



Second report on Key Performance Indicators

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Table of Contents

Acronyms and Abbreviations.....	5
Summary.....	6
1. Introduction.....	7
2. Comprehensive overview of the projects and the defined KPIs	9
3. Conclusions.....	29
4. References.....	31
List of Tables.....	33
Appendix I.....	35

Acronyms and abbreviations

PU:	Public
WP:	Work package
T:	Task
D:	Deliverable
M:	Month
EU:	European Union
KPIs:	Key performance indicators
IS:	Industrial symbiosis
CE:	Circular economy
RFCs:	Research fund for coal and steel
CO:	Carbon monoxide
CO₂:	Carbon dioxide
P:	Phosphorus
ACM:	Alternative carbon materials
ASR:	Automobile shredder residue
SRA:	Secondary reducing agent
HTC:	Hydrothermal carbonization
H₂:	Hydrogen
GHG:	Greenhouse gas
BF:	Blast furnace
BOF:	Basic oxygen furnace
EAF:	Electric arc furnace
LF	Ladle furnace
TRL:	Technology readiness level
kg_{CO2}/t_{HRC}:	Kilograms of carbon dioxide emitted per tonne of hot rolled coil
RDF:	Refuse derived fuel

Summary

This Deliverable summarizes the KPIs obtained or extracted from a series of research and innovation projects funded by the EU and national programs, targeting IS practices in the energy- and resource-intensive industries. The results were structured and presented, based on the KPIs defined in D3.1 “Report on Key Performance Indicators” under T3.1. “Monitoring of key performance indicators” within the Symbio-Steel project.

The aim of defining and monitoring KPIs is to provide quantitative and qualitative insights into measuring the progress of the IS demonstration activities and analyzing the main results of completed or ongoing projects funded by the EU and national programs.

1. Introduction

Energy- and resource-intensive industries possess an important role in the European economy. However, they are also significant contributors to raw material consumption, process-related emissions, and the generation of industrial residues. In this context, research and innovation projects funded by the EU and national programs have aimed at transforming these industries and their value chains. This transformation involves using new process technologies, improving material recovery strategies, and integrating alternative resources. The Symbio-Steel project evaluates the results of these initiatives by defining and tracking a set of KPIs.

This Deliverable presents a comprehensive overview of the defined KPIs and the projects in which these indicators were either calculated or quantitatively reported. Each KPI is defined according to the methodology outlined in previous Deliverable D3.1. The list of previously defined KPIs related to the IS is presented in Table 1.

Table 1. List of the defined KPIs.

KPI No.	KPI name
KPI I	Energy efficiency
KPI II	Direct CO ₂ emissions (Scope 1) reduction
KPI III	Reduction in virgin raw material usage
KPI IV	Enhancing the recycling of low-quality steel scrap
KPI V	Slag recycling rate
KPI VI	Dust and sludge recovery and reuse
KPI VII	Recycling rate of iron-rich residue streams
KPI VIII	Replacement rate of fossil carbon materials
KPI IX	CO ₂ capture rate from process/off-gasses
KPI X	Share of carbon content in process gas (CO ₂ /CO) transformed into products
KPI XI	Technology readiness level

This Deliverable (D3.1) offers a clear and numerical assessment of chosen KPIs from 50 European and nationally funded projects (see Appendix I). Out of these, 19 show effective implementation of IS with the necessary data for KPI evaluation. These projects cover various processes and activities, such as cokemaking, iron ore sintering, BF, BOF, EAF, LF operations, slag valorization, plastic and biomass/charcoal/biochar use, and CO₂ utilization technologies.

By using the KPIs, this Deliverable allows for comparative analysis and supports prioritizing industrial innovation pathways based on evidence. It also provides a method for tracking progress toward long-term goals in reducing emissions, substituting resources, and minimizing waste and by-products in iron and steelmaking, as well as in related energy- and resource-intensive industries. It contributes to the broader scientific and policy discussions on industrial change and the role of innovation in developing process resilience.

2. Comprehensive overview of the projects and the defined KPIs

The “Flexible injection of alternative carbon material into the blast furnace”, Flexinject¹ project (2008–2011) focused on increasing the flexibility and sustainability of carbon use in the BF process by developing methods to inject ACM, such as BF flue dust, sludge, and plastics. The project investigated physical and chemical characterization, pre-treatment (notably using the Tornado process), pneumatic conveying, and injection of these materials, both in pilot and industrial-scale BFs. This project exemplifies IS by reusing waste/by-product materials (dust, sludge, plastics) from steelmaking and other industrial processes as valuable inputs in BF operations. At its core, IS involves one industry's waste becoming another industry's resource, for instance, utilizing external waste streams like plastics from ASR, typically sent to landfill or incineration, as alternative carbon sources. Table 2 presents the available KPIs related to this project, specifically the replacement rate of fossil carbon materials (KPI VIII) and the TRL (KPI XI).

Table 2. Flexible injection of alternative carbon material into the blast furnace.

Project title		Flexible injection of alternative carbon material into the blast furnace	
Project abbreviation	Flexinject		
Duration	01/07/2008–31/12/2011		
Funding programme	RFCS		
KPI No.	VIII	XI	
KPI Name	Replacement rate of fossil carbon materials	TRL	
Method to obtain	Calculated	Reported	
Unit	%	-	
KPI value	25	7	
Baseline value unit	%	-	
Baseline value	0	-	
Reference value unit	%	-	
Reference value	25	-	
Remarks	Based on the industrial injection of shredded plastic from industrial waste at a 25% share.		-

The “Alternate carbon sources for sintering of iron ore”, Acasos² project (2007–2010), funded under the RFCS programme, investigated the technical feasibility of replacing conventional fossil carbon sources (like coke breeze) with ACMs in the iron ore sintering process. The ACMs included char from biomass (e.g., charcoal, wood char), carbon-rich industrial residues (e.g., plastics, shredded residues), and secondary carbon sources (e.g., waste materials from steel production or other industries). The project involved lab-scale sintering tests, pot-grate tests, industrial trials, and an in-depth analysis of process performance and emissions. On a laboratory scale, it was possible to completely substitute coke breeze with biomass chars. However, some deterioration of sinter strength was observed. This project is a direct example of IS, as it aims at reusing carbon-rich waste and by-products from other sectors (e.g., plastics, residues, biomass) as valuable feedstock for sintering, thereby reducing dependency on fossil fuels and contributing to resource efficiency and lower environmental impact. The use of biomass-based char resulted in reduced CO₂ emissions due to its renewable carbon source. Table 3 presents KPIs, namely direct CO₂ emissions (Scope I) reduction (KPI II) and replacement rate of fossil carbon materials (KPI VIII).

Table 3. Alternate carbon sources for sintering of iron ore.

Project title		Alternate carbon sources for the sintering of iron ore	
Project abbreviation	Acasos		
Duration	01/07/2007–31/12/2010		
Funding programme	RFCS		
KPI No.	II	VIII	
KPI Name	Direct CO ₂ emissions (Scope 1) reduction	Replacement rate of fossil carbon materials	
Method to obtain	Reported	Reported	
Unit	%	%	
KPI value	7.8	100	
Baseline value unit	kg CO ₂ /t sinter	%	
Baseline value	135	0	
Reference value unit	kg CO ₂ /t sinter	%	
Reference value	124.5	100	
Remarks	CO ₂ reduced by 7.8 % using 100% char breeze in the sintering test.	100% biochar used in lab-scale sintering, replacing all fossil carbon (coke breeze).	

The “Using slag as sorbent to remove phosphorus from wastewater”, Slasorb³ project (2009–2012) investigated the potential for steel slags, a by-product of steel production, to be used as a sorbent material for removing P from municipal and industrial wastewater. The aim was to address both the issue of P pollution (a key driver of eutrophication in water bodies) and the challenge of valorising steel industry by-products. Key activities included: selecting different types of steel slags (BOF slag, EAF slag) from European producers; testing their P removal efficiency under various conditions (e.g., batch, column, and field tests); evaluating the chemical composition, reaction mechanisms, and environmental safety (e.g., leaching behaviour) of the slag after use; exploring options for recycling the P-loaded slag, including its use as fertilizer or soil improver. This project was chosen as an example of IS due to connecting the steel industry with the wastewater treatment and agriculture sectors, creating material loops where a by-product becomes a resource; transforming slag (a steelmaking residue) into a functional environmental remediation product (P sorbent), and then potentially into a nutrient source (fertilizer); reducing landfill needs and costs, and promoting resource efficiency across different industries; and offering a multi-benefit solution that addresses water

quality, waste valorisation, and P circularity. Table 4 shows the KPIs related to this project, namely reduction in virgin raw material usage (KPI III) and slag recycling rate (KPI V).

Table 4. Using slag as sorbent to remove phosphorus from wastewater.

Project title		
Using slag as sorbent to remove phosphorus from wastewater		
Project abbreviation	Slasorb	
Duration	07/01/2009–31/12/2012	
Funding programme	RFCS	
KPI No.	III	V
KPI Name	Reduction in virgin raw material usage	Slag recycling rate
Method to obtain	Calculated	Calculated
Unit	%	%
KPI value	100	100
Baseline value unit	%	-
Baseline value	0	-
Reference value unit	%	%
Reference value	100	100
Remarks	Commercial P sorbents were fully replaced by processed BOF slag fractions.	All BOF slag fractions used in experiments were reused as sorbents.

The “Sustainable EAF steel production” GreenEAF⁴ project (2009–2012), funded under the RFCS programme, focused on enhancing the sustainability and energy efficiency of EAF steel production. The primary objective was to reduce the consumption of fossil fuels, specifically coal and natural gas, while improving CO₂ emissions and overall process efficiency. The project developed and implemented an integrated control system that monitored and optimized energy use, emissions, and operational efficiency in EAF operations. A key aspect of the project was the replacement of fossil coal with biomass-derived char, which was fully substituted without any loss in performance. Char, produced through the pyrolysis of biomass, was shown to successfully replace fossil coal in the EAF process for both charging and injection purposes. This substitution demonstrated that biochar could serve as an effective alternative to fossil coal. Table 5 represents the estimated KPI

related to this project, namely KPI VIII, the replacement rate of fossil carbon materials.

Table 5. Sustainable EAF steel production.

Project title	Sustainable EAF steel production
Project abbreviation	GREENEAF
Duration	01/07/2009–30/06/2012
Funding programme	RFCS
KPI No.	VIII
KPI Name	Replacement rate of fossil carbon materials
Method to obtain	Calculated
Unit	%
KPI value	100
Baseline value unit	t/heat
Baseline value	1.0–1.4
Reference value unit	t/heat
Reference value	1.0–1.4
Remarks	Fossil coal was fully replaced by char with no loss in performance.

The project entitled “Biochar for a sustainable EAF steel production”, GreenEAF2⁵, (2014–2016), funded under the RFCS programme, exemplifies IS by fully substituting fossil coal with biochar, sourced from waste biomass such as forest residues, agricultural waste, or industrial by-products. The GreenEAF2 project (Table 6) aimed to deepen the sustainability impact of EAF steelmaking by exploring the technical, environmental, and economic potential of using biochar as a renewable alternative to fossil coal. In continuation of the original GreenEAF project, this second phase focused specifically on: testing different types of biochar as carbon injectants and recarburizers in EAF operations; evaluating the impact on steel quality, furnace performance, and emissions; as well as assessing the life cycle environmental benefits and economic viability of replacing fossil carbon with biochar. GreenEAF2 is a strong example of IS because it links the agriculture and forestry sectors (which generate biomass residues suitable for biochar production), the biochar production industry, and the steel industry. This cross-sector collaboration transforms organic waste into a valuable process input, replacing fossil carbon.

Table 6. Biochar for a sustainable EAF steel production.

Project title			Biochar for a sustainable EAF steel production		
Project abbreviation	GREENEAF2				
Duration	01/07/2014-01/06/2016				
Funding programme	RFCS				
KPI No.	II		VIII		
KPI Name	Direct CO ₂ emissions (Scope 1) reduction		Replacement rate of fossil carbon materials		
Method to obtain	Reported		Calculated		
Unit	%		%		
KPI value	20		100		
Baseline value unit	-		t/heat		
Baseline value	-		1.1–2.0		
Reference value unit	-		t/heat		
Reference value	-		1.1–2.0		
Remarks	Up to 20% CO ₂ reduction in the case of full replacement.		Fully replaced by biochar.		

The KPIs related to this project are direct CO₂ emissions (Scope 1) reduction (KPI II) and the replacement rate of fossil carbon materials (KPI VIII).

The project “Innovative Carbon Products for Substituting Coke in Ironmaking”, INNOCARB⁶, (2010–2013), funded under the RFCS programme, aimed to reduce the reliance on fossil-based metallurgical coke by developing and applying alternative carbon materials derived from biomass and plastic-rich industrial residues (Table 7). The project focused on identifying suitable waste and by-product streams, upgrading them through thermal and mechanical treatment, and validating their use as injectants or burden components in the BF.

Table 7. Innovative carbon products for substituting coke on BF operation.

Project title		
Innovative carbon products for substituting coke on BF operation		
Project abbreviation	INNOCARB	
Duration	01/07/2010–31/12/2013	
Funding programme	RFCS	
KPI No.	VIII	
KPI Name	Replacement rate of fossil carbon materials	
Method to obtain	Reported	
Unit	%	%
KPI value	25	20
Baseline value unit	%	%
Baseline value	0	0
Reference value unit	%	%
Reference value	25	20
Remarks	Pilot trials replaced 25 wt% of coke with biocarbon (thermally treated biomass char) in BF without performance loss.	Plastic-rich residues or composites could substitute up to 20 wt% of coke when suitably processed and injected.

Extensive laboratory, pilot, and industrial trials demonstrated that biomass-derived char could substitute up to 25 % of coke, while plastic-based composites achieved up to 20 % substitution.

The project exemplifies IS by transforming organic waste and plastic residues from other industries into valuable process inputs for ironmaking, enabling cross-sector material reuse and progressing the CE.

The project “Impact of Long-Term Application of Blast Furnace and Steel Slags on Soil Health and Crop Yield”, SLAGFERTILISER⁷ (2011–2015), funded under the RFCS programme, investigated the agronomic and environmental effects of applying BF and steel slags as soil amendments in agriculture (Table 8). The study evaluated the impact of slag use on soil chemistry, nutrient dynamics, microbial activity, heavy metal mobility, and crop productivity under actual field conditions.

Table 8. Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health.

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

The results showed that the application of these slags did not lead to the accumulation of harmful heavy metals, maintained soil pH and nutrient balance, and in some cases even improved crop yields due to the slow release of beneficial elements, such as calcium, magnesium, and silicon. A KPI V of the project (see Table 8), namely slag recycling rate, reached 100 % (within the German demo case), demonstrating that slag can fully substitute virgin lime in the tested agricultural applications.

The “Control of slag quality for utilization in the construction industry”, (SLACON)⁸ project (2012–2015) focused on the control and optimization of slag quality to enable its safe and efficient utilization in the construction industry (Table 9). Conducted under the RFCS programme, the project addressed the challenges associated with the variability of slag composition, particularly in relation to its long-term behaviour, environmental safety, and compliance with construction standards.

Table 9. Control of slag quality for utilization in the construction industry.

Project title		
Control of slag quality for utilization in the construction industry		
Project abbreviation	SLACON	
Duration	01/07/2012–01/12/2015	
Funding programme	RFCS	
KPI No.	III	V
KPI Name	Reduction in virgin raw material usage	Slag recycling rate
Method to obtain	Calculated	Calculated
Unit	%	%
KPI value	80	82.5
Baseline value unit	%	%
Baseline value	0	0
Reference value unit	%	%
Reference value	75–85	80–85
Remarks	Reduction of virgin raw material usage by 75 % to 85 % was achievable.	Slag was reused in construction applications.

The project developed guidelines for slag production and processing, including monitoring techniques and quality control protocols, to ensure consistent slag properties for use in concrete, road base materials, and other construction applications. According to KPI III (reduction in virgin raw materials usage) and KPI V (slag recycling rate), the project successfully demonstrated that it is possible to reuse slag in construction with high technical and environmental reliability, achieving a slag recycling rate by averaging of 82.5 % and a reduction of virgin raw material usage by averaging of 85 % (see Table 9). These results were confirmed through material characterization, performance testing, and real-case implementation scenarios. This project is a clear case of IS, as it facilitates a systematic exchange of materials between the steel industry and the construction sector.

The “Developing uses of alternative raw materials in cokemaking”, (ALTERAMA)⁹ project (2014–2017), funded under the RFCS programme, studied the substitution of conventional fossil-based raw materials in cokemaking by introducing alternative carbon sources, particularly bio-based carbon materials derived from organic waste. The aim was to reduce both the environmental impact and the consumption of virgin fossil resources in the coking process by incorporating biocarbon into coal blends. The project

included detailed laboratory testing, pilot-scale evaluations, and assessment of the impacts on coke quality and coking performance. According to KPIs III and VIII (reduction in virgin raw material usage and replacement rate of fossil carbon materials), the project achieved a replacement rate of fossil carbon materials of 33 % and a reduction of virgin raw material use by 26.5 %, with reference values ranging from 20 % to 33 % (see Table 10). The use of waste-derived biocarbon proved technically viable within optimized blending strategies and showed no significant negative impact on the performance or structural integrity of the produced coke. ALTERAMA is a strong example of IS, as it demonstrates the integration of the waste management and bioresource sectors with the steel industry.

Table 10. Developing uses of alternative raw materials in cokemaking.

Project title		Developing uses of alternative raw materials in cokemaking	
Project abbreviation	ALTERAMA		
Duration	01/07/2014–31/12/2017		
Funding programme	RFCS		
KPI No.	III	VIII	
KPI Name	Reduction in virgin raw material usage	Replacement rate of fossil carbon materials	
Method to obtain	Calculated	Reported	
Unit	%	%	
KPI value	26.5	33	
Baseline value unit	%	%	
Baseline value	0	0	
Reference value unit	%	%	
Reference value	20–33	33	
Remarks	The use of bio-based carbon materials (biocarbon from waste) in a blend has been tested.		

The “Recycling of industrial and municipal waste as slag foaming agent in EAF”, RIMFOAM¹⁰ project (2014–2017), supported by the RFCS programme, investigated the complete substitution of fossil-based carbon materials used as slag foaming agents in EAF steelmaking. The project focused on utilizing industrial and municipal waste-derived carbonaceous materials to replace conventional coke fines, which are typically used to promote slag foaming, a

key mechanism for improving energy efficiency and process stability in EAF operations. The research included material selection, processing, characterization, and full-scale industrial testing of alternative foaming agents. According to KPI VIII (replacement rate of fossil carbon materials), the project achieved a 100 % replacement rate of fossil carbon materials, demonstrating that entirely waste-based carbon sources can be used without compromising foaming performance or furnace efficiency (Table 11). RIMFOAM is a good example of IS, as it creates a direct connection between the waste management sector (including municipal solid waste and industrial by-products) and steel production.

Table 11. Recycling of industrial and municipal waste as slag foaming agent in EAF.

Project title		Recycling of industrial and municipal waste as slag foaming agent in EAF
Project abbreviation	RIMFOAM	
Duration	01/07/2014–30/06/2017	
Funding programme	RFCS	
KPI No.	VIII	
KPI Name	Replacement rate of fossil carbon materials	
Method to obtain	Reported	
Unit	%	
KPI value	100	
Baseline value unit	%	
Baseline value	0	
Reference value unit	%	
Reference value	100	
Remarks	100 % fossil-based carbon (coke fines) was replaced by industrial and municipal waste.	

The “Demonstration of innovative technologies towards a more efficient and sustainable plastic recycling”, POLYNSPIRE¹¹ project (2018–2023), funded under Horizon 2020 programme, demonstrated a suite of innovative technologies aimed at achieving more efficient and sustainable plastic recycling. The project focused on three innovation pillars: (a) chemical recycling of complex plastic waste using microwave-assisted depolymerization and smart magnetic catalysts; (b) enhancement of mechanical recycling through advanced additives and energy sources, and (c) valorisation of plastic waste as a carbon substitute in the EAF steelworks. Across these domains, POLYNSPIRE delivered

KPIs (see Table 12): direct Scope 1 CO₂ emissions were reduced from 953.1 to 945.7 kg CO₂ eq, up to 66 % of fossil carbon was replaced, and a TRL of 7 was achieved, also confirming the possibility of 30 % substitution of fossil carbon materials by plastic.

Table 12. Demonstration of innovative technologies towards a more efficient and sustainable plastic recycling.

Project title			
Demonstration of innovative technologies towards a more efficient and sustainable plastic recycling			
Project abbreviation	POLYNSPIRE		
Duration	01/09/2018–28/02/2023		
Funding programme	Horizon 2020		
KPI No.	II	VIII	XI
KPI Name	Direct CO ₂ emissions (Scope 1) reduction	Replacement rate of fossil carbon materials	TRL
Method to obtain	Reported	Reported	Reported
Unit	kg CO ₂ eq	%	-
KPI value	945.7	3.69	7
Baseline value unit	kg CO ₂ eq	kg oil eq	-
Baseline value	953.1	69.03	-
Reference value unit	kg CO ₂ eq	kg oil eq	-
Reference value	945.7	66.49	-

The “Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis”, CORALIS¹² project (2020–2025), funded by Horizon 2020 programme, is dedicated to establishing long-term IS models by developing new value chain relations and applying innovative solutions across various energy- and resource-intensive sectors. The project combines technological demonstrations, business model innovation, and social engagement strategies to overcome key barriers to implementing IS. Within the Italian demo case (see Table 13), CORALIS achieved notable results, including a 100 % slag recycling rate (KPI V), the complete recovery and reuse of dust and sludge (KPI VI), and a 100 % recycling rate for iron-rich residue streams (KPI VII), along with a 1.6 % reduction in the use of virgin raw materials (KPI III).

Table 13. Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis.

Project title				
Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis				
Project abbreviation	Coralis			
Duration	01/10/2020–31/03/2025			
Funding programme	Horizon 2020			
KPI No.	III	V	VI	VII
KPI Name	Reduction in virgin raw material usage	Slag recycling rate	Dust and sludge recovery and reuse	Recycling rate of iron-rich residue streams
Method to obtain	Reported	Reported	Reported	Reported
Unit	%	%	%	%
KPI value	1.6	100	100	100
Baseline value unit	-	-	-	-
Baseline value	-	-	-	-
Reference value unit	-	-	-	-
Reference value	-	-	-	-
Remarks	KPIs are considered within the Italian demo case. Considered sludge generated by rolling mill operations.			

The “Fostering industrial symbiosis for a sustainable resource-intensive industry across the extended construction value chain”, FISSAC¹³ project (2015–2020), funded by Horizon 2020 programme, aimed to promote IS in the construction and demolition value chain by developing a holistic and replicable model for circularity in resource-intensive industries. In terms of environmental impact, FISSAC achieved a 2.76 % reduction in Scope 1 direct CO₂ emissions (KPI II), lowering emissions from 3.98 to 3.87 kg CO₂ eq per unit of output (see Table 14). These results were achieved through optimized material flows, reduction in virgin resource use, and the incorporation of recycled inputs. FISSAC is a strong example of IS in action, demonstrating how cross-sector collaboration and material reuse can lead to measurable reductions in emissions and raw material consumption.

Table 14. Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain.

Project title	
Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain	
Project abbreviation	FISSAC
Duration	01/09/2015–29/02/2020
Funding programme	Horizon 2020
KPI No.	II
KPI Name	Direct CO ₂ emissions (Scope I) reduction
Method to obtain	Calculated
Unit	%
KPI value	2.76
Baseline value unit	kg CO ₂ eq
Baseline value	3.98
Reference value unit	kg CO ₂ eq
Reference value	3.87

The “EAF working with polymers derived from plastic residue in substitution of fossil fuel”, OnlyPlastic¹⁴ project (2020–2023), funded by the RFCS programme, demonstrated the complete substitution of fossil coal with polymers derived from hard-to-recycle plastic residues in EAF steelmaking (Table 15). The project developed and tested a novel SRA, commercially known as BLUAIR® SRA-based on plastic waste from food packaging. This SRA replaced coal in slag foaming operations at the Feralpi Lonato steel plant, using injection technologies developed by Tenova. The trials achieved 100 % substitution of coal (see Table 15), demonstrating a reduction in virgin raw material usage (KPI III) and a replacement rate of fossil carbon materials (KPI VIII).

Table 15. EAF working with polymers derived from plastic residue in substitution of fossil fuel.

Project title		
EAF working with polymers derived from plastic residue in substitution of fossil fuel		
Project abbreviation	OnlyPlastic	
Duration	01/09/2020–31/08/2023	
Funding programme	RFCS	
KPI No.	III	VIII
KPI Name	Reduction in virgin raw material usage	Replacement rate of fossil carbon materials
Method to obtain	Reported	Reported
Unit	%	%
KPI value	100	100
Baseline value unit	%	%
Baseline value	0	0
Reference value unit	%	%
Reference value	100	100
Remarks	In trials at Feralpi Lonato, virgin coal has been substituted by polymeric secondary reducing agents.	

The “Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock”, RETROFEED¹⁵ project (2019–2023), funded by Horizon 2020 programme, focused on enabling the retrofitting of resource- and energy-intensive process industries, such as cement, aluminum, and steel, towards more flexible, biobased, and circular feedstock usage. The project developed and validated a smart retrofitting framework that included advanced digital tools (like decision support systems and digital twins), as well as the integration of alternative feedstocks such as biomass, waste-derived fuels, and industrial by-products. In the cement sector, pilot trials successfully demonstrated the replacement of 60–80 % of petcoke with biomass or end-of-life tyres (see Table 16). The project achieved a 70 % replacement rate of fossil carbon materials, as indicated by KPI VIII (replacement rate of fossil carbon materials). RETROFEED is a strong example of IS in action, as it establishes cross-sectoral material loops by integrating waste streams from one industry (e.g., biomass residues, used tyres) into another as feedstock.

Table 16. Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock.

Project title		Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock
Project abbreviation	RETROFEED	
Duration	01/11/2019–31/10/2023	
Funding programme	Horizon 2020	
KPI No.	VIII	
KPI Name	Replacement rate of fossil carbon materials	
Method to obtain	Calculated	
Unit	%	
KPI value	70	
Baseline value unit	%	
Baseline value	100	
Reference value unit	%	
Reference value	60–80	
Remarks	In the cement sector, 60–80 % of petcoke was replaced with biomass or tyres.	

The “Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling”, BioReSteel¹⁶ project (2023–2027), funded under the RFCS programme, aims to demonstrate the substitution of fossil coal in EAF steelmaking using hydrochar produced from wet biomass residues via HTC. The project explores several technical routes, including hydrochar injection, top charging, and bio-oxide agglomerate charging in both laboratory and full-scale industrial settings across EAF plants in Italy and Spain. Since this is an ongoing project (Table 17), the KPI values can be mentioned as a 50 % reduction in virgin raw material usage (KPI III), aligned with a 50 % replacement rate of fossil carbon materials (KPI VIII), and achieving a TRL of 5 (KPI XI).

Table 17. Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling.

Project title			
Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling			
Project abbreviation	BioReSteel		
Duration	01/10/2023–31/03/2027		
Funding programme	RFCS		
KPI No.	III	VIII	XI
KPI Name	Reduction in virgin raw material usage	Replacement rate of fossil carbon materials	TRL
Method to obtain	Reported	Reported	Reported
Unit	%	%	-
KPI value	50	50	5
Baseline value unit	%	%	-
Baseline value	0	0	-
Reference value unit	%	%	-
Reference value	50	50	-
Remarks	Direct reduction in virgin coal usage for EAF through recovered biogenic input.	50 % replacement by hydrochar from wet biomass residues.	-

Additionally, the process facilitates the production of a P-rich fertilizer, promoting nutrient recycling and supporting the recovery of critical raw materials. BioReSteel is a notable example of IS, integrating the agriculture, waste management, and steel sectors. It transforms low-value, locally sourced biomass residues into a functional metallurgical input.

The “Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions”, FLEXCOKE¹⁷ project (2013–2017), funded under the RFCS programme, investigated the substitution of fossil coal with biochar in the cokemaking process, aiming to assess its effects on coke properties under BF conditions. Laboratory and pilot-scale trials were conducted to investigate the impact of varying biochar amounts on coke structure, strength, reactivity, and combustion behavior. Biochar produced

from biomass residues was incorporated into coal blends at 3 % and 5 %, achieving, on average, a 4 % replacement rate of fossil carbon materials (KPI VIII) with no detrimental impact on the final coke product's performance (Table 18).

Table 18. Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions.

Project title		Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions
Project abbreviation	FLEXCOKE	
Duration	01/07/2013–31/12/2017	
Funding programme	RFCS	
KPI No.	VIII	
KPI Name	Replacement rate of fossil carbon materials	
Method to obtain	Calculated	
Unit	%	
KPI value	4.0	
Baseline value unit	%	
Baseline value	0	
Reference value unit	%	
Reference value	3.0–5.0	
Remarks	Biochar in the coal blend was used to substitute 3 % and 5 %.	

The results demonstrated that low-percentage biochar blending is technically feasible and compatible with BF operation requirements. FLEXCOKE provides a valuable case of IS, linking the biomass processing and cokemaking.

The “Transforming CO₂ into added-value construction products”, Carbon4Minerals¹⁸ project (2023–2026), funded under Horizon Europe programme, focuses on transforming CO₂ emissions from industrial flue gases into value-added construction products (see Table 19). The project addresses the dual challenge of reducing process-inherent emissions in energy-intensive industries, particularly in cement production, and the decreasing availability of traditional supplementary cementitious materials, such as BF slag.

Table 19. Transforming CO₂ into added-value construction products.

Project title		
Transforming CO₂ into added-value construction products		
Project abbreviation	Carbon4Minerals	
Duration	01/01/2023–31/12/2026	
Funding programme	Horizon Europe	
KPI No.	IX	X
KPI Name	CO ₂ from off-gases reuse	Share of carbon content in process gas (CO ₂ /CO) transformed into products
Method to obtain	Reported	Reported
Unit	%	%
KPI value	100	100
Baseline value unit	-	-
Baseline value	-	-
Reference value unit	-	-
Reference value	-	-
Remarks	CO ₂ captured from industrial flue gases was used for carbonation curing of binders and construction products.	CO ₂ was chemically bound in mineral carbonates in binders and products.

Through eight industrial pilot projects, Carbon4Minerals demonstrates the integration of CO₂ capture with mineral carbonation, using captured CO₂ to produce low-carbon binders and concrete products. Since this is an ongoing project, two KPIs were reported, namely CO₂ from off-gases reuse (KPI IX) and share of carbon content in process gas (CO₂/CO) transformed into products (KPI X).

The “Innovative industrial transformation of the steel and chemical industries of Europe”, INITIATE¹⁹ project (2020–2026), funded by Horizon 2020 programme, focuses on the integrated transformation of the steel and chemical industries by enabling the reuse of steel mill off-gases for the production of ammonia and urea (see Table 20).

Table 20. Innovative industrial transformation of the steel and chemical industries of Europe.

Project title					
Innovative industrial transformation of the steel and chemical industries of Europe					
Project abbreviation	INITIATE				
Duration	01/11/2020–30/04/2026				
Funding programme	Horizon 2020				
KPI No.	II				
KPI Name	Direct CO ₂ emissions (Scope 1) reduction				
Method to obtain	Reported				
Unit	%	%	%	%	%
KPI value	29.80	80.06	94.22	41.72	66.58
Baseline value unit	kgCO ₂ /t _{HRC}	tCO ₂ /t _{NH₃}	tCO ₂ /t _{NH₃}	tCO ₂ /t _{Urea}	tCO ₂ /t _{Urea}
Baseline value	1823.9	2.28	1.87	0.53	0.33
Reference value unit	kgCO ₂ /t _{HRC}	tCO ₂ /t _{NH₃}	tCO ₂ /t _{NH₃}	tCO ₂ /t _{Urea}	tCO ₂ /t _{Urea}
Reference value	1280.5	0.45	0.11	0.31	0.11
Remarks	Steel plant	Small ammonia plant	Large ammonia plant	Small ammonia + urea plant	Large ammonia + urea plant

The project demonstrates a novel, multi-sector approach in which CO₂ and H₂-rich process gases from steelmaking are captured and redirected as feedstock for chemical synthesis. By piloting this integration across steel plants and various scales of ammonia and urea facilities, INITIATE achieves direct CO₂ emission (Scope I) reductions (KPI II) ranging from 29.8 % to 94.22 %, depending on plant size and configuration. The baseline CO₂ intensity for steel production (1823.9 kgCO₂/t_{HRC}) was reduced to 1280.5 kgCO₂/t_{HRC}, while ammonia and urea production also showed significant reductions in direct emissions. INITIATE stands as an example of IS, merging the steel and chemical sectors.

3. Conclusions

This Deliverable identifies KPIs addressed by a wide range of projects funded under the RFCS, Horizon 2020, and Horizon Europe programs. Each project contributes to one or more KPIs, demonstrating practical pathways toward low-carbon, resource-efficient industrial systems (see Table 21).

Table 21. KPI-project summary.

KPI No.	KPI Name	Projects with quantified KPI
I	Energy efficiency	Further project search should be done.
II	Direct CO ₂ emissions (Scope 1) reduction	Acasos, GREENEAF2, POLYNSPIRE, INITIATE, FISSAC
III	Reduction in virgin raw materials usage	Slasorb, SLACON, ALTERAMA, Coralis, OnlyPlastic, BioReSteel
IV	Enhancing the recycling of low-quality steel scrap	Further project search should be done.
V	Slag recycling rate	SLAGFERTILISER, SLACON, Coralis
VI	Dust and sludge recovery and reuse	Coralis
VII	Recycling rate of iron-rich residue streams	Coralis
VIII	Replacement rate of fossil carbon materials	Flexinject, Acasos, Slasorb, GREENEAF, GREENEAF2, INNOCARB, ALTERAMA, RIMFOAM, POLYNSPIRE, OnlyPlastic, RETROFEED, BioReSteel, FLEXCOKE
IX	CO ₂ from off-gases reuse	Carbon4Minerals
X	Share of CO ₂ /CO in process gas transformed into product	Carbon4Minerals
XI	TRL	Flexinject, POLYNSPIRE, BioReSteel

Among the KPIs, the replacement of fossil-based carbon materials (KPI VIII) appeared as the most widely addressed target. Several projects, including Flexinject, Acasos, Slasorb, GREENEAF, GREENEAF2, INNOCARB, ALTERAMA, RIMFOAM, POLYNSPIRE, OnlyPlastic, RETROFEED, BioReSteel, and FLEXCOKE, showed that it is possible to substitute coal and coke with alternative carbon sources. These sources include biochar, polymers from plastic waste, RDF, and industrial residues, all while keeping process efficiency. Additionally, reducing direct CO₂ emissions (Scope 1) (KPI II) was another key focus in projects such as Acasos, GREENEAF2, POLYNSPIRE, INITIATE, and FISSAC.

Significant progress was also observed in the valorisation of solid residues, such as slags, dusts, and sludge (KPIs III, V, VI, and VII). Projects like CORALIS, SLAGFERTILISER, and SLACON reported full or near-complete recycling of these materials, integrating them into construction, agriculture applications, etc. This shift not only reduces dependency on virgin raw materials but also minimizes waste and residue generation, as well as landfilling.

While some KPIs, notably KPI I (energy efficiency) and KPI IV (enhancing the recycling of low-quality steel scrap), were underrepresented, this identifies clear areas for further research and data collection for KPIs monitoring.

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- (18) *Transforming CO₂ into added-value construction products.* <https://cordis.europa.eu/project/id/101091870/reporting> (accessed 2025-07-29).
- (19) *Innovative industrial transformation of the steel and chemical industries of Europe.* <https://cordis.europa.eu/project/id/958318/results> (accessed 2025-07-29).

List of Tables

	Page
Table 1. List of the defined KPIs	7
Table 2. Flexible injection of alternative carbon material into the blast furnace	10
Table 3. Alternate carbon sources for sintering of iron ore	11
Table 4. Using slag as sorbent to remove phosphorus from wastewater	12
Table 5. Sustainable EAF steel production	13
Table 6. Biochar for a sustainable EAF steel production	14
Table 7. Innovative carbon products for substituting coke on BF operation	14
Table 8. Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health	16
Table 9. Control of slag quality for utilization in the construction industry	17
Table 10. Developing uses of alternative raw materials in cokemaking	18
Table 11. Recycling of industrial and municipal waste as slag foaming agent in EAF	19
Table 12. Demonstration of innovative technologies towards a more efficient and sustainable plastic recycling	20
Table 13. Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis	21
Table 14. Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain	22
Table 15. EAF working with polymers derived from plastic residue in substitution of fossil fuel	23
Table 16. Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock	24

Table 17. Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling	25
Table 18. Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions	26
Table 19. Transforming CO ₂ into added-value construction products	27
Table 20. Innovative industrial transformation of the steel and chemical industries of Europe	28
Table 21. KPI-project summary	29

Appendix I

List of evaluated projects.

No.	Project Title	Acronym	Report No.	Funding Program	Project Duration
1	Foaming of slag and recycling of steel dust by injection into the electric arc furnace	n.a.	EUR 20926	ECSC	07/01/1999-30/06/2002
2	Efficient use of resources in steel plant through process integration	Reffiplant	EUR 28457	RFCS	01/07/2012-31/12/2015
3	Improved cleaning of waste gases and recycling of BOF dust	n.a.	EUR 20286	ECSC	07/01/1996-30/06/2000
4	Briquetting of self-reducing blendings of waste iron oxides mixture	n.a.	EUR 20108	ECSC	01/07/1997-31/12/2000
5	Development of technologies for treatment of dust and sludges containing zinc and lead to improve their recycle and reuse	TREATDUST	EUR 19474	ECSC	01/07/1996-30/06/1999
6	Hydrometallurgical continuous treatment of ZnO-enriched powders for metal zinc	FULL-REC 2	EUR 22989	RFCS	01/09/2003-31/08/2005
7	Hearth protection in blast furnace operation by injection of TiO₂ materials	n.a.	EUR 22821	ECSC	01/07/2002-31/12/2005
8	Increased yield and enhanced steel quality by improved deslagging and slag conditioning	OPTDESLAG	EUR 27438	RFCS	07/01/2010-30/06/2013
9	Processes and technologies for environmentally friendly recovery and treatment of scrap	PROTECT	EUR 27201	RFCS	01/07/2010-31/12/2013
10	Removal of phosphorus from BOF-slag	PSP-BOF	EUR 29532	RFCS	01/07/2013-30/06/2016

11	Recycling of zinc and lead containing dust from the electric arc furnace	n.a.	BRE20116	FP3-BRITE/EU RAM 2	01/01/1993-31/12/1995
12	A new treatment process to recover magnetite, zinc and lead from iron and steel making dusts and sludges	n.a.	n.a.	FP4-INCO	01/09/1997-30/11/1999
13	Recycling of EAF dust by an integrated leach-grinding process	REDILP	n.a.	FP6-SME	01/11/2004-30/04/2007
14	Efficient mineral processing and hydrometallurgical recovery of by-product metals from low-grade metal containing secondary raw materials	CHROMIC	n.a.	H2020	30/11/2016-31/10/2020
15	High-purity zinc and ferroalloy recovery from EAF dusts through a combined pyro-metallurgical treatment	FULL-REC	EUR 20505	ECSC	01/07/1998-30/06/2001
16	Energy and productivity optimised EAF stainless steel making by adjusted slag foaming and chemical energy supply	EPOSS	EUR 25082	RFCS	07/01/2007-31/12/2010
17	Flexible injection of alternative carbon material into the blast furnace	Flexinject	EUR 25909	RFCS	01/07/2008-31/12/2011
18	Alternate carbon sources for sintering of iron ore	Acasos	EUR 25151	RFCS	01/07/2007-31/12/2010
19	Upgrading and utilization of residual iron oxide materials for hot metal production	URIOM	EUR 25081	RFCS	01/07/2007-31/12/2010
20	Using slag as sorbent to remove phosphorus from wastewater	Slasorb	EUR 26412	RFCS	07/01/2009-31/12/2012
21	Sustainable EAF steel production	GREENEAF	EUR 26208	RFCS	01/07/2009-30/06/2012
22	Biochar for a sustainable EAF steel production	GREENEAF2	EUR 29517	RFCS	01/07/2014-01/06/2016
23	Innovative carbon products for substituting coke on BF operation	INNOCARB	EUR 27121	RFCS	01/07/2010-31/12/2013

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24	Impact of long-term application of blast furnace and steel slags as liming materials on soil fertility, crop yields and plant health	SLAGFERTILISER	EUR 28447	RFCS	01/07/2011-01/06/2015
25	Control of slag quality for utilization in the construction industry	SLACON	EUR 28460	RFCS	01/07/2012-01/12/2015
26	Developing uses of alternative raw materials in cokemaking	ALTERAMA	EUR 29524	RFCS	01/07/2014-31/12/2017
27	Recycling of industrial and municipal waste as slag foaming agent in EAF	RIMFOAM	EUR 30852	RFCS	01/07/2014-30/06/2017
28	Demonstration of innovative technologies towards a more efficient and sustainable plastic recycling	POLYNSPIRE	n.a.	H2020	01/09/2018-28/02/2023
29	Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis	Coralis	n.a.	H2020	01/10/2020-31/03/2025
30	Fostering industrial symbiosis for a sustainable resource intensive industry across the extended construction value chain	FISSAC	n.a.	H2020	01/09/2015-29/02/2020
31	EAF working with polymers derived from plastic residue in substitution of fossil fuel	Only Plastic	n.a.	RFCS	01/09/2020-31/08/2023
32	Implementation of a smart RETROfitting framework in the process industry towards its operation with variable, biobased and circular FEEDstock	RETROFEED	n.a.	H-2020	01/11/2019-31/10/2023
33	Accompanying measure for dissemination, valorisation and collaborative exploitation of circularity of constructional steel products	ADVANCE	n.a.	RFCS	2023-09-01-2025-08-31
34	Valorization of wet biomass residues for sustainable steel production with efficient nutrient recycling	BioReSteel	n.a.	RFCS	01.10.2023-31.03.2027

35	Flexible production of coke using alternative coals – effects on coke properties under blast furnace conditions	FLEXCOKE	EUR 29541	RFCS	01/07/2013 – 31/12/2017
36	Transforming CO₂ into added-value construction products	Carbon4Minerals	10.303 0/1010 91870	Horizon Europe	01/01/2023- 31/12/2026
37	Innovative industrial transformation of the steel and chemical industries of Europe	INITIATE	D5.3	Horizon 2020	01/11/2020- 30/04/2026
38	Characterization, modelling & validation of the impact of iron and steel-making slags used in road construction on groundwater	n.a.	n.a.	ECSC- STEEL C	01/07/2000- 30/06/2003
39	In-situ, quick sensing system for measurements of critical components in steelmaking slags	Inquiss	EUR 22818	RFCS	01/07/2001- 30/06/2004
40	Sustainable agriculture using blast furnace and steel slags as liming agents	n.a.	EUR 22033	ECSC	07/01/2001- 30/06/2004
41	A new metallurgical route for the on-line conversion of by-products into valuable mineral and metallic products with a reduction of CO₂ emissions	n.a.	n.a.	FP5- Growth	01/01/2001- 30/09/2004
42	Alternative processing of sinter plant recycling materials	n.a.	EUR 22974	RFCS	01/07/2002- 31/12/2005
43	Short term CO₂ mitigation for steelmaking	SHOCOM	EUR 24989	RFCS	01/07/2005- 31/12/2008
44	Carbon cycle economy demonstration	C-CED	n.a.	Klima und Energiefonds	01/07/2021- 01/06/2025
45	Innovative use of iron and steel making by-products for the sealing and securing of steel industry deposits	n.a.	EUR 21361	ECSC	01/01/1999- 30/06/2002
46	Turning industrial waste gases (mixed CO/CO₂ streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings	Carbon4PUR	DOI: 10.303 0/7689 19	Horizon 2020	01/10/2017- 31/03/2021

47	Concerted European action on Sustainable Applications of REfractories	CESAREF	DOI: 10.3030/101072625	Horizon Europe	01/10/2022-30/09/2026
48	Recycling renewable hydrogen for climate neutrality	RecHycle	DOI: 10.3030/101058692	Horizon Europe	01/06/2022-30/11/2026
49	Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem	C2FUEL	DOI: 10.3030/838014	Horizon 2020	01/06/2019-30/10/2023
50	Optimising slag reuse and recycling in electric steelmaking at optimum metallurgical performance through on-line characterization devices and intelligent decision support system	iSlag	n.a.	RFCS	n.a.