blast-furnace, sintering and cokemaking projects, including Flexinject, Acasos, INNOCARB, ALTERAMA and FLEXCOKE[6]. D3.3 adds the GreenHeatEAF trials[7]. The stakeholder signal is moderate: biomass and polymers or plastics were identified as underutilised resources by 28% and 21% of respondents, respectively (n = 47)[8].

Within the EAF, basket charging and pneumatic injection impose different requirements. A charge material must survive handling and reach the intended reaction zone without excessive premature oxidation. An injectant must be metered and conveyed consistently and interact with slag or metal at the required location. Carbon content alone is consequently insufficient to qualify a replacement. The assessment also requires moisture, volatile matter, ash composition, particle-size distribution, bulk density, mechanical degradation and material-specific reaction behaviour. The evidence regarding GREENEAF2 and OnlyPlastic (D3.4, Sections 2.2.18 and 2.2.27) demonstrates the importance of matching material preparation with the feeding system[2].

Other incoming secondary resources include ferrous scrap, recovered metallic units and selected mineral materials. Their substitution function differs from that of SCCs and requires a separate balance. For example, iron recovery cannot be quantified from the total mass of a residue without its iron content and recovery yield. Scrap upgrading remains part of the broader landscape: sorting, de-coating and sensor-based characterisation can improve compatibility with steel-grade requirements and allow lower-quality scrap to be used (KPI IV)[2].

3.3 Slags and mineral residue pathways

Slag is the largest resource family in D3.4, with 26 project entries, and the family with the strongest stakeholder signal in D4.1: EAF, BOF and ladle slags were identified as underutilised by 62%, 51% and 49% of respondents (n = 47), and construction was the receiving sector most frequently indicated (78%, n = 32), followed by fertilisers (53%) and agriculture (47%)[8].

Slag valorisation encompasses distinct material classes. Granulated blast-furnace slag, BOF slag, EAF oxidising slag and ladle-furnace slag have different formation conditions and mineralogical characteristics. Established use of one class does not establish the suitability of another for the same application. In particular, replacement of aggregate, use in clinker raw meal, use as a reactive cement constituent and use as a liming or fertilising material are different functions, each requiring its own performance and environmental qualification[2].

For steelmaking slags, the treatment chain may combine segregation, metallic recovery, size reduction, controlled ageing and further modification of chemistry or mineralogy. Qualification must address volume stability and contaminant release as well as mechanical performance. The response to conditioning can be element-specific: in SLACON (D3.4, Section 2.2.14), barium, chromium and vanadium leaching from EAF slag were reduced by liquid-stage measures, whereas molybdenum and selenium could not be stabilised in the same way[2,6]. A reduction in the release of one element therefore cannot be extrapolated to all regulated constituents. The relevant outcome is an accepted material for a defined use, accompanied by a traceable test record.

Agricultural use is an established but distinct receiving duty. In SLAGFERTILISER (D3.4, Section 2.2.12), long-term field and lysimeter trials across several European countries found yields with slag-based liming and fertilising materials comparable to or better than those with natural materials, while chromium and vanadium accumulated in soil over time, less so in crops[6]. SLASORB (D3.4, Section 2.2.8) demonstrated BOF slag fractions as phosphorus sorbents in small wastewater-treatment plants, with the saturated material considered for subsequent use as fertiliser[6]. Emerging pathways include carbonation, modified slag production and separation into fractions with different destinations. These may improve resource recovery but also introduce energy, reagent and residual-treatment demands, which remain inside the assessment boundary. The future availability of slag suitable for cement and agricultural applications must also be re-examined as BF-based production declines and DRI–EAF or smelter routes develop[3].

3.4 Dust, sludge, mill scale and metal-recovery pathways

Dusts, sludges and mill scale form the second-largest family in D3.4 (24 distinct projects) and are relevant to KPIs VI and VII. They can contain recoverable iron, zinc and alloying elements, but their composition and handling characteristics depend on their origin. Zinc-bearing EAF dust, oily rolling-mill scale and wet gas-cleaning sludge cannot be represented by a common treatment yield. D3.4 documents pyrometallurgical, hydrometallurgical and combined routes, briquetting and pelletising, injection and recirculation to the sinter plant, BF or EAF[2]. Stakeholders also see these streams as substitutes for primary raw materials: dust and sludge were selected by 43% and 41% of respondents, respectively (n = 37)[8].

The cross-sector configuration typically links a steelworks to a specialised processor and a metal-product receiver. The processor must account for the distribution of each relevant element between recovered products, remaining solids, water and gaseous emissions. A high recovery of a target metal may coexist with a substantial residual stream; it is therefore distinct from the fraction of total residue recycled. These quantities correspond to different engineering questions and must not be substituted for one another in KPIs VI or VII[5].

Despite its broad technical base, this family is not developed as a fifth detailed scenario. Most documented routes are internal recirculation loops or established metal-recovery services, and the WP3 dataset provides quantified KPIs VI and VII for one project only (CORALIS, 100% for rolling-mill sludge in the Italian demonstration case)[6]. This single case does not provide the element-specific mass balances, treatment yields, residual-stream destinations and external receiver data required for a transferable cross-sector implementation scenario. The family is therefore retained in the landscape, the material cluster in Section 7.3.1 and Appendix D, and is identified as the first candidate for a follow-up scenario once these data become available (Section 9.11.4).

3.5 Process gas and CO_2 utilisation pathways

Steel process gases provide links to the chemical sector through gas conditioning, conversion and separation. D3.4 reviews 11 projects, mostly funded under Horizon 2020 and Horizon Europe, addressing routes to ethanol, methanol, polyols, formic acid, dimethyl ether, ammonia and urea, and CO_2 mineralisation[2]. Off-gases were identified as underutilised by 45% of respondents (n = 47), and chemicals were indicated as a receiving sector by 47% (n = 32)[8]. The composition of BFG, BOFG and coke-oven gas differs, as do the requirements of catalytic synthesis and biological conversion. A proposed exchange therefore requires identification of the actual gas source, composition, pressure, contaminants and temporal profile.

INITIATE (D3.4, Section 3.2.13) provides the principal reference configuration for Scenario S3, involving BOF gas, sorption-enhanced water-gas shift and ammonia/urea production[2,15]. Ammonia contains no carbon: its production can exploit hydrogen obtained through gas conversion, but carbon incorporation into products must be assessed separately through carbon-containing outputs such as urea. Captured CO_2, CO_2 supplied for use and carbon retained in a product are different accounting quantities[5]. A second route, documented by Carbon4Minerals (D3.4, Section 3.2.19), binds CO_2 from industrial flue gases into carbonated binders and construction products; it links the gas family to the mineral receivers of S1 rather than to the chemical sector[2,6].

The conventional use of process gases within the steelworks is also material to the assessment. Diverting a gas to chemical production can reduce fuel available for heating or power generation. The resulting replacement energy must be included before drawing conclusions on total energy demand or emissions.

3.6 Waste heat, water, refractories and other resource pathways

Waste heat has the widest gap between stakeholder interest and documented evidence. It was the second most frequently cited underutilised resource (57%, n = 47), and energy was indicated as a receiving sector by 50% (n = 32)[8], yet heat recovery is addressed explicitly in only two D3.4 entries and no WP3 project provides a KPI I value[2,6]. Waste-heat exchanges depend on temperature and time as well as energy quantity. D3.4 distinguishes low-grade heat below 100 °C, medium-grade heat at approximately 100–400 °C and high-grade heat above 400 °C. These ranges are descriptive categories rather than acceptance limits for a particular receiver. The usable fraction is determined by the source temperature, return temperature, heat-transfer equipment and simultaneous demand[2].

Water reuse requires equivalent attention to quality; wastewater was identified as underutilised by 45% of respondents (n = 47)[8]. A flow suitable for one cooling duty may be unsuitable for a process with tighter requirements for dissolved salts, suspended solids or organic contaminants. Treatment, purge requirements and the destination of concentrated contaminants must be included. Spent refractories (21%, n = 47) similarly require segregation by composition and service history before reuse in refractory production or other mineral applications[2,8].

These streams may support an integrated cluster, but their coupling cannot be assumed to improve overall performance automatically. For example, using recovered heat for drying SCC feedstock may reduce heat available to an external customer. The two uses must be represented as competing or cascaded demands on the same physical resource.

3.7 Receiving sectors and cross-sectoral connections

The principal receivers considered in the scenario portfolio are construction-material and cement producers, agricultural users of liming and fertilising materials, EAF operators, chemical producers, neighbouring heat users and district-heating operators. Table 3.2 summarises the receiving sectors indicated by stakeholders. In addition, 77% of respondents (n = 48) considered that the underutilised resources they identified could be exploited within the steel sector itself[8]. These findings indicate stakeholder interest; they do not quantify available material, contracted demand or industrial acceptance.

Table 3.2 Receiving sectors indicated for underutilised resources (D4.1 survey, n = 32)[8].

Receiving sector	Share of respondents	Relevant scenario
Construction and buildings	78%	S1
Fertilisers	53%	S1 (S1c)
Energy	50%	S4
Agriculture	47%	S1 (S1c)
Chemicals	47%	S3
Non-ferrous metals	34%	Dust and sludge (landscape)
CO_2 capture and usage	28%	S3
Refractories	28%	Landscape
Minerals	22%	S1

The relationship must be specified at process level. A cement works may accept a material as part of its kiln feed while a concrete producer requires a qualified constituent for a different duty. Likewise, an industrial steam user and a hot-water network have different interface requirements. The actor mapping in Appendix E therefore links organisations to functions in the exchange, without treating historical project participation as a commitment to future implementation.

3.8 Main implementation gaps

The gaps below are derived from D3.4, D5.1 and D5.2 and are consistent with the barriers reported by stakeholders. In the D4.1 survey, economic barriers were the most frequently selected obstacle to IS adoption (63.9%, n = 36), followed by financial (58.3%), regulatory (58%), organisational (47%) and logistics barriers (41%); technological barriers were selected by 22% of respondents[8].

3.8.1 Technical and resource-quality gaps

The central technical gap is the absence of a verified operating envelope connecting resource variability to receiver acceptance. Average composition is insufficient where occasional high contaminant concentrations, unstable mineral phases or irregular feeding can cause rejection. The required evidence comprises representative sampling, variability over the relevant production period and performance testing under the intended conditions. Numerical acceptance limits must originate from the receiving process, product specification or applicable regulatory requirement; D4.2 does not assign universal tolerances to heterogeneous resources[2,3].

3.8.2 Infrastructure, logistics and geographical gaps

Solid-material exchanges require suitable loading, transport, storage and unloading capacity. Heat and gas connections also require continuity of supply and access to dedicated

infrastructure. Geographical proximity can reduce transfer costs but does not compensate for incompatible quality or demand. Distance screening must use a feasible route and its constraints, rather than only the straight-line separation between sites[9].

3.8.3 Regulatory and legal gaps

Uncertainty over resource classification and the authorisation of treatment or use can delay an otherwise technically credible exchange. Almost half of the survey respondents (47%, n = 36) reported regulatory or policy-related difficulties[8], and D5.2 identifies differences between jurisdictions and application-specific requirements as recurrent barriers[9]. The implementation gap is therefore a documented route from the material's current status to its intended use, including responsibilities for supporting evidence and authority engagement. The distinction between by-product and end-of-waste routes is addressed in Section 9.5.

3.8.4 Economic and market gaps

The available documents do not provide comparable delivered costs for the four scenarios. Conditioning, transport, quality assurance and residual disposal can offset the value of avoided primary inputs. Gas and heat exchanges also incur an opportunity cost where the resource has an existing internal use. D4.1 reports that approximately half of the respondents considered current economic incentives insufficient to encourage IS practices[8]. Economic screening consequently requires the actual counterfactual and a sensitivity analysis of the variables controlling each pathway[9].

3.8.5 Organisational and governance gaps

Implementation requires agreement on ownership, operation, maintenance, rejection and interruption management. An exchange can fail where no actor accepts responsibility for an interface between otherwise functioning installations. D5.2 identifies facilitation and sustained coordination as practical responses to this problem[9]. The proposed governance framework assigns responsibility to named functions before the exchange advances to investment preparation.

3.8.6 Information and data-exchange gaps

Incompatible units, incomplete analytical bases and unrecorded sampling conditions can create a false resource match. Confidentiality may also prevent potential receivers from evaluating a resource. A common dataset must therefore distinguish information suitable for initial screening from restricted operating data required for engineering and contracting[9]. Chapter 8 defines the exchange procedure, and Appendix C provides the corresponding template.

3.8.7 Social and market-acceptance aspects

Acceptance depends on confidence in material performance, environmental control and continuity of service. Construction and agricultural users require evidence that a secondary constituent meets the intended duty; heat customers require a reliable thermal service. Communication should explain the relevant test results, operating arrangements and

limitations. D5.2 identifies trust and perceptions of secondary materials as implementation factors[9], but the available evidence does not support a quantitative forecast of local acceptance for an unspecified installation.

3.9 Priority pathways for detailed scenario development

The screening in Section 2.13 (Table 2.5) retains four scenarios that represent different implementation configurations and evidence conditions. S1 examines mineral qualification and product acceptance; S2 examines supply-chain quality and metallurgical integration; S3 examines gas conversion and coupled carbon and energy balances; S4 examines thermal matching and shared infrastructure. The portfolio is not a ranking of environmental benefit, commercial attractiveness or readiness for investment. S1–S3 contain project-specific quantitative benchmarks with different boundaries, whereas S4 is supported mainly by stakeholder evidence, public cases and interface requirements. Table 3.3 therefore reports evidence strength and the extent of defensible quantification rather than a common performance score.

Table 3.3 Rationale and evidence strength of the selected scenarios.

Scenario	Evidence supporting selection	Main implementation question	Extent of quantitative assessment
S1 Slag valorisation	26 D3.4 entries; SLACON, SLAGFERTILISER, SLASORB, CORALIS (D3.2); Slagreus (D3.3); strongest stakeholder signal	Can a specified slag fraction meet a defined construction, cement or agricultural duty?	Project-specific benchmarks; no site-wide slag balance
S2 SCCs for EAF	7 EAF entries; GREENEAF, GREENEAF2, RIMFOAM, OnlyPlastic, BioReSteel (D3.2); GreenHeatEAF (D3.3)	Can a qualified SCC replace a defined carbon function under stable operation?	Broadest set of industrial-trial benchmarks, with stream-specific denominators
S3 Steel gases to chemicals	11 D3.4 entries; INITIATE and Carbon4Minerals (D3.2)	Can gas diversion and chemical production deliver a net system benefit?	Modelled assessment cases with two different boundaries; no plant mass balance
S4 Waste-heat integration	2 D3.4 entries; public PITAGORAS case; high stakeholder interest	Is usable residual heat available when and where it is required?	Qualitative; interface data only, no KPI I value available

4. Development of Selected Future Industrial Symbiosis Implementation Scenarios

4.1 Common scenario-development structure

The four scenarios are transferable configurations developed from the reviewed evidence. Each is described through the same eleven subsections defined in Section 2.13, linking the source and resource to conditioning, transfer, receiver and substitution. The assessment then identifies actors, required data, applicable KPIs, implementation conditions and replication limits. Appendix A provides a concise assessment sheet for each configuration.

The reported technologies and project results are distinguished from the implementation arrangements proposed in D4.2. No named site is assumed to supply material, purchase products or finance infrastructure for these scenarios. Technical qualification, legal eligibility, commercial agreement and data validation are separate decisions. A positive result in one area does not remove an unresolved condition in another.

4.2 Scenario S1 — Steelmaking slag valorisation in construction, cement and agricultural value chains

4.2.1 Scenario rationale and objective

S1 connects the generation and processing of steelmaking slag with a receiver requiring a mineral input. Its objective is to increase the fraction of a defined slag stream accepted for a useful application while reducing demand for the conventional material performing that function. The scenario distinguishes three variants: S1a, aggregate applications; S1b, cement-related applications; and S1c, agricultural liming and fertilising materials. This avoids assuming that mechanical suitability as an aggregate establishes cementitious reactivity or agronomic

value[2]. The use of slag as a phosphorus sorbent (SLASORB) is a further documented duty, retained in the landscape (Appendix D).

4.2.2 Source and resource stream

The source is a BOF, EAF or ladle-furnace operation, with slag segregated by process and, where required, steel grade or treatment history. Blast-furnace slag provides an established reference for steel–cement cooperation, but is not used as a property surrogate for steelmaking slag. The exchange begins at the specified point where slag becomes available for conditioning; upstream changes made specifically to enable valorisation must also be included in the assessment[2,3].

4.2.3 Resource characteristics and requirements

The resource specification covers major oxides, relevant trace elements, mineral phases, residual metallic content, particle-size distribution and moisture. Volume stability and leaching behaviour require dedicated testing; total elemental composition does not substitute for a leaching test[2]. For S1a, the receiver must additionally define the mechanical and durability requirements of the intended application. For S1b, raw-meal use requires compatibility with the kiln-feed balance, whereas use as a binder constituent requires evidence of reactivity and performance in the intended formulation. For S1c, the relevant properties are liming value, available nutrients and the long-term behaviour of trace elements in soil; SLAGFERTILISER showed that chromium and vanadium can accumulate in soil over repeated applications[6].

4.2.4 Conditioning and technical integration

The proposed chain begins with controlled segregation and metallic recovery, followed by crushing and classification. Ageing or other stabilisation is included only where required by the selected slag and end use. Additional grinding, separation, thermal modification or carbonation must be justified by the target specification. Each operation generates a distinct output: recovered metal, qualified mineral fraction and any rejected or residual material. These outputs must be measured separately to avoid counting recovered metal as construction-grade slag.

The treatment sequence is selected jointly by the producer, processor and receiver. A treatment that improves environmental performance may change grading or reactivity, so qualification is repeated on the final material rather than inferred from the untreated slag[2].

4.2.5 Transport, infrastructure and geographical configuration

S1 is assessed as a steelworks connected to an on-site or regional processing facility and one or more mineral-product receivers. Storage must retain batch identity and prevent contamination between qualified and unqualified fractions. Logistics assessment includes actual route length, transported moisture, loading and unloading capacity, seasonal demand — particularly relevant for construction and agricultural outlets — and storage needs. No

universal economic radius is imposed because the feasible distance depends on transport mode, product value, treatment cost and the displaced material[9].

4.2.6 Receiver and substitution function

In S1a, a construction-material producer replaces a specified aggregate fraction in a defined formulation. In S1b, a cement producer either substitutes a raw-meal component or uses a qualified constituent to reduce clinker demand. In S1c, a fertiliser producer or distributor supplies slag-based liming or fertilising material in place of natural liming materials. The substitution factor must be demonstrated for the specific duty: one kilogram of slag is not assumed to replace one kilogram of clinker or of natural lime. Changes in binder content, activator demand, application rate or product yield must be retained when comparing equivalent performance.

4.2.7 Actors and partnership configuration

The essential actors are the slag producer, a processor where separate, and the receiving manufacturer or distributor. A laboratory provides characterisation and qualification data, while logistics operators maintain batch traceability. The receiver owns the acceptance specification; the producer and processor own their respective production controls. For S1c, agricultural advisory bodies and end users are additional stakeholders. A facilitator can coordinate multiple outlets where a single receiver cannot absorb the qualified supply. Historical project partners provide examples of the required expertise, not confirmed participants in S1[2,9].

4.2.8 Data-exchange requirements

The initial exchange includes slag origin, current destination, available dry mass, variability, analytical results and candidate application. Detailed qualification adds sampling methods, leaching-test conditions, stability results, treatment yields and the receiver's acceptance criteria. Operational records must link the dispatched batch to the processing history, certificate, delivered mass and acceptance outcome. Stock movements are recorded separately from recycling, allowing the balance to distinguish generated, stored, dispatched and accepted material.

4.2.9 Relevant WP3 KPIs and available quantitative evidence

KPI V measures the proportion of slag from the defined process sent to recycling; KPI III addresses the reduction in virgin raw-material use. The two require different denominators and should be reported together only when both are available[5]. D3.2 provides slag-related values for SLACON, SLAGFERTILISER, SLASORB and CORALIS, and D3.3 for Slagreus[6,7]; their interpretation is discussed in Section 5.3. KPI XI is retained for a specified treatment or integrated route where a documented maturity assessment exists. No recycling rate is assigned to a hypothetical S1 plant.

4.2.10 Implementation barriers and enabling conditions

The principal barriers are variable slag quality, unresolved end-use qualification, treatment costs and uncertain or seasonal demand. Enabling conditions are an agreed product specification, a qualified conditioning route, a legal basis for transfer and use, and an off-take arrangement that identifies accepted and rejected fractions. Where market demand fluctuates, multiple qualified outlets — for example, construction and agricultural users — may reduce dependence on one receiver, provided each outlet has a separate specification. A change of destination does not automatically preserve the material's acceptance status[9].

4.2.11 Replication potential and remaining data gaps

Replication depends on reproducing the relationship between slag origin, conditioning and receiving application. The missing site inputs are annual generation, composition and variability, conditioning yields, available storage, delivered costs and verified demand. Future DRI-based slag must be qualified independently if its formation conditions differ from the reference case. The result transferable between regions is the qualification procedure; the accepted composition and substitution fraction remain application-specific[3].

4.3 Scenario S2 — Secondary Carbon Carriers supplied to EAF steelmaking

4.3.1 Scenario rationale and objective

S2 links external carbon-bearing resources to a defined EAF carbon duty. It comprises S2a, biogenic SCC supply, and S2b, non-biogenic recycled carbon supply. The objective is to reduce a specified conventional carbonaceous input while maintaining the required steel quality and furnace performance. Basket carbon, injected foaming carbon and other additions are assessed separately. Complete replacement of one stream does not constitute complete replacement of all fossil carbon entering the furnace[2,7]. S2 focuses on the EAF because its share is expected to grow[3]; evidence from blast-furnace, sintering and cokemaking applications is retained as contextual evidence only and is not transferred quantitatively to the EAF scenario.

4.3.2 Source and resource stream

S2a begins with a traceable biomass residue and its conversion into a qualified carbonaceous product — for example charcoal from pyrolysis (GREENEAF, GREENEAF2) or hydrochar from the hydrothermal carbonisation of wet biomass residues (BioReSteel)[6]. The source record includes feedstock origin and the conversion route because changes in feedstock or treatment can alter ash, fixed carbon and volatile matter. S2b begins with a segregated waste-derived stream and the treatment needed to obtain a consistent feedstock, such as prepared polymer fractions (OnlyPlastic) or industrial and municipal wastes used as slag-foaming agents (RIMFOAM)[6]. Mixed waste is not assumed suitable solely because it contains carbon[2].

4.3.3 Resource characteristics and requirements

The minimum characterisation combines proximate and elemental analyses with moisture, heating value, particle-size distribution, density and feeding behaviour. Elemental carbon and fixed carbon are recorded separately. Sulphur, phosphorus, chlorine and relevant metals are evaluated against steel, slag, off-gas and residue constraints. For injection, the qualification includes the conveying behaviour of the actual material; for agglomerated charging, it includes mechanical integrity and degradation during storage and handling. GREENEAF showed that char reactivity can affect furnace behaviour even where substitution is technically feasible[6].

No common carbon-content or particle-size tolerance is prescribed for all SCCs. The receiver establishes limits from the intended function and equipment. Where a test method, basis or detection limit changes, results are not merged into a single material specification without reconciliation.

4.3.4 Conditioning and technical integration

S2a may require drying, thermochemical conversion, classification and agglomeration. The sequence is selected from the documented feedstock route and receiving duty; pyrolysis yield or drying demand is not introduced as a generic constant. S2b may require sorting, contaminant removal, size control or densification. Both routes require trials of storage, metering and delivery before full production integration[2]. OnlyPlastic combined material supply with an injector designed for co-injection with lime (D3.4, Section 2.2.27), illustrating that the feeding system is part of the qualification[2].

The EAF trial programme should compare matched production conditions and record the metallic charge, carbon additions, oxygen, electricity, natural gas, tap mass and temperature. Steel composition, slag behaviour, metallic yield, dust and off-gas observations provide the evidence for operational acceptance. Material substitution alone is insufficient where it increases other inputs or reduces product yield.

4.3.5 Transport, infrastructure and geographical configuration

The configuration may involve a distributed feedstock network supplying a central SCC producer, followed by delivery to one or several EAF plants. Transport must be evaluated on delivered usable material, accounting for moisture and bulk density. Storage and handling assessments must consider dust generation, material degradation, self-heating where relevant and the requirements of the installation. A low-cost feedstock at its origin may cease to be competitive after preparation and delivery.

4.3.6 Receiver and substitution function

The receiving EAF operator defines the carbon duty and reference practice. Replacement is assessed for a named stream and reporting period, using compatible mass and composition bases. A mass ratio between SCC and coal is not assumed to be unity. D3.4 reports that

OnlyPlastic required adaptation of the injected mass and feeding practice; this supports functional qualification rather than simple mass-for-mass substitution[2].

4.3.7 Actors and partnership configuration

The supply chain includes resource owners, a processor or biocarbon producer, transport providers and the EAF operator. Feeding-equipment suppliers and analytical laboratories support qualification. The SCC producer controls product consistency; the steelmaker controls metallurgical acceptance. Their agreement must provide for notification of feedstock or treatment changes, since a product manufactured from a different source may require renewed qualification even when its trade name remains unchanged.

4.3.8 Data-exchange requirements

The supplier transmits the batch identity, origin, preparation history, analytical certificate and delivered quantity. The steelmaker links the batch to heat records and documents the selected carbon duty, SCC and conventional additions, process settings and product results. Data are retained on both as-received and dry bases where moisture affects the balance. Biogenic and non-biogenic carbon fractions are identified where supported by evidence; mixed-origin material is not assigned a wholly biogenic status without verification.

4.3.9 Relevant WP3 KPIs and available quantitative evidence

KPI VIII is the principal indicator and requires a defined carbon-material stream. KPI III may apply to the corresponding reduction in a specified primary input, while KPI II requires a consistent direct-emissions comparison. KPI XI is technology- and integration-specific. S2 has the broadest quantified evidence of the four scenarios: KPI VIII values for GREENEAF, GREENEAF2, RIMFOAM, OnlyPlastic and BioReSteel[6], and the GreenHeatEAF trials, which record complete substitution of one carbon stream while distinguishing its contribution to total furnace fossil carbon7. These benchmarks are examined in Section 5.4.

4.3.10 Implementation barriers and enabling conditions

The principal barriers are supply variability, mismatch with feeding equipment and uncertainty over metallurgical response. Biogenic supply additionally requires documented feedstock availability and conversion performance; non-biogenic supply requires reliable segregation and contaminant control. Enabling measures include a receiver-approved product specification, a representative trial campaign and change-control rules linking supplier production to EAF qualification. Commercial terms should relate to usable material and agreed quality, not only gross delivered mass[2,9]. Where a recognised product specification exists for the secondary material, it can support technical qualification and commercial transfer. In OnlyPlastic, polymer materials from plastic residues were selected and prepared in accordance with UNI 10667-17[6].

4.3.11 Replication potential and remaining data gaps

Replication is most credible where the receiving EAF has comparable feeding technology and carbon requirements. Differences in scrap mix, steel grade, slag practice and oxygen injection can change the outcome. Required data include long-term supply, batch variability, material consumption per tonne of tapped steel and the effect on other furnace inputs. The available project evidence supports technically defined opportunities; it does not establish a universal SCC replacement fraction or a common CO_2-saving factor.

4.4 Scenario S3 — Steel process gases as feedstock for the chemical sector

4.4.1 Scenario rationale and objective

S3 connects steel residual gases with ammonia and urea production, using the INITIATE concept as its main technical reference[15]. The objective is to reduce conventional chemical-feedstock demand while retaining a consistent energy and carbon balance across the participating industries. The scenario includes both gas-conversion performance and the consequences of diverting gas from its existing use[2]. CO_2 mineralisation into construction products (Carbon4Minerals) is recorded as an alternative route with a different receiver and boundary (Section 5.5 and Appendix D).

4.4.2 Source and resource stream

The source comprises BOFG or a defined combination of BFG and BOFG. The available gas is the quantity remaining after steelworks requirements and existing commitments have been considered. BOF generation is batch-dependent, so a mean annual flow cannot describe the full supply interface. The source specification must include recoverable operating periods, composition and pressure profiles, existing gas-holder arrangements and conditions under which gas is diverted or unavailable.

4.4.3 Resource characteristics and requirements

The gas dataset includes CO, CO_2, H_2, N_2, water and process-relevant contaminants, together with temperature, pressure and flow. Composition must state whether it is on a wet or dry basis. Any normalised volumetric flow must state its reference temperature and pressure. Limits for particulates, sulphur species and other contaminants are set by the selected conversion and separation equipment. Average gas composition cannot substitute for excursions that determine catalyst or sorbent protection requirements.

4.4.4 Conditioning and technical integration

The reference pathway combines gas cleaning, pressure and flow management, conversion and separation, followed by ammonia synthesis and a carbon-containing product route where applicable. In the water-gas shift reaction, CO reacts with water to produce CO_2 and H_2. Sorption-enhanced operation couples conversion with CO_2 separation. The integration must

also account for steam demand, regeneration, auxiliary energy, hydrogen or nitrogen adjustment where required, and the disposition of separated CO_2[2].

A complete balance identifies gas entering the system, conversion products, purge streams, exported chemicals and CO_2 sent to utilisation, storage or emission. It also includes energy imported to replace the gas's previous internal service. The availability of a CO_2 stream alone does not demonstrate utilisation or permanent storage.

4.4.5 Transport, infrastructure and geographical configuration

Co-location or short pipeline connections can simplify gas transfer but still require an agreed pressure interface, metering and interruption strategy. Where CO_2 or chemical products move to external destinations, their conditioning and transport are separate parts of the pathway. The proposed configuration must identify which actor owns the connection and how gas is managed when the chemical plant is unavailable. No pipeline length, compressor duty or storage capacity is assumed without site data.

4.4.6 Receiver and substitution function

The chemical receiver uses the conditioned stream to provide the hydrogen and, where relevant, carbon required by its product route. The displaced input is defined through an equivalent conventional chemical-production system. Ammonia production does not place carbon in ammonia; carbon incorporation is assessed through products such as urea, with the source of that carbon traced separately. Subsequent product use can release carbon, so utilisation is not automatically treated as permanent removal.

4.4.7 Actors and partnership configuration

The configuration requires a steelworks operator, a gas-conversion operator, a chemical producer and technology suppliers. Electricity, steam and other utility providers become relevant where these services are supplied externally. A CO_2 transport or storage operator is included only if that destination is part of the assessed case. Agreements must allocate responsibility for gas specification, plant availability, diversion, product quality and the accounting of environmental benefits.

4.4.8 Data-exchange requirements

Source and receiver exchange synchronised gas-flow and composition data, utility consumption, plant availability and product output. The carbon ledger tracks the origin and destination of carbon by stream. Metering boundaries must distinguish capture from transfer, utilisation and storage. For assessment, the partners must disclose enough information on the displaced steelworks energy and conventional chemical process to establish an equivalent comparison. Restricted process data can remain under controlled access while agreed aggregate results are released for reporting.

4.4.9 Relevant WP3 KPIs and available quantitative evidence

KPIs IX and X concern the reuse of CO_2 from off-gases and the incorporation of process-gas carbon into products, respectively. KPI II is applicable only to a consistent direct-emissions boundary. Two sets of INITIATE values are available and refer to different boundaries: D3.4 reports climate-impact values per tonne of hot-rolled coil for the coupled steel–urea system[2], whereas D3.2 reports emission intensities for the steel plant and, separately, for ammonia and urea plants, taken from the INITIATE base and reference cases[6]. Neither set provides the flow data needed to calculate KPI IX or X for a new site. Section 5.5 reconciles the two sets. The primary periodic report also describes outstanding demonstration work at its reporting cut-off; the targeted TRL 7 is therefore not treated as a verified achieved level for the complete chain[15].

4.4.10 Implementation barriers and enabling conditions

Key barriers are coupling of plant availability, gas variability, utility demand and the opportunity cost of existing gas use. The commercial assessment is also sensitive to chemical-product value and the cost of managing separated CO_2. Enabling conditions include an agreed gas-delivery envelope, a tested control and diversion strategy, and contracts covering the material and energy consequences of interruptions. The availability of lower-carbon electricity can materially affect the system assessment, as recognised in the INITIATE evidence[2].

4.4.11 Replication potential and remaining data gaps

Replication requires compatibility between the future steelmaking route and the gas-dependent chemical installation. A transition away from the BF–BOF route can change gas quantity and composition, affecting the useful life of dedicated assets. Remaining inputs include time-resolved gas availability, contaminant data, utility balances, conversion yields and the long-term source plan. Alternative gases or feedstocks require renewed process assessment; they are not assumed interchangeable[3].

4.5 Scenario S4 — Steel waste-heat recovery and cross-sector energy integration

4.5.1 Scenario rationale and objective

S4 exports usable residual heat from steelmaking to an external thermal demand. It distinguishes S4a, a neighbouring industrial heat user, from S4b, a district-heating network. The objective is to displace a defined thermal service after internal heat-recovery opportunities, temperature compatibility and continuity have been assessed. Useful delivered heat is the performance quantity; installed recovery capacity alone does not establish annual utilisation[2,5]. S4 is retained because of the strong stakeholder signal and because it represents a distinct infrastructure-based configuration (Section 2.13). Since D3.4 contains only two heat-related entries and no WP3 project reports a KPI I value, S4 is assessed qualitatively.

4.5.2 Source and resource stream

Potential sources include recoverable heat from off-gases, cooling circuits and other process streams documented for the selected installation. Each source must be assessed separately before aggregation. The resource record identifies the recovery point, current heat destination, temperature range, availability and constraints imposed by steel production. Heat already required elsewhere in the steelworks is not counted as freely available for export.

4.5.3 Resource characteristics and requirements

The thermal specification includes source and return temperatures, pressure, heat-transfer medium, allowable cooling and time-resolved heat duty. For S4a, the receiver defines the required process temperature and operating schedule. For S4b, the network operator defines seasonal supply and return conditions and dispatch requirements. Where direct exchange is insufficient, a heat pump may be investigated, with its electricity demand and operating-temperature dependence explicitly represented. No coefficient of performance is assumed for an unspecified system.

4.5.4 Conditioning and technical integration

The proposed arrangement uses an appropriate heat-recovery unit and, where needed, an intermediate circuit separating the steel process from the external user. Design addresses fouling, corrosion, variable load and maintenance access. Storage and backup are assessed against the duration and frequency of supply–demand mismatch. Their capacity is derived from the temporal balance rather than selected as a generic percentage of source duty.

The public PITAGORAS Brescia case documents a steel-to-district-heating configuration with seasonal operation and an Organic Rankine Cycle. It is used here as evidence of an interface configuration; its quantitative reporting is discussed in Section 5.6[20].

4.5.5 Transport, infrastructure and geographical configuration

The transfer system includes the feasible pipeline route, temperature and pressure losses, pumping, metering and connection works. Road crossings, land access and other route constraints influence both cost and implementation time. Thermal proximity must be evaluated through deliverable temperature and load, not distance alone. A nearby intermittent user can be less suitable than a more distant, stable demand, but the comparison requires measured profiles and route-specific losses.

4.5.6 Receiver and substitution function

S4a replaces a specified industrial heating duty, such as a drying or hot-water service. S4b supplies the network at its agreed interface and displaces the heat source that would otherwise operate at that time. The displaced source may vary seasonally. The assessment therefore avoids multiplying annual recovered heat by a single assumed fossil-emission factor where network dispatch has not been established.

4.5.7 Actors and partnership configuration

The essential actors are the steelworks, the heat receiver or network operator, and the operator of the connecting infrastructure. Equipment providers support design and maintenance, while local authorities may be involved in route access and network planning. The agreement specifies ownership at the heat-transfer interface, operational control, metering, backup and responsibilities during outages. For district heating, the receiver's service obligation requires explicit treatment of interruptions.

4.5.8 Data-exchange requirements

The partners exchange timestamped temperature, flow, available heat and demand records, together with operating and maintenance calendars. The time interval must resolve the fluctuations relevant to equipment sizing and dispatch. Annual totals support reporting but cannot establish temporal compatibility. Heat meters at agreed boundaries distinguish source recovery, network delivery and useful external consumption; auxiliary electricity and backup heat are recorded separately.

4.5.9 Relevant WP3 KPIs and available quantitative evidence

KPI I measures recovered heat reused by other industries relative to total residual heat available within the defined boundary[5]. The definition explicitly refers to other industries. For an exclusively residential district-heating receiver, D4.2 therefore reports delivered heat and a separately labelled external heat-utilisation ratio; formal inclusion within KPI I requires WP3 agreement on the receiver boundary. No KPI I value is available from the WP3 dataset[6]. Section 5.6 identifies the available interface data and the missing denominator.

4.5.10 Implementation barriers and enabling conditions

The principal barriers are temporal mismatch, insufficient temperature, infrastructure cost and uncertainty over long-term operation of the source. Enabling conditions include a verified heat-demand profile, a feasible connection, agreed backup and a commercial arrangement allocating the consequences of variable supply. Heat-sale revenue must be considered together with recovery, pumping, maintenance and replacement-service costs. D5.2 identifies these contractual and economic conditions as relevant to sustained heat cooperation[9].

4.5.11 Replication potential and remaining data gaps

Replication depends on the local thermal system and the future steelworks operating plan. Missing inputs include time series of temperature and recoverable duty, receiver demand, route constraints, thermal losses and installed costs. The pathway remains relevant across steelmaking routes, but its heat source and temperature profile must be reassessed after major process changes. The present evidence supports a qualification and planning procedure, rather than an assumed annual export capacity.

5. Quantitative Benchmarks and WP3-Linked Impact Assessment

5.1 Assessment approach and reference conditions

The quantitative assessment retains the original scope of each project result. A benchmark describes demonstrated or assessed performance under its stated conditions; it is not assigned directly to a future installation. The evidence register in Appendix B records each numerical input, its source, basis, status and permitted use, following the statuses defined in Section 2.8. Values are distinguished as measured, source-calculated, modelled, targeted or expected; only arithmetic derived in D4.2 from reported inputs is labelled Calculated. Project targets and expected performance are not presented as achieved results. The project values used in this chapter come from the WP3 KPI dataset underlying D3.2[6], from D3.3[7] and from D3.4[2], supplemented by primary project records where noted.

Calculated values in this chapter are limited to transparent arithmetic on source data. No assumed annual plant flow, treatment yield, operating time or cost is introduced. For units, 1 t = 10^3 kg and 1 MWh = 3.6 GJ; tonne- and time-based industrial quantities are retained where they are used by the source, with the basis stated. Material quantities distinguish wet and dry mass, and gas quantities require reference conditions. A temperature difference is expressed in K, whereas operating temperatures may be expressed in °C.

The appropriate functional reference depends on the scenario: a qualified mineral product for S1, a defined EAF carbon duty or tonne of tapped steel for S2, equivalent steel and chemical outputs for S3, and delivered useful heat at a specified interface for S4. These functions are not combined into a single average percentage benefit.

5.2 Application of the WP3 KPI framework to the selected scenarios

The operational definitions in D3.1 take precedence over shortened labels used elsewhere in the project[5]. Table 5.1 therefore distinguishes three reporting categories: formal WP3 KPIs

calculated within the D3.1 definition and boundary; extended diagnostics calculated with a different receiver, emissions or system boundary; and relevant indicators that cannot be calculated because the required numerator or denominator is unavailable. KPI I is formally limited to recovered heat reused by other industries, and KPI IX concerns CO_2 actually reused from off-gases rather than capture efficiency. Any extension beyond these definitions is reported separately and is not presented as a formal WP3 KPI result.

Table 5.1 Applicable KPI definitions and boundary conditions[5].

KPI	Operational expression	Required boundary condition
I Heat recovered	100 × Q_reused / Q_residual	Same period and source boundary; heat reused by other industries. Residential district heat requires a separately declared extension.
II Direct CO_2 reduction	D3.1: 100 × M_CO_2,reused / E_initial	D3.1 restricts the definition to direct reductions through cross-industrial CO_2 reuse. Broader use in later WP3 reports requires reconciliation.
III Virgin raw-material reduction	100 × (M_base − M_case) / M_base	Same material and equivalent function. Application at a non-steel receiver is an explicit extension of the steel-process definition.
V Slag recycling	100 × M_slag,recycled / M_slag,generated	Same slag-producing process, period and mass basis.
VI Dust and sludge recovery and reuse	100 × M_dust+sludge,reused/recycled / M_dust+sludge,generated	Same dust/sludge stream, period and mass basis; recovered metal yield reported separately.
VII Recycling rate of iron-rich residue streams	100 × M_iron-rich residues,recycled / M_iron-rich residues,generated	Same iron-rich residue family, period and mass basis; recovered metal yield reported separately.
VIII Alternative carbon-material share	100 × M_alternative / M_carbon materials,total	Named carbon-material stream; consistent mass basis. Carbon-element or energy shares are separate diagnostics.

IX CO_2 reuse from off-gases	100 × M_CO_2,reused / M_CO_2,off-gas	Traceable reused CO_2 and total off-gas CO_2 for the declared boundary.
X Process-gas carbon in products	100 × M_C,products / M_C,CO+CO_2,input	Carbon attributable to the selected gas; all relevant outlets and external carbon inputs reconciled.
XI Technology readiness	Documented TRL for the defined technology	Distinguish target from achieved TRL and component from integrated chain.

Here, Q denotes energy, E direct CO_2 emissions expressed as mass, and M a mass on the specified basis. Ratio indicators are not calculated when the denominator is missing or zero. The numerator of KPI VIII follows the material-based WP3 definition; a reduction relative to historical coal consumption can additionally be reported, but remains a different calculation when total feed mass changes.

D3.1 defines KPI II using the quantity of CO_2 reused, whereas later WP3 reporting also associates KPI II with emission comparisons derived from SCC substitution or life-cycle assessment. D4.2 retains the D3.1 definition as the formal project reference and reports broader direct-emissions comparisons separately. Where comparable inventories exist, the diagnostic is calculated as 100 × (E_base − E_case) / E_base and is labelled explicitly with its boundary and emission scope; formal mapping of this diagnostic to KPI II requires agreement with WP3. CO_2 physically reused is not automatically equal to avoided emissions. Likewise, mineral savings at a cement, construction or agricultural receiver are reported with their receiver boundary rather than assumed to fall within the original steel-process scope of KPI III.

5.3 Scenario S1 — Quantitative benchmarks and applicable KPIs

Table 5.2 summarises the slag-related values available in the WP3 evidence. They differ substantially in scale and denominator and are therefore read individually.

Table 5.2 Slag-related KPI values reported in WP3.

Project (variant)	KPI	Reported value	Basis and limitation
SLACON (S1a)	III	80% (range 75–85%)	Calculated in WP3 from an achievable range; not a plant-average result[6]
SLACON (S1a)	V	82.5% (range 80–85%)	Reported; slag reused in construction applications[6]
SLAGFERTILISER (S1c)	V	100%	Calculated WP3 value for the German demonstration case; slag used as liming/fertilising material showed performance comparable to equivalent natural materials[6]
SLASORB (sorbent)	V; III	100%; 100%	All BOF slag fractions used in the experiments reused as sorbents; commercial sorbents fully replaced at demonstration scale[6]
CORALIS	V; III	100%; 1.6%	Italian demonstration case[6]
Slagreus (S1b)	V	up to 25%	Substitution applications; restrictions associated with chromium[7]

For SLACON, the WP3 dataset gives a calculated KPI III value of 80%, derived from a reported achievable range of 75–85%, and a reported KPI V value of 82.5%, based on 80–85%[6]. An arithmetic midpoint of a range is not a measured or mass-weighted plant result; D4.2 therefore retains the ranges in the evidence register and does not use these values for a harmonised site comparison.

The 100% values reported for SLAGFERTILISER, SLASORB and CORALIS refer to the specific project cases and must retain their original demonstration boundaries; they should not be interpreted as the share of total slag generation at an unspecified steelworks. For SLAGFERTILISER, D3.2 reports KPI V = 100% within the German demonstration case. For SLASORB, D3.2 explicitly reports KPI V = 100% and KPI III = 100%: all BOF slag fractions used in the experiments were reused as sorbents and commercial phosphorus sorbents were fully replaced. These results demonstrate the reported use cases but do not provide a harmonised plant-wide slag balance[6].

D3.3 reports a value of up to 25% under KPI V for Slagreus and discusses restrictions associated with chromium. The surrounding discussion concerns several substitution applications, and a source-to-destination mass balance is not provided, so the value cannot

establish that 25% of total slag generation was recycled. It is retained as a benchmark requiring denominator confirmation[7].

For an S1 installation, the primary balance would record generated slag, additions, accepted mineral products, recovered metal, rejected solids, water and stock changes. KPI V is calculated for the original slag boundary, excluding added water or conditioning reagents from the numerator. KPI III is calculated at the receiver from the conventional material actually displaced for equivalent output. A fraction accepted for construction or agricultural use and a fraction entering a processor must therefore remain distinguishable in the underlying dataset.

5.4 Scenario S2 — Quantitative benchmarks and applicable KPIs

Table 5.3 lists the fossil-carbon replacement values available for EAF steelmaking. The values for blast-furnace, sintering and cokemaking projects are listed separately because EAF replacement fractions cannot be transferred to other process units, and vice versa.

Table 5.3 Fossil-carbon replacement (KPI VIII) and related values reported in WP3.

Project (variant)	Replaced stream and value	Basis and limitation
EAF steelmaking (S2)		
GREENEAF (S2a)	Coal replaced by charcoal: 100%	Industrial trials at multiple EAF plants; baseline coal 1–1.4 t per heat; char-reactivity and feeding issues investigated[2,6]
GREENEAF2 (S2a)	Coal replaced by biochar: 100%; 50% with palm-kernel-shell char and anthracite[2,6]	Baseline 1.1–2.0 t per heat. Up to 20% CO_2 saving from LCA under full replacement — a life-cycle value, not Scope 1[6]
RIMFOAM (S2b)	Coke fines for slag foaming replaced by industrial and municipal waste: 100%	Slag-foaming duty only[6]
OnlyPlastic (S2b)	Coal replaced by recycled polymers: 100% (KPI III and VIII)	Trials at one EAF plant; dependent on operating conditions[2,6]
BioReSteel (S2a)	Coal replaced by hydrochar: 50%; TRL 5	Ongoing project (2023–2027); interim values[6]
GreenHeatEAF (S2a)	Fifth-hole carbon stream replaced by biochar: 100%	Less than 15% of total furnace fossil carbon[7]
Other process units (context only)		
Flexinject	Plastics in BF injection: 25%; TRL 7	Industrial injection of shredded plastic[6]

Acasos	Coke breeze in sintering replaced by biomass char: 100%	7.8% lower CO_2 per tonne of sinter in sintering tests[6]
INNOCARB	Coke replaced by alternative carbon materials: up to 25% biocarbon; up to 20% plastic-rich materials	Material-dependent results[6]
ALTERAMA	Biocarbon in coking blend: 33%	Blend tested[6]
FLEXCOKE	KPI VIII = 4.0% (biochar tested at 3% and 5% in the coal blend)	Calculated WP3 value; low-percentage biochar blending was reported as technically feasible without detrimental effects on coke performance[6]

GreenHeatEAF provides a documented example of complete substitution within a restricted carbon stream. D3.3 reports 196–203 kg for the reference fifth-hole carbon addition and 227 kg for the biochar trial addition[7]. The ratio of reported material masses is therefore 227/203 to 227/196, or approximately 1.12–1.16 kg of biochar per kilogram of reference material. This calculated comparison describes the reported additions; it is not a carbon-efficiency or energy-equivalence factor, because the complete composition and process balance are not supplied. The same source records 100% replacement of the fifth-hole stream and indicates that this stream represents less than 15% of total fossil carbon. These statements are compatible because the denominators differ. S2 therefore records both the affected stream and its share of the broader furnace carbon requirement before using a replacement percentage.

For OnlyPlastic, the WP3 dataset records 100% substitution of virgin coal in the documented trials[6]. D3.4 provides the necessary context: polymer-only operation was demonstrated, while another trial used 200–300 kg of basket coal under low-carbon scrap conditions[2]. D4.2 consequently treats complete replacement as an operating configuration demonstrated under particular conditions, not an unconditional property of polymer injection.

For GREENEAF2, the WP3 dataset lists up to 20% CO_2 reduction under KPI II, but the accompanying remark attributes this value to a life-cycle assessment under full replacement[6]. It is therefore not a Scope 1 value and is not used to calculate S2 emissions. This distinction is essential when comparing biogenic SCCs with recycled fossil-carbon materials, since the accounting of biogenic carbon depends on the convention adopted.

5.5 Scenario S3 — Quantitative benchmarks and applicable KPIs

Two sets of INITIATE values are available (Table 5.4). They are both modelled assessment cases, but they refer to different system boundaries and must not be combined.

Table 5.4 INITIATE assessment values and their boundaries.

Source and boundary	Case values	Reported change
D3.4: climate impact of the coupled steel–urea system, per tonne of hot-rolled coil (HRC)[2]	Base 2.4; 2030 case 1.06; 2050 case 0.805 t CO_2/t HRC	Calculated in D4.2: −1.34 and −1.595 t CO_2/t HRC (−55.8% and −66.5%)
D3.2: steel plant, from INITIATE base and reference cases[6]	1823.9 → 1280.5 kg CO_2/t HRC	−29.8% (reported)
D3.2: small ammonia plant[6]	2.28 → 0.45 t CO_2/t NH_3	−80.1% (reported)
D3.2: large ammonia plant[6]	1.87 → 0.11 t CO_2/t NH_3	−94.2% (reported)
D3.2: small ammonia and urea plant[6]	0.53 → 0.31 t CO_2/t urea	−41.7% (reported)
D3.2: large ammonia and urea plant[6]	0.33 → 0.11 t CO_2/t urea	−66.6% (reported)

Note: The percentage changes reported for the D3.2 assessment cases are retained as stated in WP3. Since the displayed emission-intensity values are rounded, recalculation from these rounded figures may not reproduce the reported percentages exactly.

The D3.4 values express the climate impact of the coupled production system; the stated production context includes 3.1 Mt of hot-rolled coil and 0.49 Mt of urea per year[2]. The D3.2 values separate the steel plant from the chemical plants. The steel-plant reduction (−29.8%) is therefore smaller than the coupled-system reduction (−55.8% or −66.5%), because part of the benefit arises on the chemical side and in the energy supply assumed for the future cases. Neither set is a KPI II value in the sense of D3.1, a CO_2 capture efficiency or a fraction of process-gas carbon incorporated into urea. The WP3 dataset lists the steel-plant value under KPI II; D4.2 retains it with its original boundary label.

The primary periodic report of INITIATE gives a minimum SPECCA of −2.5 GJ per tonne of CO_2, whereas D3.4 reproduces the value as 2.5 without the minus sign; the negative sign of the primary source is retained here. The primary report also distinguishes targeted pilot validation from completed work at its reporting cut-off[15]. These points prevent a modelled energy benefit or a target maturity from being presented as achieved industrial performance.

For the alternative mineralisation route, Carbon4Minerals reports KPI IX and KPI X values of 100%: the CO_2 captured from industrial flue gases and used for carbonation is chemically bound in mineral carbonates[6]. These values describe the fate of the CO_2 that enters the carbonation step, not the share of a steelworks' total off-gas CO_2. They confirm that complete incorporation is possible for the CO_2 actually used, but they cannot be transferred to S3.
Calculation of KPIs IX and X for S3 still requires matched input and output flows. The carbon in urea must be traced to the relevant gas stream, while CO_2 sent to storage, emitted or supplied to other users is accounted for separately. No numerical value is assigned to these KPIs for S3 from the available summary data.

5.6 Scenario S4 — Quantitative benchmarks and applicable KPIs

No WP3 project provides a KPI I value, and the heat-related quantitative evidence is limited to interface data from two sources[6]. D3.4 describes a CORALIS heat-transfer example from pulp and paper production to a greenhouse, with a 45–55 °C supply and a 25 °C return. This non-steel example is used only to illustrate temperature matching; it is not an S4 design condition[2]. The corresponding temperature difference is 20–30 K, calculated directly from the reported values, but heat duty cannot be calculated without a flow rate and heat-transfer-fluid properties.
For the steel-related PITAGORAS Brescia case, the European Commission's site description gives a network delivery set point of 107 °C and summer electricity production of around 1.8 MW, presented as expected impact rather than a metered annual heat balance. The separate "10 MWh" winter-heat entry lacks a time basis and is not converted into power or used in a balance. These reporting limitations preclude the calculation of KPI I[20].
For a measured single-phase heat-transfer stream, useful heat is obtained by integrating mass flow multiplied by the specific-enthalpy difference over time. The simplified expression $Q = \int \dot{m}\, c_p\, \Delta T\, dt$ is used only when the heat-capacity approximation is appropriate; for steam or phase-changing streams, inlet and outlet enthalpies must be used. Source-recovered heat, delivered heat and heat finally reused by external industry are identified at separate boundaries. No annual useful-heat total follows from a nameplate capacity without the operating profile.

[20] European Commission, Smart Cities Marketplace. PITAGORAS Site Brescia. Project demonstration description and expected-impact figures.

5.7 Data quality, assumptions and limitations

The calculations in this chapter follow the evidence hierarchy and data-gap rules established in Sections 2.8 and 2.12. No hypothetical industrial operating parameters are introduced, and D4.2 recommendations are distinguished from observed or reported plant performance.

The main unresolved quantitative limitations concern the slag benchmark denominators, complete SCC carbon and emissions balances, gas-to-product carbon partitioning, and the residual-heat denominator combined with a matched demand profile. Evidence coverage is uneven: S2 provides several industrial-trial values; S1 and S3 rely on project-specific values with limited comparability; and S4 has no KPI I value. These limitations prevent a defensible common-basis ranking of the four scenarios in terms of CO_2 avoided, annual resource savings or return on investment, but they identify the data required for subsequent site-specific assessment (Table B.2).

6. Cross-Scenario Assessment

6.1 Cross-scenario assessment framework

The comparison evaluates implementation conditions using the criteria established in Chapter 2. It distinguishes documented capability, site-specific qualification and unresolved evidence. No weighted score is assigned, because the available evidence does not support common numerical scales or agreed stakeholder weights. The comparison is intended to identify the next decision for each pathway, rather than to select a universal preferred technology.

6.2 Technological maturity and scale-up requirements

Maturity varies within each scenario. Established aggregate processing and agricultural use do not establish the maturity of every steel-slag binder route. Demonstrated SCC feeding for one EAF does not establish compatibility with another furnace. S3 requires assessment of the integrated conversion chain, while S4 requires reliable operation across a source–network interface. Reported TRLs are available for only a few projects — for example TRL 7 for Flexinject and TRL 5 for BioReSteel[6]. For KPI XI, the technology, scale, environment and evidence date are stated explicitly; TRLs of individual components are not averaged into a cluster TRL[2,5].

6.3 Resource availability, quality and receiver compatibility

S1 and S2 primarily require management of batch variability, although their annual supply also matters. S3 and S4 additionally require synchronisation between source and receiver, because gas and heat availability can vary within production cycles. Storage may moderate variability but introduces its own capacity and operating constraints. The minimum evidence for all four scenarios is a source envelope and a receiver envelope on compatible bases, together with a verified means of reconciling the two.

6.4 Resource-efficiency and environmental performance

S1 can displace mineral inputs and natural liming materials; S2 can displace selected conventional carbon materials; S3 can alter chemical-feedstock and energy demand; S4 can replace a delivered thermal service. These outcomes are assessed against equivalent functions

and actual counterfactuals. Additional preparation, utilities, transport and residual treatment remain inside the evaluation boundary. Improvements in one resource indicator do not establish a net climate benefit without the corresponding emissions analysis, as the different INITIATE boundaries illustrate (Section 5.5).

6.5 WP3 KPI synthesis

S1 is primarily associated with KPIs III and V, S2 with KPI VIII and conditionally II and III, S3 with KPIs IX and X and conditionally II, and S4 with KPI I for an industrial receiver. KPI XI may support all scenarios when properly documented. The association identifies relevance rather than a claim of quantified achievement. The strongest numerical examples concern specific project configurations, mostly in S2; none constitutes a complete common-basis assessment of S1–S4 as future sites.

6.6 Economic and market conditions

For S1, treatment and transport costs must be compared with the value of the accepted mineral fraction and its actual alternative destination. For S2, the relevant cost is that of providing the carbon function, including effects on other EAF inputs and yield. S3 requires valuation of gas, replacement energy, chemicals and CO_2 management within one consistent system. S4 depends on heat sold when usable, connection cost and service continuity. These different cost structures prevent the use of one generic payback or material-price threshold[9]. D4.1 reports that approximately half of the respondents considered current economic incentives insufficient to encourage IS practices; this is treated as a cross-cutting economic concern for all four scenarios[8].

6.7 Infrastructure, logistics and geographical conditions

Solid resources can often be stored and transported through existing logistics systems, although moisture, bulk density and quality preservation remain constraints. Dedicated gas and heat infrastructure creates stronger dependence between specific sites. Geographical compatibility is therefore treated as a pathway property: relevant measures include feasible route, transfer losses, interface capacity and access rights. No scenario is ranked solely by source–receiver distance.

6.8 Regulatory and legal conditions

S1 and S2 place particular emphasis on the legal status and permitted use of secondary materials; for S1c, national fertiliser and soil-protection requirements are added. S3 adds

requirements associated with gas processing, chemical manufacture and the selected CO_2 destination. S4 requires assessment of the heat connection and receiving system. In each case, technical qualification and authorisation follow distinct evidence routes. Unresolved classification or permitting is recorded as an implementation condition rather than converted into an assumed cost premium[9].

6.9 Organisational, governance and contractual conditions

The four scenarios require an accountable interface between producer and receiver. Solid-material arrangements need agreed sampling, rejection and liability provisions. Gas and heat arrangements also require procedures for interruption, restart and backup. Shared assets require ownership and maintenance rules that remain effective if a participant changes production or leaves the arrangement. D5.2 supports sustained facilitation where independent actors cannot resolve these issues through a simple bilateral contract[9].

6.10 Information and data-exchange requirements

S1 and S2 rely strongly on batch certificates linked to processing or heat records. S3 and S4 require timestamped operating data as well as periodic totals. All cases require versioned specifications, stated units and reference conditions. Confidential commercial information is separated from technical acceptance data, and public reporting uses a validated subset. The procedure in Chapter 8 provides a common method while allowing pathway-specific fields.

6.11 Stakeholder and social dimensions

The relevant stakeholders extend beyond the direct resource seller and buyer. Construction customers and farmers influence the acceptance of S1 products; resource suppliers and recycling actors influence S2 continuity; chemical off-takers and infrastructure operators affect S3; heat customers and network planners affect S4. Stakeholder consultation should therefore be linked to concrete decisions such as product acceptance, route selection and service reliability. The aggregate findings of D4.1 indicate priorities but cannot establish approval of a specific future configuration[8,9].

6.12 Replication potential

The transferable elements are the assessment sequence, dataset, interface specification and verification procedure. Transfer of a particular numerical performance requires comparable resource properties, process conditions and system boundaries. S1 and S2 can potentially

serve several receivers through qualified supply chains; S3 and S4 depend more on local infrastructure and synchronised operation. All scenarios require reassessment when the steelmaking route changes[3].

6.13 Cross-scenario comparison matrix

Table 6.1 summarises the assessment. The entries identify the controlling implementation conditions rather than high, medium or low scores unsupported by common data.

Table 6.1 Comparative implementation conditions.

Criterion	S1 Slag	S2 SCCs	S3 Gases	S4 Heat
Strength of WP3 evidence	Several project values; limited comparability	Broadest set of industrial-trial values	Modelled cases with two boundaries	No KPI I value; qualitative
Main qualification	End-use performance and environmental release	Carbon duty and feeding response	Conversion feed and integrated operation	Usable temperature and concurrent demand
Critical resource record	Slag origin and batch variability	Feedstock and preparation history	Gas composition and time profile	Heat and demand time profiles
Principal interface	Qualified mineral delivery	Metered material feeding to EAF	Gas, utilities and product transfer	Thermal delivery and backup
Main economic unknown	Cost per accepted product fraction	Cost per verified carbon duty	Net value after displaced internal energy	Cost per useful heat unit delivered
Main transition exposure	New slag composition and markets	Changed EAF carbon requirements	Reduced or altered BF–BOF gas supply	Changed source temperature and availability
Next decision	Select application and qualify final material	Select stream and perform matched trials	Validate source lifetime and full balance	Establish temporal match and feasible connection

7. Cross-Sectoral Cluster Configurations and Replication Potential

7.1 From bilateral exchanges to Industrial Symbiosis clusters

A cluster combines several exchanges whose material, energy or infrastructure requirements are related. Its additional value must arise from an identifiable interaction, such as shared treatment, complementary demand or improved use of infrastructure. Merely locating several bilateral exchanges in the same region does not establish a combined benefit. The cluster assessment therefore begins with individually qualified pathways and then evaluates their interactions[9],[16]. This follows the Hubs for Circularity perspective introduced in Section 2.2.2[12,13].

7.2 Actors and stakeholder roles in cross-sector configurations

The steelworks can be a resource provider, a receiver and an infrastructure participant within the same cluster. Processors convert heterogeneous inputs into qualified supplies, while off-takers determine the conditions under which those supplies have productive value. Laboratories support evidence generation, infrastructure operators manage shared services and facilitators coordinate information and negotiations. Authorities remain responsible for their statutory decisions. Appendix E assigns these functions without assuming that one organisation performs every role. The willingness to cooperate exists: 84% of survey respondents reported that their organisation, or one they collaborate with, already applies some IS practice[8].

7.3 Steel-centred Industrial Symbiosis cluster configurations

7.3.1 Material-resource cluster configuration

A material cluster can connect slag processing to construction and agricultural receivers while linking dust or sludge treatment to metal recovery and the steelworks. Shared sampling, weighing or logistics may reduce duplication, but streams retain separate identities and specifications. A further connection can supply SCCs to the EAF. The dust and sludge family, which is not developed as a detailed scenario (Section 3.4), fits naturally in this configuration: the CORALIS Italian demonstration case reports full recovery of rolling-mill sludge within a multi-sector IS setting[6]. Such a configuration requires explicit records of which resource enters each process and which product or residue leaves it; aggregation must not obscure impurity accumulation or rejected fractions[2,17].

7.3.2 Energy-based cluster configuration

An energy cluster can connect one or more steelworks heat sources with industrial users and a heat network. Complementary demand profiles may increase utilisation, provided temperatures and transfer capacities are compatible. A gas-to-chemical connection may also exchange utilities with the cluster. However, the same gas cannot simultaneously be credited in full as chemical feedstock and as fuel for heat generation. Dispatch and counterfactual energy provision must be assessed jointly.

7.3.3 Integrated multi-resource cluster configuration

An integrated configuration combines material and energy exchanges, for example using suitable recovered heat in SCC preparation while supplying processed slag to a construction receiver, or using captured CO_2 for the carbonation of slag-based products as in Carbon4Minerals[6]. These are D4.2 candidate configurations, not documented complete industrial cases. Their feasibility requires a specific receiver duty and source profile. Any heat assigned to drying is deducted from the heat available for other users, and any additional emissions or residues from conditioning enter the cluster balance.

7.4 Geographical proximity and spatial clustering

Spatial screening identifies potential receivers, existing infrastructure and feasible transport corridors. The assessment should first map capacity and quality requirements, then examine actual routes and access constraints. For bulk solids, distance affects delivered cost; for gas and heat, it additionally affects pressure, temperature or network requirements. A geographical map is therefore an initial planning aid, not evidence that a technically acceptable or commercially viable match exists[9].

7.5 Governance and Industrial Symbiosis facilitation

The proposed governance arrangement comprises an operational contact for each exchange and a coordination function for shared decisions. A facilitator maintains the opportunity register, organises technical discussions and records unresolved dependencies. The participating companies retain responsibility for their own equipment, data and commercial commitments. D5.2 identifies continuity of facilitation as an enabling factor[9]; D4.2 therefore recommends assigning both a responsible organisation and a funding arrangement for this function.

7.6 Shared infrastructure and services

Candidate shared services include laboratories, weighing, storage, logistics coordination and utility networks. Each proposal must identify capacity, access rights, cost allocation and maintenance responsibilities. Sharing can reduce duplication but may also create a common point of failure. The assessment should examine how each participant operates during maintenance or loss of the shared service, including whether alternative outlets or backup supply are technically and contractually available.

7.7 Replication across European industrial regions

Replication should begin with the regional resource and receiver structure, rather than copying a reference layout. The assessment compares steelmaking route, resource quality, available users, infrastructure and the applicable authorisation pathway. A region with established cement capacity may support a different S1 configuration from a region dominated by road-construction or agricultural demand. Similarly, an existing heat network changes the S4 infrastructure requirement. Appendix D provides the screening record for documenting these differences[3,9,17].

7.8 Transferability across steelmaking routes and industrial contexts

D5.1 identifies the modification of by-product characteristics as a consequence of emerging steelmaking technologies[3]. Long-lived symbiosis assets should therefore be evaluated against the source's expected process development, including changes in slag chemistry, gas availability and heat profiles. Contracts and designs may incorporate requalification or alternative supply where justified. Continued availability of a historical by-product stream is not assumed over the investment period.

8. Cross-Industrial Planning and Data-Exchange Framework

8.1 Role of data exchange in Industrial Symbiosis implementation

Task 4.2 explicitly requires procedures supporting consistent data exchange, cross-industrial planning and impact assessment linked to WP3[4]. The procedure proposed here converts a potential resource match into a traceable technical record. It is designed for implementation by participating actors; it has not been validated as an operating consortium-wide data platform. The minimum dataset and responsibilities below extend the data structure of Section 2.11 and provide an actionable starting point for such validation.

8.2 Minimum dataset for cross-industrial resource exchange

Each exchange receives a unique identifier linking the source, resource, receiver and intended function. A dataset is complete for a decision only when the fields needed for that decision are available and accepted by the responsible reviewers. Missing values are marked as missing rather than recorded as zero. Appendix C provides the field structure and separates measured values from calculated estimates and contractual requirements.

Table 8.1 Core dataset and validation responsibility.

Data group	Minimum content	Units or reference basis	Principal validator
Identity and origin	Exchange ID, site/process, stream and batch or period	Persistent identifiers and timestamp	Source operator
Quantity and availability	Flow or mass, variability, operating calendar, current destination	kg, t, kg s^{-1}; defined period and wet/dry basis	Source operator with metering owner
Quality	Composition, contaminants, physical or thermal characteristics	kg kg^{-1}, mg kg^{-1}, m, kg m^{-3}, K or °C; method stated	Laboratory and receiver

Conditioning	Treatment sequence, additions, yields and residues	Mass and energy per declared input or output	Processor
Transfer	Mode, route, storage, capacity and transfer losses	m or km; kg, GJ and stated period	Logistics or network operator
Receiver	Intended use, capacity, limits and rejection criteria	Process-specific limits and equivalent output	Receiver
Assessment	Baseline, KPI boundary, numerator and denominator	Same period, basis and function	Joint technical assessment lead
Governance	Owner, access, version, approval and change history	Versioned metadata	Data owner and coordinator

For gases, molar or volumetric composition includes wet/dry basis and the reference state of any standardised volume. For heat, source and receiver time series use a common time basis. For leaching data, concentration, extraction conditions and liquid-to-solid ratio remain associated; values obtained by different methods are not directly combined. These metadata are necessary for engineering interpretation, not optional administrative fields.

Flow and energy units should be selected according to the physical stream and reported together with their reference basis. Solid flows may be expressed, as appropriate, in kg per batch, t/d or t/y on a declared wet or dry basis; gaseous flows as mass flow or normalised volumetric flow with the reference temperature, pressure and wet/dry basis stated; liquid flows as mass or volumetric flow; and thermal exchanges as both instantaneous thermal power and integrated energy over a declared period, together with the relevant supply and return temperatures.

8.3 Data-exchange procedure

The procedure advances through six stages, with recorded outputs at each transition (Table 8.2). A stage can be reopened when the resource, process or receiver changes. No calendar duration is imposed, because the time required depends on access to representative data, qualification work and the applicable decisions.

Table 8.2 Proposed data-exchange procedure.

Stage	Action	Required output	Condition for progression
1 Identification	Register source, resource, candidate receiver and current use	Initial exchange record	Identifiable substitution function and responsible contacts
2 Controlled disclosure	Agree access and share screening data	Versioned preliminary dataset	Sufficient quantity and quality information for compatibility screening
3 Technical reconciliation	Align units, methods, periods and boundaries	Validated dataset and gap register	No unresolved ambiguity affecting the next calculation or trial
4 Joint qualification	Define and execute the necessary tests or engineering study	Acceptance specification and assessment record	Receiver acceptance and a documented route for unresolved conditions
5 Operational exchange	Link dispatch and receipt to quality and meter records	Traceable delivery or operating records	Authorised operation and agreed contracts and controls
6 Verification and change control	Reconcile quantities, KPIs and deviations	Periodic review and updated dataset	Continued compliance with the agreed operating envelope

During Stage 3, the partners compare measurement uncertainty, sampling representativeness and missing periods. During Stage 4, acceptance limits and permissible deviations are fixed by the relevant technical owners before trials are evaluated. D4.2 does not impose an arbitrary universal balance-closure tolerance. A residual outside the agreed uncertainty envelope triggers investigation and prevents the affected result from being released as verified.

8.4 Cross-industrial planning interfaces

Planning coordinates four interfaces: resource production, conditioning and storage, transport or network operation, and receiver demand. Each actor provides its operating schedule, planned interruptions and constraints on short-term changes. The coordinator identifies dependencies, such as a maintenance shutdown that interrupts gas delivery or a seasonal drop in construction or agricultural demand that increases slag inventory. The resulting joint plan records normal operation, reduced-load operation and interruption management.

The planning dataset must preserve physical constraints. Storage inventory is updated from measured receipts and withdrawals; heat and gas demand are compared with supply on a compatible time grid. Potential synergies are screened against existing commitments before

being offered to additional receivers. This prevents the same available capacity from being allocated twice.

8.5 Data interoperability, confidentiality, ownership and governance

Interoperability requires stable identifiers, a shared data dictionary, stated units and explicit version control. A spreadsheet or structured file can support the initial implementation if it preserves these requirements; a bespoke platform is not a prerequisite. Numeric values, units and quality flags should occupy separate fields. Machine-readable timestamps retain the time zone, and decimal and missing-value conventions are declared.

The data-sharing agreement assigns ownership and permitted uses, distinguishing public summaries, partner-shared technical records and restricted commercial or process information. Access is limited to the information required by each role, and an approved public extract is produced separately from the operational dataset. Limited data sharing due to competition and security concerns was among the challenges mentioned by survey respondents[8]. The same principle is applied in this deliverable: D4.1 has a sensitive dissemination level while D4.2 is public, so only aggregated findings are reproduced[4,8].

8.6 Roles and responsibilities of participating actors

The source operator validates origin and generation records; the processor validates treatment inputs, outputs and yields; the receiver approves the application specification and acceptance results. Metering and logistics operators validate transferred quantities at their interfaces. Laboratories report methods, sampling limitations and uncertainty where available. The assessment lead reconciles boundaries and calculates the agreed KPIs, while the coordinator maintains versions, decisions and outstanding actions. A calculation is released only after the actors controlling its inputs have reviewed them.

8.7 Digital tools, databases and Industrial Symbiosis matching approaches

Digital matching can identify candidate pairs by resource type, quantity, location and receiver requirements. It cannot replace qualification where composition or operating constraints determine acceptance. The methodological roadmap of Krzeminski et al. places mapping, feasibility assessment, opportunity selection and implementation in a connected sequence[16], and IS2H4C is developing a platform for sharing resources, infrastructure and information within Hubs for Circularity[13]. D4.2 therefore proposes that any matching tool retain the

reason a match was suggested and the evidence still required before it becomes an operational exchange.

Data-driven models and digital twins can support dynamic gas or energy integration where sufficient validated data exist. Their outputs are labelled as predictions with a defined applicability range. D4.2 does not claim that a validated Symbio-Steel matching platform or digital twin has been developed.

8.8 Consistency with the WP3 impact-assessment framework

Every KPI record contains its WP3 identifier, operational definition, boundary, period, numerator, denominator and evidence status. Raw delivery data remain accessible behind aggregate results. A revision to a source quantity or specification triggers review of dependent calculations. This structure preserves continuity with WP3 while making explicit the distinctions identified in Chapter 5: capture versus reuse, material substitution versus elemental-carbon replacement, life-cycle versus direct emissions, and industrial heat reuse versus a broader district-heating indicator.

9. Implementation Guidance and Roadmap

9.1 General implementation requirements

Implementation requires a qualified resource–receiver relationship, sufficient supply and demand, a feasible transfer arrangement and an agreed allocation of responsibilities. The roadmap is organised around evidence and decisions rather than fixed dates. Its short-, medium- and longer-term stages are proposed implementation horizons, not contractual milestones or a claim that deployment will occur within the Symbio-Steel project period[4,16,17].

9.2 Actor engagement and partnership development

Engagement should begin with the actor controlling the resource and the actor able to use it. Their first joint output is a written definition of the intended exchange, the current baseline and the unresolved requirements. Processors, infrastructure operators and technical-support organisations are then involved according to the pathway. Expressions of interest are recorded separately from commitments to supply, purchase, invest or share restricted data, so that the partnership record reflects actual implementation readiness.

9.3 Technology qualification and process integration

Qualification proceeds from representative resource characterisation to receiver testing and the required integration trials. The test plan defines the reference practice, measured outcomes and acceptance envelope before performance is assessed. Relevant measures include product quality, specific input consumption, process availability, recovery yields and emissions within the agreed boundary. The trial scale and duration must address the identified technical risk; a short successful campaign does not demonstrate seasonal supply stability or long-term equipment wear.

9.4 Logistics, infrastructure and supply-chain requirements

The implementation study establishes the delivered resource specification, transport or connection capacity and the ability to operate during supply or demand interruptions. Solid-

material chains need stock and rejection arrangements. Gas and heat chains need an explicit diversion, backup or safe-interruption strategy. Infrastructure design is coordinated with the production plans of both source and receiver, including foreseeable changes in steelmaking technology[3,9].

9.5 Regulatory, permitting and end-of-waste considerations

The assessment of alternative resource-management routes should also consider the waste hierarchy established by Article 4 of Directive 2008/98/EC and, where relevant, the overall environmental outcome of the available options. A new Industrial Symbiosis outlet is therefore not assumed to be environmentally preferable solely because it creates an additional use for a residual stream; its performance should be considered against the existing management route, including any additional conditioning, transport and residual-treatment requirements.

The Waste Framework Directive distinguishes a by-product route under Article 5 from end-of-waste status following recovery under Article 6. The former requires a certain and lawful further use, use without processing beyond normal industrial practice, and generation as an integral part of production. The latter requires recovery and fulfilment of the relevant conditions concerning use, demand, technical and legal requirements, and environmental and health effects[21].

For implementation, the responsible actor must identify the applicable EU and national provisions and any material-specific criteria or authority decision. 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 case shows (Section 4.3.10). The project record should retain the classification basis, intended use, required authorisations and responsible authority, with re-evaluation after a material or application change. No universal end-of-waste determination is made for S1 or S2 in this report.

9.6 Commercial conditions and long-term off-take arrangements

Commercial preparation should define quantity and quality commitments, price or cost-allocation rules, sampling and dispute resolution, rejection, interruption and termination. Where dedicated infrastructure is required, the agreement must address the consequences

[21] European Parliament and Council. Directive 2008/98/EC on waste and repealing certain Directives, as amended. Consolidated text dated 16 October 2025, Articles 4–6.

of early loss of the source or receiver. Benefits and costs are assessed for each actor as well as for the combined system, because an exchange with an overall positive balance may remain unacceptable if one participant bears disproportionate cost or risk[9].

9.7 Monitoring and KPI-based performance verification

Monitoring uses the agreed baseline and the KPI definitions in Chapter 5. S1 records generation, inventories, accepted destinations and displaced mineral input; S2 links material batches to carbon additions and comparable production results; S3 reconciles gas carbon, products, CO_2 destinations and replacement energy; S4 measures useful external heat and the residual-heat boundary. Deviations are investigated against the agreed measurement uncertainty and operating envelope. Quantitative results remain provisional when an unresolved gap affects their interpretation.

9.8 Governance, facilitation and stakeholder coordination

Each exchange needs an operational owner and a route for resolving cross-company decisions. A cluster coordinator maintains the shared action register and convenes reviews when a change affects several participants. The facilitator's role should be resourced over the implementation period, with responsibilities distinct from those of plant operators and public authorities. D5.2 identifies discontinuity of coordination as a barrier, supporting early agreement on how this function will be maintained[9].

9.9 European partnerships, networks and cross-sector cooperation

The Clean Steel and Processes4Planet partnerships provide relevant European cooperation contexts for steel and wider process-industry innovation, and the European Commission identifies Hubs for Circularity activities as a means of supporting industrial circularity[12],**Errore. Il segnalibro non è definito.** . D4.1 reports a strong willingness among respondents to participate in European initiatives or funded projects fostering IS[8]. For the scenarios in this report, network participation should serve a specific purpose: locating a receiver, accessing a qualification facility, comparing infrastructure solutions or identifying demonstration partners. Membership or participation alone is not treated as evidence of deployment readiness.

9.10 Funding and financial enabling mechanisms

RFCS is relevant to steel-focused research and demonstration, while Horizon Europe provides a wider context for collaborative industrial innovation. The Innovation Fund supports the demonstration and deployment of innovative low-carbon technologies [22] , [23] , [24] These programmes are identified as potential routes, not confirmed sources of finance for the scenarios. Eligibility, supported activities and call conditions must be checked for the specific proposal at the time of application.

A financing strategy should connect each unresolved need to an appropriate activity: characterisation and qualification, pilot integration, engineering, infrastructure or deployment. The business case must distinguish support-dependent cash flows from operating revenues and costs. No grant percentage, award probability, investment return or application deadline is assumed in this roadmap.

9.11 Implementation roadmap

9.11.1 Short-term actions

The first stage establishes a specific resource–receiver pair and closes the gaps that prevent technical screening. The outputs are an agreed exchange description, a preliminary dataset, source and receiver contacts, and a gap register with owners. For S1, this means selecting the slag and application; for S2, the SCC and EAF carbon stream; for S3, the gas and chemical-product route; for S4, the heat source and receiver duty. For S4, collecting synchronous source and demand data is the first action, because no quantified evidence is currently available. Progression requires sufficient evidence to justify the next qualification activity.

9.11.2 Medium-term actions

The second stage establishes technical and implementation feasibility through the required testing, balances and engineering. The partners agree acceptance limits, baseline and KPI boundary, then evaluate logistics, authorisation and commercial conditions. The outputs are a validated operating envelope, an implementation study and a documented decision on further investment. A result below an agreed acceptance condition leads to adaptation or discontinuation rather than automatic progression.

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[22] European Commission, Directorate-General for Research and Innovation. Energy-Intensive Process Industries. Partnership and cooperation information.

[23] European Commission, Directorate-General for Climate Action. What is the Innovation Fund? Programme information.

[24] European Commission, Directorate-General for Research and Innovation. Research Fund for Coal and Steel. Programme information.

9.11.3 Longer-term actions

The third stage covers implementation, sustained monitoring and replication after the preceding decisions have been resolved. Performance is assessed over representative operating conditions and reviewed against source and receiver changes. Replication begins with a new compatibility assessment using the reference configuration's documented lessons. It does not inherit the original site's acceptance limits, costs or KPI results without verification.

9.11.4 Research and innovation needs

For S1, priorities include mineralogical control, stable environmental performance, the long-term behaviour of trace elements in soil for agricultural use, and the qualification of slags from emerging routes. For S2, they include the relationship between SCC properties, feeding and metallurgical function over variable EAF conditions. For S3, priorities include dynamic integration, contaminant management and transparent combined carbon and energy accounting. For S4, they include the characterisation of recoverable heat at steelworks, variable-source recovery and matching with future heat demand. Beyond the selected scenarios, dust, sludge and mill-scale recovery is recommended as the first candidate for a follow-up scenario, requiring element and residue balances. These priorities extend the resource-specific needs identified in D3.4, D5.1 and the REUSteel roadmap[2,3,17].

9.11.5 Demonstration, scale-up and replication needs

Demonstration should address the unresolved interface between the participating processes. Required evidence may include extended batch qualification, representative EAF campaigns, integrated gas-to-product operation or seasonal thermal performance. Scale-up must account for availability, maintenance, product acceptance and contractual operation in addition to conversion efficiency. Table 9.1 defines the principal evidence needed before each scenario can progress from a transferable configuration to a site-specific investment proposal.

Table 9.1 Evidence needed for implementation decisions.

Scenario	Required technical evidence	Required implementation evidence	Principal owners
S1	Final product tests; slag and treatment balances; soil behaviour for S1c	Confirmed use route, off-take and delivered cost	Producer, processor and receiver
S2	Representative supply and matched EAF trials	Qualified supply contract and handling integration	SCC supplier and EAF operator
S3	Dynamic gas, carbon and utility balances	Source lifetime, product off-take and CO_2 destination	Steelworks, conversion and chemical operators
S4	Synchronous source–demand data and metered heat balance	Connection feasibility, backup and heat-sale arrangement	Steelworks and heat or network operator

10. Conclusions

10.1 Main findings

D4.2 translates the technological portfolio of 82 funded projects, the WP3 KPI evidence and the stakeholder consultation into four transferable IS implementation scenarios: slag valorisation in construction, cement and agricultural value chains (S1); SCC supply to EAF steelmaking (S2); steel-gas conversion for chemical production (S3); and external recovery of steelworks heat (S4). Their implementation depends on a verified resource–receiver relationship extending from conditioning through transfer to the substituted function. The principal contribution of D4.2 is a common structure for describing, comparing and verifying such exchanges, supported by a minimum dataset and a six-stage data-exchange procedure.

10.2 Priority Industrial Symbiosis opportunities

S1 is supported by the largest number of reviewed project entries and the strongest stakeholder signal among the selected pathways; its agricultural variant is supported by documented applications in several European countries, while construction and cement uses depend on consistent qualification for an identified application. S2 has the broadest quantified evidence, with industrial trials demonstrating the replacement of specific carbon streams, subject to material and furnace conditions. S3 provides a route for integrated steel–chemical production, provided that gas conversion and replacement energy are assessed together. S4 can provide an external thermal service where usable heat and demand coincide, but it currently rests on stakeholder interest and public cases rather than quantified project results. These are priorities for detailed site assessment, not a ranking of universal environmental or economic performance.

10.3 Remaining gaps and uncertainties

The available documents do not supply complete site datasets for any of the four scenarios. Missing information includes resource availability and variability, receiver limits, treatment and conversion balances, transfer conditions, costs and contractual commitments. Several published values also require clarification of their denominators or boundaries, as shown for the slag benchmarks and for the two sets of INITIATE values. Consequently, D4.2 does not claim new site-level recycling rates, CO_2 savings, annual heat exports or investment returns. The gaps are linked explicitly to the records needed to resolve them (Table B.2). Dust, sludge and mill-scale recovery remains the main pathway not developed as a scenario and is the first candidate for follow-up.

10.4 Key enabling conditions for implementation

Implementation requires consistent resource specifications, representative qualification, feasible logistics or infrastructure, an established authorisation pathway and workable commercial arrangements. These conditions reflect the barriers most frequently reported by stakeholders — economic, regulatory, financial and organisational — rather than technological ones[8]. Data ownership and validation responsibilities must be agreed before quantitative impacts are released. Sustained facilitation is particularly relevant where several independent actors share services or depend on the same resource.

10.5 Implications for future steel-driven Industrial Symbiosis and European R&I

Future research and demonstration should address the compatibility of emerging steelmaking routes with downstream resource use and the reliability of the interfaces between industries. Changes in slag composition, gas supply and heat availability make requalification essential. The procedures and scenario records developed here provide input to the WP5 guidelines for improving current synergies (D5.3)[4] and can support the preparation of collaborative implementation studies. Their use should preserve the distinction between measured evidence, modelled assessment, proposed arrangements and unresolved data requirements.

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12. Appendices

12.1 Appendix A — Detailed Scenario Assessment Sheets

These sheets consolidate the selected configurations for subsequent site qualification. They record the evidence available at report level and the conditions still requiring confirmation. The full technical rationale is provided in Chapter 4 and the quantitative evidence in Chapter 5.

Scenario S1 — Slag valorisation

Assessment field	Scenario record
Objective and status	Qualify steelmaking slag for a defined construction (S1a), cement (S1b) or agricultural (S1c) duty. Transferable scenario; no committed site.
Source and resource	Separately identified BOF, EAF or ladle slag; current destination to be documented.
Quality	Major oxides, mineralogy, metallic content, grading, moisture, stability and leaching; for S1c, liming value, nutrients and trace-element behaviour in soil. Receiver-specific limits missing.
Conditioning	Segregation, metal separation and classification; further stabilisation or processing selected by duty. Actual yields missing.
Transfer	On-site or regional processing and delivery; route, storage, seasonal demand and delivered costs missing.
Receiver and substitution	S1a aggregate fraction; S1b raw-meal or qualified binder function; S1c natural liming or fertilising material. Substitution factor to be verified for each duty.
Actors	Steelworks, processor, receiver or distributor, laboratory and logistics; agricultural advisory bodies for S1c; facilitator as required.
Data exchange	Batch certificate, processing history, dispatch and acceptance records, stock balance.
Evidence and KPIs	Largest D3.4 family (26 entries). SLACON, SLAGFERTILISER, SLASORB and CORALIS (D3.2); Slagreus (D3.3), with denominator caveats. KPIs III, V and documented XI.
Barrier and enabling condition	Variable material and uncertain application acceptance; joint specification, qualified treatment route and multiple qualified outlets.
Replication decision	Requalify each slag–application pairing. Advance after receiver tests and a feasible use route.

Scenario S2 — Secondary Carbon Carriers for EAF steelmaking

Assessment field	Scenario record
Objective and status	Replace a specified conventional EAF carbon duty. Transferable scenario with several industrial-trial precedents.
Source and resource	S2a traceable biogenic SCC (charcoal, biochar, hydrochar); S2b segregated recycled non-biogenic SCC (polymers, industrial and municipal wastes).
Quality	Fixed and elemental carbon, volatiles, ash, moisture, contaminants, density, size, reactivity and feeding response.
Conditioning	Feedstock-dependent preparation, conversion or agglomeration; equipment compatibility to be tested.
Transfer	Qualified SCC delivered to EAF storage and feed system. Supply continuity and logistics to be confirmed.
Receiver and substitution	Named charging, injection or slag-foaming stream. No assumed mass-for-mass equivalence.
Actors	Resource owner, SCC producer, laboratory, transport and equipment suppliers, EAF operator.
Data exchange	Supplier batch linked to heat ID, additions, production conditions and steel, slag and off-gas observations.
Evidence and KPIs	GREENEAF, GREENEAF2, RIMFOAM, OnlyPlastic, BioReSteel (D3.2); GreenHeatEAF (D3.3). KPI VIII primarily; II and III conditionally; documented XI.
Barrier and enabling condition	Supply variability and metallurgical or feeding mismatch; specification, representative matched trials and change control.
Replication decision	Confirm comparable material, feeding technology and furnace duty; repeat qualification after relevant changes.

Scenario S3 — Steel process gases to chemicals

Assessment field	Scenario record
Objective and status	Integrate steel residual gases with ammonia and urea production. Reference concept based on INITIATE; mineralisation route (Carbon4Minerals) recorded as alternative.
Source and resource	BOFG or defined BFG/BOFG combination remaining after existing steelworks commitments.
Quality	Time-resolved composition, contaminants, pressure, temperature and flow with stated reference conditions.
Conditioning	Cleaning, flow and pressure management, conversion and separation, chemical synthesis; utility demands included.
Transfer	Defined gas interface; CO_2 or product transport only for the selected configuration.
Receiver and substitution	Conventional chemical feedstock displaced for equivalent product output; lost internal gas service included.
Actors	Steelworks, conversion and chemical operators, equipment and utility providers, selected CO_2 destination operator.
Data exchange	Synchronised gas and utility records; carbon ledger to products, reuse, storage, purge and emissions.

Evidence and KPIs	INITIATE values from D3.4 (coupled system) and D3.2 (steel plant and chemical plants), not combinable; Carbon4Minerals (D3.2). KPIs IX, X and conditional II; no verified whole-chain TRL.
Barrier and enabling condition	Interdependent operations and future gas supply; full balance, defined source lifetime and interface agreements.
Replication decision	Assess future steelmaking route and dynamic compatibility before dedicated infrastructure investment.

Scenario S4 — Waste-heat recovery

Assessment field	Scenario record
Objective and status	Export useful residual heat to an industrial user (S4a) or a district-heating network (S4b). Qualitative, stakeholder-driven scenario.
Source and resource	Identified heat-recovery point after existing internal use; source profile missing.
Quality	Temperature, pressure, medium, available duty and temporal variability.
Conditioning	Appropriate recovery and transfer equipment; storage, heat pump or backup only if justified by the balance.
Transfer	Feasible network route, pumping, losses, ownership and maintenance to be established.
Receiver and substitution	S4a specified industrial duty; S4b network heat service with season-dependent counterfactual.
Actors	Steelworks, heat receiver or network operator, infrastructure and equipment providers; authorities where relevant.
Data exchange	Aligned source and demand time series, meter boundaries, useful heat, auxiliary electricity and backup.
Evidence and KPIs	Two D3.4 entries; PITAGORAS interface data; strong stakeholder signal (57%, n = 47). No KPI I value available; KPI I for industrial reuse, separate ratio for a residential boundary.
Barrier and enabling condition	Temporal or temperature mismatch and continuity; validated thermal match and service agreement.
Replication decision	Collect source and demand data first; confirm source operating plan and feasible connection; no assumed annual export.

12.2 Appendix B — Quantitative Input Data, Reference Conditions and Calculation Basis

The register applies the evidence-status definitions established in Section 2.8. R denotes a value stated in a source, with qualifiers used where relevant to identify its nature; C denotes arithmetic performed in D4.2 from reported input values; G denotes a data gap. Formal KPI equations follow D3.1 and Table 5.1. No explicit analytical assumptions have been introduced.

Table B.1 Quantitative evidence register.

ID and pathway	Value / reference basis	Status and source	Interpretation and limitation
S1 — Slag valorisation			
B01 SLACON	KPI III 80%; source reference range 75–85%	R (source-calculated in WP3)[6]	D3.2 reports KPI III = 80% and classifies the method as calculated. The project-specific calculation basis is not further specified; the 75–85% range is retained and no D4.2 recalculation is performed.
B02 SLACON	KPI V 82.5%; source reference range 80–85%	R (source-calculated in WP3)[6]	D3.2 reports KPI V = 82.5% and classifies the method as calculated. The underlying project-specific calculation basis is not further specified; the value is not treated as a plant-wide mass-weighted recycling rate.
B03 SLAGFERTILISER	KPI V 100% (German demonstration case)	R (source-calculated in WP3)[6]	D3.2 reports KPI V = 100% for the German demonstration case. The underlying slag-generation denominator is not provided; the value is therefore retained as a project-specific benchmark, not a plant-wide recycling share.
B04 SLASORB	KPI V 100%; KPI III 100%	R (source-calculated in WP3)[6]	D3.2 states that all BOF slag fractions used in the experiments were reused as sorbents and that commercial P sorbents were fully replaced. The 100% values apply to these experimental boundaries, not to total steelworks slag generation.
B05 CORALIS	KPI V 100%; KPI III 1.6%	R[6]	Reported for the Italian demonstration case; no D4.2 recalculation is performed.
B06 Slagreus	Up to 25%, labelled KPI V	R[7]	Reported application value; the total-slag-generation denominator is not provided, so it cannot be interpreted as 25% of all slag generated.
S2 — Secondary Carbon Carriers			

B07 GREENEAF	KPI VIII 100%; baseline coal 1.0–1.4 t/heat	R (source-calculated in WP3)[6]	Industrial trials at multiple EAF plants. D3.2 reports complete replacement for the considered coal stream; the project-specific calculation is not reconstructed in D4.2.
B08 GREENEAF2	KPI VIII 100%; baseline 1.1–2.0 t/heat; 50/50 PKS-char/anthracite campaign	R (KPI source-calculated in WP3; 50/50 campaign reported in D3.4)[2,6]	The 100% KPI and the 50/50 campaign describe different operating configurations and must not be combined into a single replacement factor.
B09 GREENEAF2	Up to 20% CO_2 saving, listed as KPI II	R (reported LCA result)[2,6]	Life-cycle result under full replacement; it does not follow the D3.1 operational formula for Scope 1 KPI II and is not recalculated as KPI II in D4.2.
B10 RIMFOAM	KPI VIII 100%	R[6]	D3.2 reports complete replacement for the slag-foaming carbon duty. D3.4 also documents partial and full-replacement trial conditions; the 100% value must therefore remain stream- and trial-specific, not a whole-EAF fossil-carbon replacement.
B11 OnlyPlastic	KPI III and VIII 100%	R[6]	Reported for the documented polymer-substitution trials. Complete substitution refers to the specified coal duty under those operating conditions, not to an unconditional whole-furnace replacement.
B12 OnlyPlastic	200–300 kg basket coal in another trial	R[2]	Reported operating condition under low-carbon-scrap conditions; not a KPI and not a universal prescription.
B13 BioReSteel	KPI III and VIII 50%; TRL 5	R[6]	Reported interim values from an ongoing project; no D4.2 recalculation.
B14 GreenHeatEAF	196–203 kg reference addition; 227 kg biochar	R[7]	Reported fifth-hole additions. The masses do not imply equal carbon content or equal energy input.
B15 GreenHeatEAF	Approximately 1.12–1.16 kg biochar/kg reference addition	C from B14	227/203 = 1.118 and 227/196 = 1.158. Material-mass ratio only; not a carbon-efficiency or energy-equivalence factor.
B16 GreenHeatEAF	100% fifth-hole substitution; <15% of total fossil carbon	R[7]	Both values are reported by D3.3 and use different denominators. The 100% value does not mean complete replacement of total EAF fossil carbon.
S3 — Process gases			
B17 INITIATE (D3.4)	2.4; 1.06; 0.805 t CO_2/t HRC	R (modelled)[2]	Modelled coupled steel–urea system; base, 2030 and 2050 cases.

B18 INITIATE	$\Delta = -1.34$ and -1.595 t CO_2/t HRC; -55.8% and -66.5%	C from B17	Δ2030 = 1.06 − 2.4 = −1.34; Δ2050 = 0.805 − 2.4 = −1.595. Relative reductions: 100×(2.4−1.06)/2.4 = 55.8% and 100×(2.4−0.805)/2.4 = 66.5%. These are D4.2 diagnostics, not KPI II, IX or X.
B19 INITIATE (D3.2)	1823.9 → 1280.5 kg CO_2/t HRC; reported −29.8%	R (modelled)[6]	Steel-plant assessment boundary. Retain the −29.8% reported by D3.2; do not relabel the arithmetic check as a D4.2 KPI calculation.
B20 INITIATE (D3.2)	Ammonia 2.28 → 0.45 and 1.87 → 0.11 t CO_2/t NH_3; reported	R (modelled)[6]	Small and large ammonia-plant assessment cases. Reported percentages are retained as stated in D3.2; the rounded intensity values displayed in D3.2 do not reproduce them exactly.
B21 INITIATE (D3.2)	Urea 0.53 → 0.31 and 0.33 → 0.11 t CO_2/t urea; reported −41.72% and −66.58%	R (modelled)[6]	Small and large ammonia–urea assessment cases. Reported percentages are retained as stated in D3.2; the rounded displayed intensities do not reproduce them exactly.
B22 INITIATE	Minimum SPECCA −2.5 GJ/t CO_2	R (modelled)[15]	Primary-source modelled result; the negative sign of the primary source is retained. Not an achieved industrial energy balance.
B23 Carbon4Minerals	KPI IX 100%; KPI X 100%	R[6]	Reported for the CO_2 entering the carbonation route. The values do not mean that 100% of total steelworks off-gas CO_2 is reused or converted. Not transferred to S3.
S4 — Waste heat			
B24 CORALIS	Supply 45–55°C; return 25°C	R[2]	Reported non-steel heat-exchange example (pulp/paper → greenhouse); used only for interface illustration.
B25 CORALIS	ΔT = 20–30 K	C from B24	45−25 = 20 K; 55−25 = 30 K. Flow rate and fluid properties are unavailable, therefore no heat duty is calculated.
B26 PITAGORAS	Delivery set point 107°C; summer electric output ≈1.8 MW	R (expected impact)[19]	Expected-impact/interface values, not a metered annual balance and not KPI I.
B27 PITAGORAS	Winter heat entry "10 MWh"	R (insufficient basis)[19]	Reported value, but the time/reference basis is unspecified; it is therefore excluded from calculations and must not be converted to MW.
B28 KPI I	No value in WP3 dataset	G	No WP3 value provides the numerator and denominator required by KPI I for the selected steel-related S4 scenario.

Table B.2 Missing inputs controlling site-level assessment.

Scenario	Missing quantitative data	Calculation currently prevented	Data owner to approach
S1	Slag generation, treatment outputs, stocks, accepted destinations, equivalent mineral displacement; soil data for S1c	Site KPIs III and V; material balance	Producer, processor and receiver
S2	Matched material composition, all relevant additions, production outputs and emissions inventory	Whole-furnace KPI VIII; reproducible KPIs II and III	SCC supplier and EAF operator
S3	Time-resolved gas input, conversion outputs, product carbon, utilities and replacement energy	Site KPIs IX and X; consistent system impact	Steelworks and chemical or conversion operators
S4	Residual heat, source and demand profiles, useful external heat, losses and auxiliaries	KPI I or declared external-use ratio; annual savings	Steelworks and receiver or network operator
All	Installed and operating costs, baseline prices, utilisation and contract conditions	Comparable economic assessment	Participating companies and infrastructure owners

12.3 Appendix C — Cross-Industrial Data-Exchange Template

The template below is proposed for implementation of the procedure in Chapter 8. Each completed record contains an exchange cover sheet, one or more stream records, a receiver specification and a decision log. Empty numerical fields are marked "not supplied"; zero is entered only when a value is known to be zero. No project data have been simulated to populate the template.

C.1 Exchange cover sheet

Field	Content to enter	Control rule
exchange_id	Unique identifier	Retained through all revisions
scenario_variant	S1a, S1b, S1c, S2a, S2b, S3, S4a or S4b	Variant and substitution function stated
source / receiver	Organisation, site and process	Use authorised contacts and disclosure level
resource_origin	Generation point and preparation history	Different origins have separate stream records
current_destination	Existing use, treatment or disposal	Forms part of the counterfactual
intended_function	Input or thermal service displaced	Equivalent-performance basis stated
reporting_period	Start and end, with time zone	Same basis for linked balances
data_owner / access	Owner, approved users and permitted uses	Public and restricted extracts separated
version / validation	Version, date and validating roles	Earlier versions retained in change history

C.2 Stream and property records

Field	Content to enter	Validation requirement
record_id / stream_id	Unique property record and stream link	Connected to exchange_id and batch or time interval
parameter	Flow, mass, composition, temperature or other property	Controlled name with unambiguous meaning
value / unit	Numeric value and separate unit field	Valid unit; missing value flagged
basis	Dry or as-received, wet or dry gas, reference state or product basis	Mandatory when interpretation depends on basis
time_or_batch	Timestamp or interval, batch or heat ID	Traceable to the physical exchange
method / sample	Test method, sample plan and analytical record	Detection limits and test conditions preserved
uncertainty / variability	Measurement uncertainty and observed range, separately	A process range is not substituted for analytical uncertainty
evidence_status	R (measured, modelled or target), C, assumption or G	Calculated records linked to inputs and equation

source_reference	Meter, certificate, report, table or dataset	Sufficient detail to locate the evidence
validator / approval	Responsible role, decision and date	Required before operational or KPI use

Scenario extensions are mandatory where applicable. S1 adds slag type, mineralogy, stability, leaching method and accepted destination, and for S1c liming value and trace-element data. S2 adds feedstock origin, carbon forms, preparation route, feeding duty and heat linkage. S3 adds gas reference state, contaminants, carbon destinations and utility demand. S4 adds meter boundary, supply and return enthalpy information, simultaneous demand, auxiliary energy and backup.

C.3 Receiver specification and acceptance

Field	Content to enter	Decision rule
specification_id	Receiver-approved version	Must match the delivered resource and application
parameter_limit	Lower or upper limit, or permitted range, with unit	Set by receiver or applicable requirement; never estimated
test_basis	Method, sample basis and frequency	Agreed before acceptance assessment
quantity_capacity	Maximum and minimum accepted delivery or demand	Time period and variability stated
deviation_action	Hold, reject, re-treat, divert or investigate	Responsible operator and disposition record assigned
acceptance_record	Accepted quantity, date and evidence	Linked to batch or meter record
change_trigger	Source, process, composition or end-use change	Need for requalification stated

C.4 KPI and decision log

Each KPI entry records its identifier, equation, boundary, baseline, period, input references, calculation and validation status. Each unresolved issue records the decision affected, the required evidence, the responsible actor and the agreed next review. A scenario progresses only when the evidence required for that decision is available. This condition is specific to the decision; it does not require every optional field to be populated before preliminary screening.

12.4 Appendix D — Pathway Screening and Cross-Scenario Assessment Matrix

The long list is grouped by the technological families reviewed in D3.4; section numbers refer to the project entries in D3.4[2]. Selection means development as one of the four representative scenarios, not approval for investment. Retention in the landscape recognises relevance without creating a further detailed scenario. The decisions are D4.2 analytical judgements using the criteria of Chapter 2[2,3,6,8,9].

Table D.1 Pathway screening record.

Pathway	Technical and cross-sector evidence	Decision	Reason and unresolved requirement
Steel slag to aggregates and construction	D3.4 slag family (e.g. SLACON, Section 2.2.14); D3.2 values	Selected S1a	Largest family and strongest stakeholder signal; qualify stability, leaching and performance.
Steel slag to cement value chain	D3.4 slag family; Slagreus (D3.3)	Selected S1b	Distinct raw-meal and binder functions; substitution and balance require confirmation.
Slag as liming material and fertiliser	SLAGFERTILISER (Section 2.2.12); D3.2 values	Selected S1c	Established outlet; fertilisers 53% and agriculture 47% as receiving sectors; trace-element behaviour in soil to be monitored.
Slag as phosphorus sorbent	SLASORB (Section 2.2.8)	Retained in landscape	Demonstration scale; small wastewater-treatment receivers.
Biogenic SCC to EAF	GREENEAF, GREENEAF2, BioReSteel (D3.2); GreenHeatEAF (D3.3)	Selected S2a	Broadest trial evidence; ensure feeding and supply consistency.
Recycled non-biogenic SCC to EAF	OnlyPlastic (Section 2.2.27), RIMFOAM (D3.2)	Selected S2b	Industrial configurations documented; contaminants and furnace conditions remain decisive.
SCC use in BF, sintering or cokemaking	Flexinject, Acasos, INNOCARB, ALTERAMA, FLEXCOKE (D3.2)	Retained in landscape	Different metallurgical requirements; declining relevance with the transition to EAF routes.
Steel gases to ammonia and urea	INITIATE (Section 3.2.13); D3.2 and D3.4 values	Selected S3	Integrated steel–chemical pathway; dynamic gas and carbon balances needed.
CO_2 mineralisation in construction products	Carbon4Minerals (Section 3.2.19); D3.2 values	Retained as S3 alternative	Links gas and slag families; different receiver and boundary.
Gas to methanol, ethanol and other chemicals	D3.4 off-gas family	Retained as S3 alternatives	Different conversion and product boundaries; not combined with INITIATE values.

Steel heat to industry or network	Two D3.4 entries; PITAGORAS	Selected S4	Strong stakeholder signal, contrasting infrastructure case; no KPI I value; qualitative assessment.
Zinc and iron recovery from dust	D3.4 dust family (22 entries)	Retained; priority for follow-up	Second-largest family; KPI VI and VII values limited to one project; element and residue balances required.
Sludge and mill-scale recovery	D3.4 sludge family; CORALIS (D3.2)	Retained; priority for follow-up	Mostly internal recirculation; cross-sector boundary and impurity constraints to be specified.
Scrap preparation and upgrading	D3.4 scrap family (4 entries)	Retained in landscape	Supply-chain relevance (KPI IV); separate assessment of quality and metallic yield.
Refractory recovery	D3.4 refractory family (3 entries)	Retained in landscape	Segregation by composition and service history; potential cluster service.
Water reuse	One D3.4 entry	Retained in landscape	Duty-specific water quality and concentrate management required.

No weighted scores are attached. Quantitative evidence coverage is assessed in Chapter 5 and comparative implementation conditions in Chapter 6. A retained pathway may become a priority at a site where resource availability, receiver demand and supporting infrastructure are favorable.

12.5 Appendix E — Actor and Stakeholder Mapping

The actor map identifies the functions required and the evidence that each should supply. It does not report new stakeholder engagement or signed partnerships. Named examples are limited to organisations publicly documented in the reviewed projects, and no individual survey or interview information from D4.1 is reproduced.

Table E.1 Functional actor map.

Actor function	Applicable scenarios	Decision or evidence owned	Main interface
Steelworks resource owner	S1, S3, S4	Resource generation, existing use and future source plan	Processor or external receiver
Steelworks receiving operator	S2; recovered-metal loops	Metallurgical duty, operating limits and acceptance	SCC or recovered-material supplier
Resource supplier	S2	Feedstock origin, availability and variability	SCC producer
Conditioning operator	S1, S2; selected S3 steps	Treatment specification, yields and residues	Source and receiver
Mineral-product or fertiliser receiver	S1	Intended application and product acceptance	Slag processor and laboratory
Chemical producer	S3	Feed requirements, chemical outputs and product quality	Gas converter and off-takers
Industrial heat user or network operator	S4	Demand profile, thermal interface and continuity	Heat source and infrastructure operator
Technology provider	All, as required	Equipment performance and integration conditions	Operators on both sides of the interface
Logistics or infrastructure operator	All	Capacity, transfer records, maintenance and access	Resource sender and receiver
Laboratory or technical assessor	All	Sampling, test methods, uncertainty and qualification evidence	Source, processor and receiver
Assessment lead	All	Consistent boundaries and traceable KPI calculation	Owners of input data
Competent authority	Case-dependent	Applicable authorisations and statutory decisions	Responsible applicant or operator
Facilitator or cluster coordinator	Multi-actor configurations	Opportunity register, coordination and decision follow-up	Participating organisations
Customers and local stakeholders	Application-dependent	Product or service requirements and local concerns	Receiver and project promoter

Table E.2 Publicly documented examples of relevant actor combinations.

Reference case	Actor combination documented in the evidence	Relevance to D4.2
SLACON	Building-materials research institute (FEhS), research partners and steel producers[2,6]	Joint slag qualification and process-control expertise for S1a and S1b.
SLAGFERTILISER	FEhS, steel producers and agricultural research bodies across several countries[6]	Long-term field evidence and market experience for S1c.
GREENEAF / GREENEAF2	EAF steelmakers and research organisations, including CSM[6]	SCC characterisation and EAF trials for S2a.
OnlyPlastic	CSM, Feralpi, Tenova and polymer-supply actors[2,6]	Coupling material supply, feeding technology and EAF operation for S2b.
INITIATE	Steel, chemical, technology and research actors, coordinated by TNO[6,15]	Integrated gas-conversion and chemical-production expertise for S3.
CORALIS	Multi-sector demonstration cases coordinated by CIRCE[6,10]	IS governance, roadmaps and cluster configurations (Chapter 7).
PITAGORAS Brescia	Steel-related heat source and local heat-network connection[19]	Physical and operational source–receiver interface for S4.

For a site-specific follow-up, each functional role is assigned an authorised contact and an engagement status: identified, contacted, technically engaged or contractually committed. These are distinct records. No actor is advanced to a stronger engagement status merely because it participated in an earlier funded project.

13. List of tables

Table 1.1 WP3 Key Performance Indicators. 13
Table 2.1 Resource families and D3.4 project entries. 20
Table 2.2 Elements of the common pathway architecture. 22
Table 2.3 Screening criteria. 23
Table 2.4 Pathway families and potentially applicable WP3 KPIs. 25
Table 2.5 Evidence profile of candidate pathway families. 28
Table 3.1 Resource families and cross-sector connections. 31
Table 3.2 Receiving sectors indicated for underutilised resources (D4.1 survey, n = 32). 36
Table 3.3 Rationale and evidence strength of the selected scenarios. 38
Table 5.1 Applicable KPI definitions and boundary conditions. 51
Table 5.2 Slag-related KPI values reported in WP3. 53
Table 5.3 Fossil-carbon replacement (KPI VIII) and related values reported in WP3. 54
Table 5.4 INITIATE assessment values and their boundaries. 56
Table 6.1 Comparative implementation conditions. 62
Table 8.1 Core dataset and validation responsibility. 66
Table 8.2 Proposed data-exchange procedure. 68
Table 9.1 Evidence needed for implementation decisions. 75

14. List of abbreviations and acronyms

Abbreviation	Definition
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
BOFG	Basic oxygen furnace gas
CAPEX	Capital expenditure
CCUS	Carbon capture, utilisation and storage
DOI	Digital object identifier
DRI	Direct reduced iron
EAF	Electric arc furnace
ECSC	European Coal and Steel Community
EIIs	Energy-intensive industries
H4C	Hubs for Circularity
HRC	Hot-rolled coil
IS	Industrial symbiosis
IT	Information technology
KPI	Key performance indicator
LCA	Life-cycle assessment
LF	Ladle furnace
OPEX	Operating expenditure
PKS	Palm kernel shell
R&I	Research and innovation
RFCS	Research Fund for Coal and Steel
SCC	Secondary carbon carrier
SEN	Sensitive (dissemination level)
SPECCA	Specific primary energy consumption for CO_2 avoided
TRL	Technology readiness level
WP	Work package