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Abbreviations, Acronyms and Units

Table 1 Abbreviations and acronyms

Abbreviation	Meaning
BF	Blast furnace
BF-BOF	Blast furnace–basic oxygen furnace route
BOF	Basic oxygen furnace
CAPEX	Capital expenditure
CFF	Circular Footprint Formula
DR	Direct reduction
DRI	Direct reduced iron
DRP	Direct Reduction Plant
EAF	Electric arc furnace
EF	Environmental Footprint
ESF	Electric smelting furnace / Smelter
EU	European Union
EUROFER	European Steel Association
GHG	Greenhouse gas
H_2	Hydrogen
HAZOP	Hazard and Operability Study
HBI	Hot briquetted iron
HCI	Hot compacted iron
HDRI	Hot direct reduced iron
HM	Hot metal
HYFOR	Hydrogen-based fine-ore reduction
ISO	International Organization for Standardization
K1-MET	K1-MET GmbH
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OPEX	Operating expenditure
PEF	Product Environmental Footprint

PEM	Proton Exchange Membrane
PPA	Power purchase agreement
PSD	Particle-size distribution
PTAT	Primetals Technologies Austria
RFCS	Research Fund for Coal and Steel
SALCOS	Salzgitter Low CO_2 Steelmaking
SSSA	Scuola Superiore Sant'Anna
TRL	Technology Readiness Level
VAS	voestalpine Stahl GmbH
WP	Work package
AT	Austria
CH	Switzerland
DE	Germany
GLO	Global
RER	Europe
RoW	Rest of World

Table 2 Units

Unit	**Meaning**
%	Percent
kg	Kilogram
t	Tonne
t/a	Tonnes per annum
kt/a	Thousand tonnes per annum
Mt	Million tonnes
Mt/a	Million tonnes per annum
t/h	Tonnes per hour
t/t HM	Tonnes per tonne of HM
kg/t HM	Kilograms per tonne of HM
km	Kilometre
DWT	Deadweight tonnes
MW	Megawatt
GW	Gigawatt
kWh	Kilowatt-hour
MWh	Megawatt-hour
MWh/t HM	Megawatt-hours per tonne of HM
TWh/a	Terawatt-hours per annum
Nm^3	Normal cubic metre
MJ	Megajoule
EUR	Euro
kg CO_2 eq	Kilograms of carbon-dioxide equivalent
kg CFC-11 eq	Kilograms of CFC-11 equivalent
kBq U-235 eq	Kilobecquerels of uranium-235 equivalent
kg NMVOC eq	Kilograms of non-methane volatile organic compound equivalent

disease incidence	Particulate-matter health impact indicator
mol H^+ eq	Moles of hydrogen-ion equivalent
kg P eq	Kilograms of phosphorus equivalent
kg N eq	Kilograms of nitrogen equivalent
mol N eq	Moles of nitrogen equivalent
CTUe	Comparative Toxic Unit for ecosystems
CTUh	Comparative Toxic Unit for humans
Pt	Eco-point / point
mPt	Millipoint; 10^{-3} Pt
kg Sb eq	Kilograms of antimony equivalent
m^3 world eq deprived	Cubic metres world-equivalent deprived; water-use indicator

PART I
HY4SMELT REPLICATION SCENARIOS

1. Introduction

Hy4Smelt combines *hydrogen-based fine-ore reduction* in the HYFOR process with continuous *electric smelting,* the Smelter, to produce hot metal (HM) from non-agglomerated fine and ultra-fine iron ores[1] . The concept is designed to address a central limitation of the transition away from blast-furnace ironmaking: many future hydrogen-based direct-reduction routes favour high-grade pellets or lump ore, whereas a large share of available iron ore occurs as fines and at grades that require beneficiation and agglomeration before conventional shaft-furnace use. Hy4Smelt is intended to broaden this feedstock window, use renewable hydrogen and electricity, and deliver HM that can be processed in existing *Basic oxygen furnace* (BOF) steelmaking[2] . The Smelter slag is simultaneously developed as a potential secondary raw material for the cement sector.

This deliverable has two linked objectives. **Part I** develops an initial replication framework for transferring Hy4Smelt from the Linz demonstration environment to other industrial locations, with primary emphasis on the European steel industry. **Part II** presents the preliminary **Life Cycle Assessment** prepared by **SSSA** (*Scuola Superiore Sant'Anna*). The replication analysis identifies where Hy4Smelt may create value, what configuration could be used at different sites, which technical and infrastructure conditions determine suitability, and what must still be proven by the demonstrator before commercial scale-up. The preliminary **LCA** establishes the environmental baseline against which the final green-hydrogen Hy4Smelt route can later be assessed using primary demonstration data.

The European market is large enough to justify a structured replication assessment but should not be interpreted as a uniform addressable market. EU crude steel production was 125.8 Mt in 2025, of which 68.2 Mt, or 54.2%, was produced through the basic-oxygen route [3]. Hy4Smelt is most relevant where several conditions coincide:

- a need to replace blast-furnace ironmaking;
- value in retaining BOF,
- casting and rolling assets;
- a strategic benefit from using fine or lower-grade ore rather than relying exclusively on direct-reduction-grade pellets;
- access to scalable low-emission electricity and hydrogen;
- suitable logistics and utilities;
- and a route for HM, steel and qualified Smelter slag.

The report therefore evaluates named European sites as replication examples rather than as statements of company intent. Donawitz is used as the principal worked case because it combines a two-blast-furnace site, an *Electric Arc Furnace* (EAF) transformation already under construction [4] , existing BOF steelmaking and direct historical links to HYFOR development. voestalpine plans to start an approximately **0.85 Mt/a EAF in 2027**, allowing one blast furnace to be shut down by 2029, and has announced a potential expansion to **1.5 Mt/a** that could enable closure of both blast furnaces and the sinter plant from 2030 [4] . This report assesses an alternative mixed configuration in which the new EAF is retained while the

remaining blast-furnace function is conceptually replaced by HYFOR plus a Smelter supplying HM to the BOF route. On a **0.75 Mt/a hot-metal basis**, the industrial assumptions already used in **D5.6** imply approximately **1.20 Mt/a of ore fines, 45 kt/a of hydrogen, 1.88 TWh/a of process electricity and 75 kt/a of carbon carrier**. These values are screening estimates, not design guarantees.

D**uisburg** is the closest external technology benchmark because **thyssenkrupp Steel** is implementing a 2.5 Mt/a hydrogen-capable direct-reduction plant with two downstream electrically operated melters to produce approximately **2.3 Mt/a** of HM while retaining subsequent steelmaking steps [5,6]. This validates the broader industrial logic of direct reduction followed by electric melting and hot-metal integration; the potential Hy4Smelt differentiation lies mainly in fine-ore and ore-quality flexibility. **Dunkirk and IJmuiden** provide strong coastal transformation cases with major ore-handling infrastructure and phased replacement of blast-furnace capacity [7] . **Salzgitter** provides an important comparison with a committed DRI-EAF transformation [8] , while **Bremen [9] , Fos-sur-Mer [9] and Raahe [10]** are retained as additional screening examples where investment timing, energy supply or the selected future production architecture differ.

International examples remain secondary to the European focus. **Australia** [11,12] **and Brazil** [13,14] illustrate resource-linked configurations in which HYFOR could be located near iron-ore production and renewable-energy resources, producing HBI or HM for local use or export. **India** combines a large and expanding steel market, substantial ore-fines availability and both BF-BOF and DRI capacity [15] . Selected Southeast Asian locations are more likely to begin with **port-based Smelter configurations** supplied by imported DRI/HBI or HYFOR products [16] . These cases confirm that replication is not the literal duplication of the Linz demonstrator; **the process chain must be adapted to local feedstock, energy, infrastructure and product requirements.**

The preliminary LCA assesses three benchmark routes: conventional BF-BOF (**Route A**), MIDREX-ESF-BOF based on natural-gas-derived reducing gas (**Route B**), and **HYFOR-ESF-BOF** supplied with grey hydrogen (**Route C**). The assessment follows **ISO 14040 and ISO 14044** and applies the **EF 3.1 impact-assessment method**. Route A has the highest overall environmental burden, while Route C has the lowest of the three benchmark routes. The contribution analysis shows that hydrogen production and electricity are major remaining environmental hotspots in the HYFOR route, indicating the significance of the project target to replace grey hydrogen with renewable hydrogen. A slag-modelling sensitivity analysis changes the magnitude of impacts but not the ranking of the three routes.

The two parts of D5.1 define an initial transferability case for Hy4Smelt. The replication analysis identifies where the technology may fit, and what must be demonstrated for a complete transferability scenario; the LCA defines how its environmental performance will be compared with established and transitional steelmaking routes. The report should therefore be read as an early-stage screening and baseline document as its conclusions will be progressively refined through WP4 demonstration results, the WP5 performance assessment, the final LCA/LCC and the project business case.

2. Hy4Smelt Technology as the Basis for Replication

2.1 Process concept and replication-relevant characteristics

Hy4Smelt combines the HYFOR fluidised-bed direct-reduction process with an electrically heated Smelter. Fine and ultra-fine iron ore is prepared, heated and reduced with hydrogen in HYFOR. The reduced material can be transferred as **hot DRI** fines or **compacted as HCI**. Remaining iron oxides are reduced in the Smelter due to the slight reducing atmosphere. The metallic phase is melted and carburised, and gangue is naturally separated into slag. The resulting HM is intended for further processing in an existing **BOF steelmaking route**. The demonstration is **fully integrated** into an existing steel site and is designed to prove the coupled operation of hydrogen reduction, material transfer, electric smelting, hot-metal production and downstream use [2] .

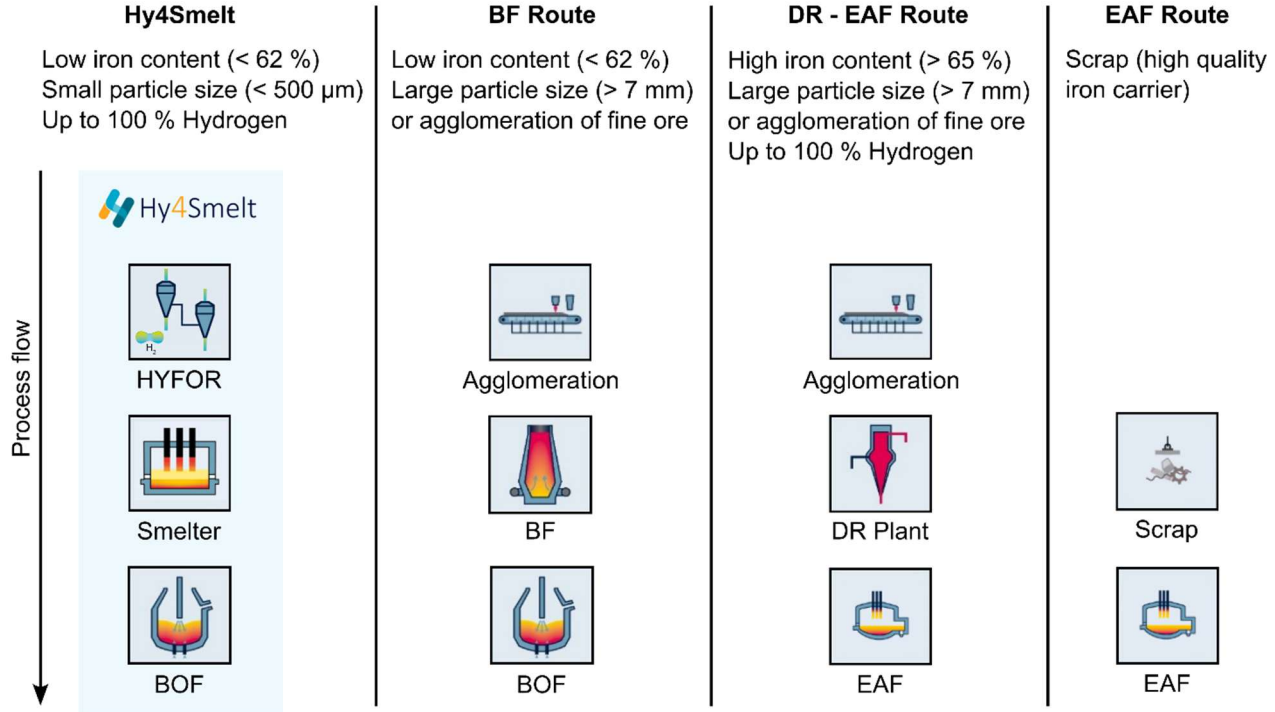

Figure 1 Comparison of conventional BF-BOF, conventional DR-EAF and Hy4Smelt process routes

The demonstration target includes HDRI production of approximately **2.2 t/h** and hot-metal production of up to **2.5 t/h**. The project targets more than **85% HDRI metallisation**, more than **90% hydrogen utilisation**, more than **80% pre-reduced iron carrier in the Smelter**, hot-metal **carburisation above 3**%, and a Smelter slag with high glass content suitable for subsequent cement-sector qualification. The demonstrator is classified in the project as a **continuous 1-5 t/h** installation intended to move the integrated concept from **TRL 5** toward **TRL 7/8**; industrial steel production is represented by continuous capacities on the order of **50-100 t/h** [2] .

2.1.1 Iron-ore flexibility

The principal replication differentiator is the **capability to process non-agglomerated fine and ultra-fine ore** across a wider quality range than conventional shaft-furnace direct

reduction. The project proposal identifies the dependence of established DR routes on pellets or lump ore and the resulting competition for high-grade DR feed as a future constraint. Hy4Smelt is intended to reduce this dependence by **eliminating sintering and**, for suitable feeds, **pelletising** before reduction. The economic and environmental value of this feature depends on the actual ore: gangue chemistry, mineralogy, particle-size distribution, and reducibility influence hydrogen demand and thus productivity, energy use and slag generation. Replication requires feed qualification rather than a simple minimum Fe-grade threshold, as gangue content and composition may have a substantial influence on overall process efficiency and valorisation efforts.

The demonstration plant includes additional feed options for scrap, HBI and other iron carriers. Hot-metal production (**Smelter**) is expected to range around **1.5-2.0 t/h from HYFOR output** and can increase toward **2.5 t/h** when additional metallic feed is charged. This flexibility is relevant for replication because a Smelter does not necessarily need to be tied exclusively to HYFOR. A site could use a complete **HYFOR-Smelter line**, combine HYFOR material with other iron-bearing materials, or deploy just the Smelter as a separate unit connected to another DRI source. Likewise, the HYFOR can be used in combination with any downstream processing plant, e.g. EAF furnace when high grade iron ores are available. The wider Smelter market is therefore potentially larger than the market for complete HYFOR installations.

2.1.2 Production of HM and slag

Hy4Smelt is not limited as a DRI producing technology due to Smelter integration. The Smelter completes reduction and produces liquid HM with controlled carbon content. This creates a **direct interface with BOF steelmaking** and differentiates the route from configurations that send DRI directly to an EAF. For European sites with valuable converter, casting, secondary-metallurgy and rolling assets, the ability to replace fossil ironmaking while retaining part of the downstream production chain can reduce the extent of the site transformation. It can also preserve a liquid-iron route for product portfolios that benefit from high-quality ore-based metallic input.

The Smelter creates a second material stream whose value can materially affect replication. Slag chemistry is adjusted during the project with the intention of generating a granulated product that can substitute, at least in selected applications, for conventional blast-furnace slag in the cement sector. As blast-furnace production declines, established supplies of granulated BF slag are expected to decline as well. A qualified Smelter slag could therefore provide both a disposal-avoidance benefit for steel producers and a new low-clinker raw-material source for cement producers. The benefit is site-specific because product status, consistency, processing requirements, transport distance and local cement demand determine whether the slag has commercial value.

2.2 Replication Methodology

For D5.1, replication is defined as the transfer and adaptation of the Hy4Smelt process concept to another industrial environment at commercially relevant scale. Replication does not mean constructing an identical copy of the Linz demonstrator, but in adapting parts of the Hy4Smelt replication scenario onto specific localized conditions.

Commercial installations will differ in:

- production capacity,
- number of reduction modules,

- Smelter size,
- ore grade and preparation,
- hydrogen supply,
- material-handling layout,
- hot-metal logistics,
- downstream route,
- slag-processing arrangements.

A credible replication case therefore begins with the function that must be replaced at the target site and then determines which Hy4Smelt configuration can provide that function.

Table 3 Replication assessment criteria including Key screening questions

Criterion	Key questions for replication screening
Steelmaking configuration	Which BF and converter capacity is to be replaced? Which BOF, casting, rolling and secondary-metallurgy assets remain valuable? Is the site moving to EAF, DR, smelting, or a mixed route?
Raw-material fit	What ore grades and particle sizes are available? Is there strategic value in using fines or lower-grade streams? What beneficiation, pelletising, flux, scrap and carbon-carrier requirements arise?
Hydrogen and electricity	Can the site secure low-emission electricity and hydrogen at the scale required for continuous operation? What grid, pipeline, storage or on-site generation infrastructure is required?
Plant integration and logistics	Is sufficient land available? Can ore, DRI/HCI, carbon, slag and HM be handled safely? Are rail, port, oxygen, water, gas and power systems adequate?
Product and downstream route	Is HM required? Can existing BOF assets be retained? What steel-grade and metallic-input requirements must be met?
Slag and circularity	Is there a realistic local or regional outlet for qualified Smelter slag? Which standards and product-status requirements apply?
Investment and regulatory timing	When are BF relinings or replacements due? What investments are already committed? What permitting, funding, carbon-cost and customer conditions influence the decision?

The criteria are used qualitatively because confidential site data are not available for a full feasibility or economic comparison. Quantitative information is included only where credible public capacity figures or project assumptions exist. The resulting relevance categories therefore indicate compatibility with the Hy4Smelt architecture rather than investment attractiveness or company interest. The screening sequence is: define the required metallic output; test whether HYFOR offers a feedstock advantage; assess energy and infrastructure feasibility; define integration of HM, DRI/HCI, scrap and slag; and identify the demonstration evidence required before a site-specific feasibility study.

2.3 Deployment Configurations

Hy4Smelt can be replicated in several configurations depending on the existing steelmaking route, available infrastructure and local resource conditions. The main European application is the replacement of blast-furnace ironmaking while retaining existing downstream steelmaking assets. In other cases, Hy4Smelt may operate alongside EAF production or

individual HYFOR and Smelter units may be deployed separately. Table 4 summarises the principal deployment configurations considered in this report and their most relevant application contexts.

Table 4 Principal Hy4Smelt deployment configurations

Configuration	Description	Most relevant context
A. Integrated steelworks conversion	HYFOR + Smelter replaces all or part of blast-furnace ironmaking. Hot metal continues to BOF steelmaking and existing downstream assets.	Primary European Hy4Smelt configuration.
B. Mixed EAF + Hy4Smelt production	One part of the site is converted to EAF-based steelmaking while HYFOR + Smelter replaces another blast-furnace function and preserves a hot-metal route.	Sites with multiple BFs and staged transformation; central Donawitz scenario.
C. HYFOR-based green-iron production	HYFOR produces DRI/HCI/HBI near ore and renewable-energy resources. Material is transported to a separate Smelter or steelmaking site.	Resource-rich regions and port/mining hubs.
D. Stand-alone Smelter	A Smelter processes DRI/HBI from HYFOR or another reduction route, optionally with scrap and other iron-bearing feeds.	Sites that need HM or gangue removal but do not require a dedicated HYFOR plant.

2.3.1 Configuration A - Integrated steelworks conversion

This configuration represents the most direct application of the Hy4Smelt concept for an existing integrated steelworks that intends to phase out BF-based ironmaking while retaining established downstream production. The conventional ore-to-hot-metal route is replaced by HYFOR and Smelter, while BOF steelmaking, secondary metallurgy, casting, rolling, laboratories and large parts of the existing site infrastructure can remain in operation. This allows the transformation to concentrate on the carbon-intensive primary ironmaking stage without requiring a simultaneous replacement of the complete production chain.

A key advantage is the high raw-material flexibility of the Hy4Smelt route. Similar to the blast furnace, it is intended to accommodate a broad spectrum of iron ore qualities, including fine and lower-grade ores that are less suitable for conventional shaft-furnace direct reduction. This reduces dependence on a narrow supply of high-grade DR pellets and allows existing ore procurement strategies to be adapted rather than fundamentally redesigned. Where sufficient renewable electricity and hydrogen are available, this combination of ore flexibility and low-carbon processing provides a particularly strong basis for meeting future environmental and decarbonisation requirements.

Configuration A is therefore especially attractive for steelworks seeking to modernise the complete ore-to-hot-metal section of their production while preserving valuable downstream assets and operational know-how. The main engineering challenge is matching capacity; industrial HYFOR and Smelter implementations must provide a stable HM supply compatible with converter campaigns and downstream production scheduling. Once this interface is established, the transformation can remain focused on the core ironmaking step while broader downstream changes can be minimised or deferred.

2.3.2 Configuration B - Mixed EAF + Hy4Smelt production

A mixed production configuration is particularly relevant for large steelworks undergoing staged transformation, where EAF-based steelmaking and Hy4Smelt can operate in parallel as complementary production routes. In this configuration, part of the existing production is transferred to an EAF, while HYFOR and the Smelter replace part or all of the remaining blast-

furnace hot-metal function. Depending on the stage of the site transformation, one or more blast furnaces may continue to operate temporarily, but continued BF operation is not a defining requirement of the configuration. The central feature is the coexistence of an EAF route and a Hy4Smelt-based hot-metal route within the same steelworks.

A major advantage of this configuration is the ability to allocate different ore qualities and metallic feeds to the route where they provide the greatest value. Lower- and medium-grade fine ores can be directed toward the HYFOR-Smelter route, while scrap, HBI, DRI and other suitable metallic inputs can be used in the EAF. Where sufficiently high-grade ores are available, HYFOR may also produce DRI or HCI for direct use in the EAF, allowing the reduction and melting stages to be combined according to feedstock availability and production requirements. Where blast-furnace capacity remains during an intermediate transformation stage, suitable raw materials can additionally be allocated to the BF route.

The parallel production routes can also support one another operationally. Hy4Smelt can maintain an ore-based liquid hot-metal supply for BOF steelmaking, while the EAF provides flexibility through the use of scrap and other metallic inputs. This allows the site to respond more effectively to changes in ore quality, scrap availability, hydrogen supply, electricity conditions and product requirements. HYFOR can supply either the Smelter or, when suitable feed is used, an EAF, while the Smelter can process DRI from HYFOR or other reduction routes to produce hot metal.

The resulting configuration provides a flexible pathway for staged decarbonisation without requiring the entire site to rely on a single production route. It is particularly relevant where an EAF is introduced as part of the transformation but there remains value in retaining an ore-based hot-metal route and existing BOF and downstream assets. Donawitz represents the principal project-specific example considered in this deliverable, with the EAF retained while the remaining blast-furnace function is conceptually replaced by HYFOR and the Smelter.

2.3.3 Configuration C - HYFOR-based green-iron production

This configuration is particularly suited to mining regions where iron ore resources can be combined with access to low-cost renewable electricity and sufficient land for large-scale energy infrastructure. In such locations, photovoltaic, wind or hybrid renewable generation can be developed close to the mine and used directly for hydrogen production and ironmaking. This creates the possibility of moving part of the metallurgical value chain upstream, from simple ore extraction and export toward the production of higher-value iron products.

Processing the ore close to its source can provide an important logistical advantage. Instead of transporting the full mass of lower-grade ore over long distances, including gangue that has no value for the steel producer, the ore can be reduced in HYFOR and upgraded into DRI, HCI or HBI before shipment. Where local conditions justify a further processing step, a Smelter could further enable production of HM close to the resource base. In this case, the mining company or local industrial operator can retain a larger share of the product value while reducing the volume of non-valuable material transported through railways, ports and international shipping routes.

The configuration therefore fits companies or regions that aim to establish a more integrated production chain based on their own ore supply and renewable-energy resources. Instead of supplying only ore concentrates or fines, the site can offer a broader portfolio of metallurgical products with different transport and customer requirements. **Australia** is a strong example of

this concept, as major iron-ore resources, large areas suitable for solar and wind generation and established export infrastructure are located within the same national market [17,18] . The same principle could apply wherever ore availability, renewable-energy potential and sufficient industrial land can be combined to create a **mine-linked green-iron production hub**.

2.3.4 Configuration D - Stand-alone Smelter deployment

The stand-alone Smelter configuration is relevant for producers that already have an established iron-ore beneficiation or direct-reduction route, or that can source DRI, HBI or comparable reduced iron products from external suppliers. In this specific case, HYFOR is not required and the replication opportunity is centred entirely on the Smelter and the downstream production options enabled by it. This considerably broadens the potential market beyond sites considering the complete Hy4Smelt process chain. The project itself foresees flexibility in Smelter feeding, including HBI, scrap and other iron-bearing materials in addition to HYFOR-derived HDRI.

The main benefit is the ability to convert a comparatively wide range of metallic feeds into a controlled liquid hot-metal product. This can be attractive where DRI is available, but direct EAF processing is limited by gangue content, product requirements or the desired downstream route. The Smelter can complete the final reduction, separate gangue into a dedicated slag phase and provide carburised HM suitable for further processing in an existing BOF route. At the same time, additional metallic inputs such as scrap, HBI and potentially qualified iron-rich residues can be incorporated, giving the furnace a broader recycling and feed-balancing function than a process designed around a single metallic input. The Hy4Smelt project specifically includes the investigation of scrap, HBI and iron-rich residues as potential feed streams or future extensions of the process concept.

This configuration is therefore particularly suitable for steelworks that already have access to reduced iron but require a flexible melting aggregate, wish to retain a liquid hot-metal route, or want to increase the share of recyclable ferrous materials within their production system. It can also serve as an interface between different reduction technologies and conventional downstream steelmaking, allowing the site to change or diversify its upstream iron supply without necessarily redesigning the complete steelmaking chain. Duisburg provides a strong external benchmark for this general industrial logic, where direct reduction is combined with electric melting before conventional downstream steelmaking.

3. European Market and Replication Potential

3.1 European primary steelmaking base

EU crude steel production reached 125.8 Mt in 2025. Basic-oxygen and related production accounted for 68.239 Mt, or 54.2%, while EAF production accounted for 57.552 Mt, or 45.8% [3] . The basic-oxygen share does not translate directly into a Hy4Smelt market because some capacity may close, some sites will select EAF-only routes, and others will adopt shaft-furnace DRI, imported HBI, carbon capture or different combinations. It nevertheless defines the scale of the European ore-based production system that must be transformed over the coming decades.

The project proposal contains an indicative scenario in which Hy4Smelt could replace 25 Mt/a of European hot-metal production by 2050, corresponding to approximately 9-17 blast

furnaces depending on furnace size. D5.6 further translates the assumed global fluidised-bed DR market into approximately 25-50 full-scale HYFOR installations globally, including up to 25 in Europe, and uses an indicative Smelter capacity of around 1.2 Mt/a for market-scaling purposes. These values should be treated as scenario assumptions used to describe scale, not forecasts of secured market share.

Table 5 Indicative commercial-scale assumptions used for replication screening

Parameter	Indicative value
HYFOR commercial capacity	~1-2 Mt/a DRI per plant; modules ~0.5-1.0 Mt/a
Smelter commercial capacity	~1.2 Mt/a HM
Iron ore fines	1.6 t/t HM
Hydrogen	60 kg/t HM
Process electricity	2.5 MWh/t HM
Green/secondary carbon	100 kg/t HM

The strongest European replication cases are not necessarily the largest steelworks. The fit is determined by the interaction of plant architecture and local constraints. A high-potential site would typically have one or more blast furnaces approaching a major replacement decision, a reason to retain BOF or other downstream assets, access to ore fines for which HYFOR creates a feedstock advantage, a credible route to several hundred megawatts of low-emission electricity and large-scale hydrogen, and established bulk-material logistics. Coastal sites gain advantages in imported ore, HBI and future hydrogen/ammonia infrastructure; inland sites can remain attractive where downstream asset reuse and ore flexibility compensate for logistics constraints.

Transformation timing is particularly important. Many European producers have already committed to EAF or DRI-EAF investments [19,20] . Such sites remain valuable benchmarks because they demonstrate the technical functions that Hy4Smelt would have to replace or complement, but they are not automatically near-term commercial opportunities. Sites where later transformation stages remain open may offer more flexibility, but the lack of a committed route can also reflect difficult economic factors such as grid constraints or uncertain hydrogen availability. Therefore, separating technical compatibility from market timing is crucial.

3.2 Representative European Replication Cases

This chapter applies the screening framework to representative European sites using public information available in September 2026. The cases are hypothetical transferability examples. They do not indicate commercial discussions, endorsement or technology selection by the companies concerned. The announced company pathways are presented first; the Hy4Smelt scenario is then described explicitly as an alternative or complementary project case.

Table 6 Summary of representative European replication cases

Site	Public transition context	Potential Hy4Smelt role	Screening relevance
Donawitz, Austria [21]	EAF start 2027; one BF can close by 2029; EAF expansion could enable	Mixed EAF + HYFOR-Smelter replacing the remaining BF function while retaining a BOF hot-metal route.	Very high as worked project case

	full electrification from 2030.		
Duisburg, Germany [21]	2.5 Mt/a DR plant + two melters -> ~2.3 Mt/a HM; downstream steelmaking retained.	Benchmark or later-stage alternative in which HYFOR provides flexible fine-ore reduction upstream of electric melting.	Very high technical benchmark
Dunkirk, France [22]	2.0 Mt/a EAF planned for 2029; smaller BF to be idled after EAF ramp-up; larger BF remains.	Future replacement of remaining BF function with HYFOR-Smelter, potentially supporting BOF and/or EAF metallic mix.	High
IJmuiden, Netherlands [23]	Phase 1 DRP-EAF replaces BF7 and coke/gas plant 2; Phase 2 closes remaining BF.	Alternative for the later remaining ore-based line, particularly if retaining liquid-metal/downstream assets creates value.	High
Salzgitter, Germany [8]	SALCOS stage 1 builds DR + EAF and replaces one BF and one converter; later stages delayed to 2028/29 decisions.	Benchmark for later-stage replacement; Hy4Smelt could be compared with additional DRI-EAF capacity where ore flexibility is valuable.	Medium-high

Assessment reflects compatibility with the Hy4Smelt architecture using public information, not investment attractiveness or company interest.

The screening indicates that Hy4Smelt is most relevant at sites where the transformation of primary ironmaking is still ongoing and where substantial downstream assets can continue to be used. The most promising candidates are therefore not simply the largest blast-furnace sites, but those where the ore-to-hot-metal section can be replaced while BOF steelmaking, casting, rolling and other established production infrastructure remain in service.

Donawitz is particularly well suited as the principal worked case because its staged transition allows a realistic assessment of a mixed production route. **Duisburg** provides a strong technical benchmark for the broader concept of combining direct reduction with electric melting while retaining downstream steelmaking. **Dunkirk and IJmuiden** represent further large integrated sites where remaining blast-furnace capacity could, in principle, be replaced by Hy4Smelt during later transformation stages. **Salzgitter** is less directly aligned with the Hy4Smelt concept because its transition is centred on DR-EAF production, but it remains a useful comparison case for evaluating where Hy4Smelt could provide additional value through greater ore flexibility and the continued availability of a hot-metal route.

Overall, the European screening suggests that the strongest replication potential exists at sites combining four conditions: remaining BF-BOF infrastructure, valuable downstream assets with continued service life, access to hydrogen and low-carbon electricity, and a strategic need to maintain flexibility in ore quality and metallic inputs

3.2.1 Donawitz, Austria

Donawitz is particularly relevant as a Hy4Smelt replication case because few European steelmaking sites combine such a strong history in primary steelmaking innovation with direct experience in hydrogen-based iron reduction and an ongoing transformation of the industrial production route. More importantly for the present assessment, Donawitz became one of the

birthplaces of modern oxygen steelmaking: the second industrial BOF steelworks in the world entered operation, and the site played an important role in bringing the Linz-Donawitz process to industrial maturity. The BOF process subsequently became one of the dominant steelmaking technologies worldwide [24,25] .

This history remains directly visible in the current production structure. Donawitz continues to operate an integrated ore-to-steel route in which blast-furnace HM is refined in BOF converters and subsequently processed through secondary metallurgy, continuous casting and specialised downstream facilities. The importance of these downstream assets is particularly high because the site is focused on demanding long-product applications rather than commodity steel alone. This makes the question of how primary ironmaking is transformed without compromising established metallurgical and product capabilities especially relevant.

Donawitz is also considerably further advanced in hydrogen-based ironmaking experience than a typical potential replication site. The HYFOR pilot plant was operated directly at Donawitz, and the site subsequently demonstrated that hydrogen-reduced iron can be incorporated into demanding downstream products. In 2024, hydrogen-reduced material from HYFOR was melted together with scrap in the site's Technikum Metallurgie research steelworks and processed into high-quality wire rod for roller-bearing steel [26]. In 2025, the same development chain was extended to the production of what voestalpine reported as the world's first hydrogen-based rail, again using HYFOR material produced at Donawitz and subsequently processing the steel in the neighbouring rail rolling mill [27]. These demonstrations are particularly relevant because they connect hydrogen reduction not only with iron production, but with finished premium products manufactured through the existing Donawitz value chain.

At the same time, Donawitz is already undergoing a major industrial transformation. Construction of the new EAF production route is well advanced, and the latest site update from August 2026 reports that the two EAF units, EAF 1 and EAF 2, are already taking physical shape [28] . The first stage is scheduled to enter operation in 2027 with approximately 850,000 t/a of CO_2-reduced steel capacity [29] . voestalpine announced in June 2026 that one blast furnace could be shut down by 2029 and that, subject to the remaining funding conditions, approximately EUR 100 million of further investment could expand the EAF route to as much as 1.5 Mt/a by 2030. This would permit complete electrification of Donawitz steel production and a reduction of more than 90% in site CO_2 emissions compared with 2019.

The Hy4Smelt scenario considered in D5.1 is therefore **not the currently announced voestalpine investment pathway**, but an alternative replication scenario that uses Donawitz to examine a different long-term configuration. Instead of ultimately replacing the complete remaining blast-furnace route with additional EAF capacity, one option would be to retain the new EAF while replacing the remaining blast-furnace function with HYFOR and a Smelter. Hot metal from the Smelter could continue to supply the existing BOF route, while the EAF would provide a complementary steelmaking route based on scrap, HBI/DRI and other suitable metallic inputs.

Donawitz is especially suitable for examining such a configuration because the individual elements are already represented at the site in different stages of development. It has experience with HYFOR, existing BOF steelmaking and premium downstream production, active EAF construction, and demonstrated processing of hydrogen-reduced iron into both wire rod and rail. The replication question is therefore less hypothetical than at an unrelated steelworks: it concerns how technologies and capabilities already demonstrated individually

at Donawitz could potentially be combined at industrial scale into a flexible low-carbon production system.

From a future-replication perspective, this could provide an alternative to a complete dependence on scrap- and externally supplied HBI-based electric steelmaking. HYFOR would preserve an internal ore-based metallic route and, together with the Smelter, could extend this route to ore qualities that are difficult to use directly in conventional shaft-furnace DRI production. The EAF and Hy4Smelt routes could then complement each other according to metallic availability, energy conditions, production requirements and product scheduling. This combination is particularly relevant at Donawitz because the site's recent history already shows a repeated pattern of introducing new metallurgical technology while retaining and adapting high-value downstream production.

3.2.2 Duisburg, Germany

The Duisburg site is one of the most relevant European reference cases for Hy4Smelt because thyssenkrupp Steel is pursuing a transformation concept that is similar in overall architecture but significantly different in the reduction step. The site has a long history in integrated steelmaking and retains extensive downstream facilities for oxygen steelmaking, casting and further processing. Its transformation therefore focuses on replacing conventional blast-furnace ironmaking while preserving a large part of the existing production chain [30] .

The tkH_2Steel project combines a hydrogen-capable shaft-furnace direct-reduction plant with two electrically operated melters. The planned system has a capacity of approximately 2.5 Mt/a DRI and around 2.3 Mt/a HM, which is then transferred to the existing downstream steelmaking units. In this respect, the Duisburg configuration follows the same general principle as Hy4Smelt: iron ore is reduced without a blast furnace, the reduced material is subsequently melted in an electric furnace, and liquid HM is produced for conventional downstream steelmaking [31] .

The principal difference lies in the upstream reduction technology and, consequently, in the raw-material requirements. The Duisburg route is based on conventional shaft-furnace direct reduction, which generally requires mechanically stable pellets or suitable lump ore and therefore places comparatively strict requirements on feed quality and particle size. HYFOR instead uses fluidised-bed reduction and is specifically designed for non-agglomerated fine and ultra-fine ores, including lower- and medium-grade materials. This avoids the need for pelletising and potentially expands the range of ores that can be used in hydrogen-based ironmaking.

This distinction is particularly important for large integrated sites such as Duisburg, where future competitiveness will depend not only on hydrogen availability but also on access to suitable iron-bearing feedstocks. The recent expansion of thyssenkrupp Steel's ore-testing capabilities illustrates the increasing importance of feed qualification as the company moves toward direct reduction. A HYFOR-based route could provide additional flexibility by opening access to ore fines and qualities that are less suitable for shaft-furnace operation, while the downstream Smelter would continue to remove gangue and produce a controlled hot-metal product.

The two approaches should therefore be viewed as related but not interchangeable. tkH_2Steel demonstrates the industrial viability of the broader DR–electric melting–BOF architecture, while Hy4Smelt addresses a different raw-material window within the same general

transformation logic. For Duisburg, the potential value of Hy4Smelt would lie primarily in complementing or extending the future reduction portfolio where greater ore flexibility, avoidance of pelletising or the direct use of fine ores provides a technical or economic advantage.

3.2.3 Dunkirk, France

ArcelorMittal Dunkirk is a particularly relevant European replication case because the site is already moving toward a mixed production structure rather than replacing all primary ironmaking with a single route. The site is one of ArcelorMittal's major European flat-steel production locations, with extensive downstream assets and strong coastal raw-material logistics. Its location also gives it access to imported ore, HBI/DRI and other metallic feeds, which is important for future flexibility [32,33].

ArcelorMittal confirmed a EUR 1.3 billion investment in a 2.0 Mt/a EAF, with first heat planned for 2029 and ramp-up to full production from 2030. The planned configuration retains the larger blast furnace, with around 3.5 Mt nameplate capacity, while the new EAF is expected to operate with approximately 60% recycled scrap, 20% DRI/HBI and 20% HM [7,34] . The smaller blast furnace is intended to be permanently idled once the EAF reaches stable operation.

This transition makes Dunkirk especially interesting for Hy4Smelt because the future site will already depend on several complementary metallic streams. Hy4Smelt could provide a later route for replacing the remaining blast-furnace hot-metal function while preserving the advantages of a liquid-metal supply. HYFOR could process suitable fine ores, while the Smelter would produce HM that could support the existing converter route and, depending on the final plant configuration, also contribute to the EAF metallic mix. This would reduce reliance on coke-based ironmaking without forcing the site to abandon the flexibility created by its mixed production system.

The distinction from the announced Dunkirk pathway is important. The current plan combines EAF production with HM from a remaining blast furnace and externally sourced DRI/HBI [7] . A Hy4Smelt configuration could instead introduce an internal hydrogen-based ore route, providing greater control over metallic supply and potentially allowing a wider range of ore qualities to be used. This would be particularly valuable if future competition for high-grade DR pellets and HBI increases, as HYFOR is designed to work with non-agglomerated fines and a broader ore-quality range than conventional shaft-furnace DR.

Dunkirk also has favourable enabling conditions for such a future route. Its coastal location supports large-scale ore and metallic imports, while ArcelorMittal has secured a long-term low-carbon electricity supply agreement with EDF for its French operations. The 18-year nuclear power allocation contract began supplying electricity in 2026 and directly improves the conditions for electrified steelmaking at sites such as Dunkirk.

The principal challenge is scale. Replacing the remaining 3.5 Mt/a blast-furnace function would require several commercial HYFOR and Smelter modules, or larger modules than the indicative capacities currently used in the Hy4Smelt scaling assumptions. Dunkirk is therefore less a simple equipment-replacement case than a strong example of how Hy4Smelt could be integrated into a large, staged transformation where EAF, hot-metal and externally sourced metallic routes already coexist.

3.2.4 IJmuiden, Netherlands

Tata Steel IJmuiden is a major integrated flat-steel site with more than a century of steelmaking history and an annual steel production of around 7 Mt. The approximately 750-hectare site is located directly on the North Sea and contains the complete production chain from raw-material handling and primary ironmaking through oxygen steelmaking, casting and rolling [35,36] . Its coastal location is particularly relevant for replication, as large ocean-going vessels can deliver iron ore and other raw materials directly to the works, while extensive internal rail, conveyor and utility networks support the movement of large material flows across the site [37] .

The Green Steel Project foresees a phased replacement of coal-based production. In Phase 1, a Direct Reduction Plant (DRP) and Electric Arc Furnace (EAF) are planned to replace Blast Furnace 7 and Coke and Gas Plant 2. The DRP is initially intended to operate predominantly on natural gas, with increasing use of biomethane and/or hydrogen as these energy carriers become sufficiently available and economically competitive. Carbon capture and storage is also foreseen as an intermediate measure for part of the remaining CO_2 emissions associated with the DRP. In Phase 2, the remaining Blast Furnace 6 and Coke and Gas Plant 1 are to be replaced, completing the transition away from coal-based primary ironmaking. Tata Steel currently envisages completion of this transition through the DRI-EAF route, although the detailed configuration and technologies required for Phase 2 remain under development and subject to further technical assessment [38,39] .

IJmuiden therefore differs significantly from the Duisburg case. Duisburg is designed to retain a hot-metal route by placing electrically powered melters downstream of direct reduction, enabling liquid HM to continue feeding the existing oxygen steelworks. IJmuiden's current Phase 1 instead combines direct reduction with EAF steelmaking. For the purposes of a Hy4Smelt replication assessment, an alternative future configuration can therefore be considered in which HYFOR and the Smelter replace part of the remaining blast-furnace function and maintain an ore-based liquid-hot-metal stream for oxygen steelmaking. Such a configuration is not part of Tata Steel's currently announced Green Steel Project but represents a technically relevant alternative for comparison with the planned DRI-EAF route.

The site provides several conditions that make such a comparison relevant. IJmuiden currently processes more than 8 Mt/a of iron ore and has direct deep-sea access, giving it considerable flexibility in raw-material sourcing [40,41]. HYFOR could further extend this flexibility by allowing qualified fine ores and concentrates to enter hydrogen-based reduction without first requiring conventional sintering or pelletising. The downstream Smelter would provide final reduction and melting, separate gangue into a slag phase and produce liquid HM suitable for subsequent refining [42] . This could provide an alternative means of decarbonising part of the remaining ore-based production while retaining existing oxygen-steelmaking infrastructure.

The ongoing transition also places increasing emphasis on scrap utilisation [43]. Tata Steel plans to increase the share of scrap from approximately 17% to around 30% from 2030 onwards. A Hy4Smelt configuration could complement rather than compete with this development. The EAF route could accommodate increasing quantities of scrap together with suitable DRI or HBI feeds, while a HYFOR-Smelter line could maintain a flexible primary-iron route based on ore fines and concentrates. Such a configuration could provide greater flexibility in balancing primary and secondary metallic inputs according to ore availability, scrap quality, product requirements and energy conditions.

IJmuiden is therefore a strong replication case for assessing the potential value of maintaining a hydrogen-based hot-metal route within a large coastal steelworks. Its relevance is particularly high for the later transformation stage, where the remaining blast-furnace capacity must ultimately be replaced and the detailed Phase 2 configuration is still under development. The principal question for the Hy4Smelt replication assessment is whether greater ore-feed flexibility, favourable raw-material logistics and continued use of liquid-metal steelmaking assets could provide sufficient technical and economic value to justify a HYFOR-Smelter route alongside, or as an alternative to part of, the site's developing DRI-EAF configuration.

3.2.5 Salzgitter, Germany

The Salzgitter site is a long-established integrated steelworks and one of Germany's major flat-steel production locations [44]. Its relevance for Hy4Smelt lies in the fact that the site is already implementing one of Europe's most advanced hydrogen-capable transformation programmes. SALCOS – Salzgitter Low CO_2 Steelmaking – progressively replaces the conventional blast-furnace and converter route with direct reduction and electric steelmaking, providing a useful comparison with an alternative Hy4Smelt-based transformation [45,46].

The first SALCOS stage comprises a direct-reduction plant, an EAF and a 100 MW electrolyser [47]. Together, the new facilities are designed to produce around 2 Mt/a of low-carbon crude steel and replace one blast furnace and one converter. The direct-reduction plant uses ENERGIRON ZR technology and has a capacity of more than 2 Mt/a DRI. Reduced pellets can be transferred hot to the neighbouring EAF through the Hytemp pneumatic transport system, improving the energy efficiency of the integrated DR–EAF route. First steel from the new route is now expected from summer 2027.

The Salzgitter configuration differs fundamentally from Hy4Smelt in both the reduction and steelmaking stages. SALCOS is based on shaft-furnace direct reduction using suitable pelletised feed, followed directly by EAF steelmaking. Hy4Smelt instead combines fluidised-bed HYFOR reduction of non-agglomerated fine ores with a Smelter that produces liquid HM. This creates a different raw-material and downstream pathway: HYFOR potentially provides access to a broader range of ore fines and avoids pelletising, while the Smelter enables continued use of a liquid hot-metal route and existing converter-based steelmaking.

Raw-material flexibility is therefore one of the principal areas in which Hy4Smelt could provide additional value. SALCOS places significant importance on securing suitable DRI feed, whereas HYFOR is specifically intended to reduce fine and potentially lower-grade ores that are less suitable for conventional shaft-furnace operation. At a later transformation stage, a HYFOR–Smelter route could therefore be evaluated against further DR–EAF expansion where access to suitable pellets, ore preparation requirements or the value of maintaining part of the existing converter route become important considerations.

Salzgitter also demonstrates the scale of the hydrogen infrastructure required for large-scale hydrogen-based ironmaking. The on-site 100 MW electrolyser is expected to produce around 9,000 t/a of green hydrogen, while the first SALCOS stage can ultimately utilise up to approximately 150,000 t/a [48,49]. The remaining requirement therefore depends on external hydrogen supply and connection to the future German hydrogen network. This provides an important replication lesson for Hy4Smelt: large-scale deployment depends not only on the reduction technology itself but on the ability to secure hydrogen and electricity at industrial scale and competitive cost.

The first SALCOS stage is already committed, while investment decisions for the subsequent transformation stages have been postponed to 2028/29 following changes in the economic, political and regulatory environment. Salzgitter is therefore best treated as a comparative replication case rather than as an alternative to the facilities currently under construction. Its value for D5.1 lies in comparing two distinct hydrogen-based transformation strategies: a pellet-based DR–EAF route that progressively replaces both blast furnaces and converters, and a HYFOR–Smelter route that could offer greater ore flexibility while retaining a hot-metal and converter-based production option [50].

3.3 Additional European screening cases

3.3.1 Bremen and Eisenhüttenstadt, Germany

ArcelorMittal Bremen and Eisenhüttenstadt are both integrated flat-steel sites with existing blast-furnace production and substantial downstream assets. Bremen is the larger site, with two blast furnaces and crude-steel capacity of up to about 3.6 Mt/a, while Eisenhüttenstadt produces around 2 Mt/a and serves as an important production location for Central and Eastern European markets [51,52].

The original transformation concept linked both sites through a common DRI strategy. A roughly 2 Mt/a DRI plant in Bremen was intended to supply EAF production at both Bremen and Eisenhüttenstadt, with natural gas used initially and hydrogen introduced as regional infrastructure developed. In June 2025, ArcelorMittal cancelled the planned DRI-EAF investments because the required hydrogen, energy and market conditions were not sufficiently competitive. Detailed EAF planning nevertheless continues so that projects can proceed if conditions improve.

Both sites remain technically relevant for Hy4Smelt screening. Bremen is particularly attractive because its coastal logistics, existing ore handling and multi-BF structure could support a future HYFOR-Smelter route alongside EAF production. Eisenhüttenstadt offers a smaller integrated-site case where retaining an ore-based hot-metal route could provide additional flexibility during a staged transformation. In both cases, HYFOR could reduce dependence on DR-grade pellets by processing suitable fine ores, while the Smelter could preserve liquid-metal production for existing downstream facilities.

The principal limitation is not the process configuration but the same energy-system challenge that affected the original DRI projects. Competitive hydrogen and low-carbon electricity remain prerequisites for either conventional DRI or Hy4Smelt. These sites therefore illustrate both the technical replication potential of Hy4Smelt and the importance of regional energy conditions in determining whether such a route can be implemented commercially.

3.3.2 Fos-sur-Mer, France

ArcelorMittal Fos-sur-Mer is a large integrated coastal steelworks with about 4 Mt/a production capacity and direct access to port-based ore and metallic-feed logistics. The site currently operates two blast furnaces and is studying an EAF intended to replace one BF using scrap and direct-reduced iron [53–55] .

This makes Fos-sur-Mer suitable for a mixed-route Hy4Smelt scenario. HYFOR and the Smelter could later replace the remaining blast-furnace function, maintaining an ore-based hot-metal route alongside EAF production. HYFOR would broaden feed flexibility toward non-

agglomerated fines and ore qualities less suited to conventional shaft-furnace DR, while the Smelter could supply HM to converter steelmaking or contribute metallic input to the EAF.

The site is further supported by emerging low-carbon hydrogen infrastructure in the Fos industrial area. Its main replication value therefore lies in combining coastal raw-material access, staged BF replacement, EAF integration and the potential retention of a flexible hot-metal route.

3.3.3 Raahe, Finland

SSAB Raahe is a large integrated steelworks with approximately 2.6 Mt/a crude-steel capacity, currently based on blast-furnace production. The site is planned as the final stage of SSAB's Nordic transformation, with the blast furnaces and coking plant replaced by EAF-based production [56,57] . SSAB has stated that the timing will depend on financing, raw-material availability, market conditions and lessons from the earlier Oxelösund and Luleå projects.

Raahe is technically relevant for Hy4Smelt because it retains a large ore-based production base, extensive site infrastructure and its own harbour. A HYFOR-Smelter route could provide an alternative to full EAF conversion where maintaining primary ore-based production and greater flexibility in iron-ore quality creates value. HYFOR could process suitable fine ores without pelletising, while the Smelter could maintain a liquid hot-metal route for downstream processing.

The specific advantage of Hy4Smelt may, however, be lower than at some Central European sites because SSAB is developing a wider Nordic metallic-supply system based on scrap and fossil-free iron products. Raahe is therefore most useful as a benchmark for comparing full EAF transformation with a more flexible HYFOR-Smelter route, particularly if future raw-material availability or product requirements favour continued ore-based hot-metal production.

Table 7 Comparative assessment of representative European cases

Site	Hy4Smelt configuration	Why Hy4Smelt fits	Main constraint / open point
Donawitz	**B – Mixed EAF + Hy4Smelt**	Direct HYFOR history; existing BOF route and premium downstream assets; Hy4Smelt could retain an internal ore-based hot-metal route alongside the new EAF.	Industrial H_2 supply and economics of retaining the BOF/hot-metal route must be demonstrated.
Duisburg	**A – Integrated conversion**	Existing DR + electric-melting concept already retains downstream steelmaking. HYFOR could extend the feed range from pellets toward non-agglomerated fines and wider ore qualities.	First tkH_2Steel route is already committed; large H_2 demand remains a major system requirement.
Dunkirk	**B – Mixed EAF + Hy4Smelt**	Planned EAF will coexist with a large remaining BF. HYFOR-Smelter could later replace this BF while retaining hot-metal production and broadening ore flexibility.	Large replacement capacity and future H_2 supply.

IJmuiden	**A/B – Integrated or mixed route**	Strong coastal ore logistics and extensive downstream assets. Hy4Smelt could provide an alternative to complete DRI-EAF conversion for the remaining ore-based production line.	Phase 1 is already centred on DRP-EAF; value of retaining a liquid-metal route must be demonstrated.
Salzgitter	**A – Alternative integrated route**	HYFOR could offer greater ore flexibility and avoid pelletising compared with the pellet-based SALCOS DR route.	SALCOS is already strongly committed to DR-EAF and progressively removes converter capacity.
Bremen	**A/B – Integrated or mixed route**	Multi-BF site with coastal raw-material access and substantial downstream assets; suitable for fine-ore HYFOR integration.	Previous DRI project was stopped because of energy, H_2 and economic conditions.
Fos-sur-Mer	**B – Mixed EAF + Hy4Smelt**	Planned EAF plus continuing BF production creates a later replacement opportunity; port access supports flexible ore sourcing.	EAF investment remains under development and regional H_2 capacity is still limited.
Raahe	**A – Alternative integrated route**	Existing integrated infrastructure could support HYFOR-Smelter in place of BF production.	Access to Nordic fossil-free metallics reduces the specific value of Hy4Smelt ore flexibility.

Assessment reflects compatibility with the Hy4Smelt architecture using public information, not investment attractiveness or company interest.

The comparison demonstrates that the best European replication logic is not simply the replacement of any blast furnace. Hy4Smelt is strongest where the site still values a hot-metal/BOF route and where ore flexibility creates a supply-chain advantage [58]. Donawitz is the clearest project-specific worked example; Duisburg validates the direct-reduction-plus-melting architecture at large scale; Dunkirk shows a future mixed EAF and hot-metal configuration; and IJmuiden demonstrates the scale and infrastructure requirements of a coastal transition. Salzgitter, Bremen, Fos-sur-Mer and Raahe broaden the screening range and show how investment commitment, energy conditions and alternative metallic supply can change the relative value of Hy4Smelt.

4. Selected International Replication Cases

International replication of Hy4Smelt is shaped by different conditions than the European cases. Outside Europe, the strongest opportunities are often found where large iron-ore resources coincide with renewable-energy potential, available industrial land and established export infrastructure. Deployment can therefore be designed around favourable combinations of ore supply, hydrogen production, electricity cost and product logistics rather than the preservation of existing downstream steelmaking assets. This allows a broader range of configurations. HYFOR may be located near mining operations to convert fine ores into DRI, HCI or HBI for export, while a complete HYFOR-Smelter route can produce HM or other higher-value iron products near the resource base. Stand-alone Smelter applications are also relevant where DRI or HBI is already available. These cases show how Hy4Smelt can support both steelworks transformation and the development of green-iron hubs and integrated mine-to-metal value chains.

Table 8 Selected international replication scenarios

Region	Principal deployment model	Hy4Smelt rationale	Main constraints
Australia - Western Australia / Whyalla [59]	Mine-linked HYFOR-HBI or integrated green-iron hub; possible integrated-site application at Whyalla.	Very large fine-ore resource base; strong wind/solar potential; established rail and port logistics; Rio Tinto is a formal Hy4Smelt value-chain partner and supplies most demonstration ore.	Large hydrogen and grid build-out; water; product transport; commercial scale-up and product qualification.
Brazil - Minas Gerais / Espirito Santo / coastal hubs [60]	Mine-linked HYFOR, coastal green-iron hub or Smelter integrated with steelmaking.	Major ore industry and high renewable share in electricity; opportunity to add value to fines before export and link qualified slag to cement markets.	Firm low-cost power, transmission, hydrogen scale-up, permitting and mine-port-energy integration.
India - Odisha / Chhattisgarh / coastal clusters [61]	Integrated HYFOR-Smelter route or stand-alone Smelter complementing domestic DRI.	Large and growing steel market; abundant ore fines; extensive BF-BOF and DRI capacity; growing renewable and hydrogen policy support.	Carbon-intensive power in many regions; water, land, grid reinforcement, hydrogen cost and financing.
Selected Southeast Asia [62,63]	Port-based Smelter or integrated plant supplied with imported HYFOR DRI/HBI or other DRI.	Fast-growing steel demand and strong port infrastructure can support imported metallics while local clean-power systems develop.	Coal-heavy grids in several markets, limited local DR-grade ore, imported feed security, hydrogen infrastructure and carbon-accounting rules.

4.1 Australia

Australia represents one of the strongest international replication opportunities for Hy4Smelt because its iron-ore industry combines very large export volumes with a raw-material challenge that is directly relevant to hydrogen-based ironmaking [64]. Much of the mainstream Pilbara production consists of medium-grade fines that cannot simply be transferred into conventional shaft-furnace DR systems, which normally require mechanically stable pellets or suitable lump ore. Recent Rio Tinto and China Baowu trials have demonstrated that Pilbara Blend can be used in hydrogen-based shaft-furnace reduction, but only after pelletisation and appropriate feed preparation. HYFOR offers a different pathway by directly reducing qualified non-agglomerated fines, while the downstream Smelter can remove gangue and produce a controlled liquid iron product.

Western Australia is therefore particularly relevant for **Configuration C – HYFOR-based green-iron production**. The Pilbara already contains an exceptional mine-to-port system, including large-scale mines, almost 2,000 km of Rio Tinto rail infrastructure and several dedicated export terminals. Rather than exporting ore fines for beneficiation, agglomeration and reduction elsewhere, HYFOR could move part of the metallurgical value chain closer to the resource base. Depending on ore quality and customer requirements, the product could be exported as DRI/HCI/HBI or processed further through a Smelter to produce a higher-value iron product.

The potential advantage extends beyond avoiding pelletisation. Processing ore before long-distance transport removes part of the gangue at the production location and allows a greater share of the exported mass to consist of metallic iron. A mine-linked HYFOR-Smelter hub could therefore combine ore preparation, hydrogen reduction, gangue separation and metallic-product production within one industrial system. Australia's extensive solar and wind resources provide a strong long-term basis for such a concept, although commercial deployment would require very large additions of renewable generation, hydrogen production, water supply, transmission and associated infrastructure.

Rio Tinto's participation in the Hy4Smelt value chain makes Australia particularly relevant to the project rather than merely a theoretical resource-market example. Australian ores form an important part of the Hy4Smelt raw-material qualification work, allowing the technology to be evaluated against the ore types for which alternative hydrogen-based processing routes are actively being investigated. The scale of the potential application is also substantial: Rio Tinto's Pilbara system alone operates at several hundred million tonnes per year and is supported by established global export logistics.

Whyalla provides a different Australian application case. Unlike the mine-linked Western Australian concept, Whyalla combines local iron-ore resources, an operating integrated steelworks and port infrastructure [65] . Current government-supported transformation planning links the future steelworks with expansion of the nearby magnetite resource, with the first mining stage targeting up to approximately 2.5 Mt/a of magnetite production. The site is therefore relevant to an integrated HYFOR-Smelter scenario in which locally produced ore could be converted into low-carbon metallics and subsequently processed within the existing steelmaking value chain.

Australia consequently demonstrates two distinct Hy4Smelt replication pathways. **Western Australia represents the stronger mine-linked case**, where HYFOR can support the conversion of export fines into higher-value DRI/HBI or smelted iron products close to the ore

and renewable-energy resource. **Whyalla represents the integrated-site case**, where local ore, ironmaking and downstream steel production can potentially be combined within one low-carbon production chain. In both cases, the principal replication question is less the availability of iron ore than whether sufficiently large and competitive renewable-power and hydrogen systems can be developed around the metallurgical operation.

4.2 Brazil

Brazil is a strong international replication case because very large iron-ore production is combined with an unusually low-carbon electricity system and established mine-to-port infrastructure. Vale alone produced approximately 336 Mt of iron ore in 2025, while renewable sources accounted for 86.8% of Brazilian electricity generation [66,67]. These conditions create a credible basis for moving part of the metallurgical value chain closer to the ore resource rather than exporting predominantly untreated or agglomerated iron-bearing material.

The strongest Hy4Smelt application is **Configuration C – HYFOR-based green-iron production**, particularly along the Minas Gerais–Espírito Santo industrial corridor. Vale's Southeastern System already links the major mining complexes of Mariana, Itabira and Minas Centrais to the Vitória–Minas railway and the Port of Tubarão. This existing logistics chain could support a mine-linked or coastal configuration in which suitable ore fines are transported to a HYFOR facility, reduced with hydrogen and exported as DRI/HCI/HBI, or processed further in a Smelter before shipment.

The Brazilian case is especially interesting because an alternative low-carbon feed strategy is already developing around **agglomeration** [68]. Vale operates two iron-ore briquette plants at Tubarão with a combined nominal capacity of approximately 6 Mt/a and is promoting pellets and briquettes as feed for future direct-reduction plants. HYFOR would address the same objective from a different direction: qualified fine ores could be reduced without first being pelletised or briquetted, while the Smelter would subsequently separate gangue and produce a controlled metallic product. The replication value therefore depends on whether avoiding agglomeration and accepting a wider feed window provides sufficient technical and economic benefit for specific Brazilian ore streams.

Brazil is also already being considered for **green-HBI hubs**. Vale and Green Energy Park are studying a renewable-hydrogen facility intended to supply a future Brazilian Mega Hub producing low-carbon HBI, with European markets identified as potential customers. The project has received EU Global Gateway flagship status. This provides a relevant industrial benchmark for Hy4Smelt: both concepts seek to combine Brazilian ore and renewable energy to export a higher-value metallic product, but the proposed Vale route is currently based on agglomerated feed and conventional direct reduction, whereas HYFOR could create an alternative route based directly on qualified fines.

A second replication pathway is the integration of a **Smelter with existing Brazilian steelmaking**. Brazil retains substantial BF-BOF capacity, including major coastal integrated works such as ArcelorMittal Tubarão in Espírito Santo. In such cases, HYFOR-Smelter could ultimately replace part of conventional ore-to-hot-metal production while retaining downstream steelmaking, or a stand-alone Smelter could process DRI/HBI from other reduction routes. This gives Brazil potential for both new resource-based green-iron hubs and transformation of established steel production sites.

The main constraints are therefore infrastructure rather than ore availability. Industrial Hy4Smelt deployment would require firm low-carbon electricity at metallurgical scale, competitive hydrogen production, transmission between renewable-generation areas and ironmaking hubs, sufficient water and reliable logistics between mines, reduction facilities and ports. Where the complete HYFOR-Smelter route is used, viable outlets for the resulting slag must also be established. Brazil nevertheless provides a particularly strong case for evaluating whether fine-ore hydrogen reduction can shift the country from predominantly exporting iron ore toward exporting a larger share of higher-value low-carbon metallic products.

4.3 India

India differs from Australia and Brazil because the principal replication driver is not export-oriented green-iron production, but the combination of very large domestic steel demand, abundant iron-ore fines and an already extensive ironmaking base. India is the world's second-largest crude-steel producer, with installed steelmaking capacity of around 200 Mt/a, while sponge-iron production reached approximately 60.3 Mt in 2025/26 [69] . India has also remained the world's largest DRI producer since 2003. This creates a much broader range of potential Hy4Smelt integration points than in primarily resource-exporting markets [61,70–72].

The raw-material structure is particularly relevant to HYFOR. Indian Bureau of Mines data show that fines represented about 70.6% of national iron-ore production in 2022/23, with Odisha alone accounting for more than half of total production and Chhattisgarh forming another major producing region. A process designed to reduce qualified non-agglomerated fines could therefore address a feedstock that is already produced at very large scale. At ore-linked locations in Odisha, Chhattisgarh and similar mining regions, **Configuration C – HYFOR-based green-iron production** could convert part of these fines into DRI/HCI/HBI or, with a downstream Smelter, into a higher-value liquid iron product close to the resource base.

India is also particularly suitable for **Configuration D – stand-alone Smelter deployment** because of its exceptionally large domestic DRI industry. Much of this production is based on coal-fired rotary kilns, while a smaller but significant share uses gas-based reduction. A Smelter could potentially act as a common downstream unit for qualified DRI from HYFOR, shaft furnaces or other domestic reduction routes, completing reduction, separating gangue and producing controlled HM. This provides a pathway for introducing Hy4Smelt technology without requiring every site to adopt the complete HYFOR-Smelter process chain.

At large integrated steelworks, **Configuration A – integrated HYFOR-Smelter conversion** provides a third pathway. HYFOR-Smelter could progressively replace blast-furnace HM while existing BOF, casting and rolling assets remain in operation. The technical value would be greatest where local ore fines are economically attractive but unsuitable for conventional pellet-based hydrogen DR. India therefore provides a particularly strong test of Hy4Smelt's modularity: HYFOR can serve new ore-linked ironmaking hubs, the complete process can replace BF production, and the Smelter can be integrated independently with the country's existing DRI sector.

India is simultaneously developing the policy and technical basis for hydrogen-based ironmaking. Under the National Green Hydrogen Mission, dedicated funding has been allocated to steel-sector pilots, including 100% hydrogen DRI in vertical shafts, hydrogen injection into blast furnaces and partial replacement of conventional reducing gases in DRI production. These activities demonstrate significant national interest in hydrogen metallurgy,

although they are currently focused primarily on conventional shaft-furnace and existing ironmaking technologies rather than fluidised-bed fine-ore reduction.

The principal limitation is the energy system. India has rapidly expanded renewable capacity; more than 290 GW of renewable generation capacity was installed by July 2026, but electricity generation remains substantially dependent on thermal power [71,72]. In 2024/25, thermal plants supplied about 74.5% of national electricity generation, compared with roughly 22% from renewable sources. A Hy4Smelt installation supplied from the average grid would therefore not automatically achieve the intended low-carbon performance. Early deployment would need to be concentrated at sites with dedicated or contracted low-emission electricity, competitive hydrogen production, sufficient water and strong grid and transport infrastructure.

India consequently represents the **most diversified international Hy4Smelt case**. Unlike Western Australia or Brazil, where mine-linked Configuration C dominates, India can realistically support **Configurations A, C and D** within the same national market. Its strongest replication value lies in combining a very large fine-ore resource base with existing BF-BOF and DRI infrastructure, allowing HYFOR and the Smelter to be introduced either together or independently according to regional raw materials, energy conditions and existing plant configuration.

4.4 Southeast Asia

Southeast Asia presents a different replication logic from Australia, Brazil and India. The region combines rapidly growing steel demand with strong maritime infrastructure but generally lacks the same combination of large high-quality iron-ore resources and low-cost renewable energy. ASEAN-6 steel demand is expected to reach approximately 87.9 Mt in 2026, while import penetration remains above 60% [73,74]. This makes the region particularly relevant for configurations in which low-carbon metallics are produced in resource-rich countries and transported to coastal steelmaking centres.

The most immediate Hy4Smelt opportunity is therefore **Configuration D – stand-alone Smelter deployment**. DRI or HBI produced in Australia, Brazil, the Middle East or other competitive reduction locations could be imported through existing deep-water ports and converted into liquid HM close to the steel consumer. The Smelter would complete reduction where required, remove gangue and provide a controlled liquid product for downstream steelmaking. This separates the location of hydrogen-intensive ore reduction from the location of final steel production and allows each process step to be placed where its principal inputs are most competitive.

Vietnam provides a particularly relevant example of the scale at which such a concept could eventually operate. Hoa Phat's Dung Quat complex has developed into an approximately 12 Mt/a integrated steelmaking site and operates six blast furnaces, supported by a dedicated deep-water port capable of receiving vessels up to 200,000 DWT [63,75]. A future Smelter-based route could use imported DRI/HBI as an alternative source of primary iron while retaining large downstream steelmaking and rolling assets. At a later stage, HYFOR-Smelter could also be considered as a BF-replacement route if sufficiently competitive low-carbon electricity, hydrogen and suitable ore supply became available locally.

Indonesia offers a similar integrated-site perspective. PT Krakatau POSCO at Cilegon operates a 3 Mt/a integrated steelworks with blast-furnace ironmaking and downstream steel production. Such coastal integrated sites provide potential long-term applications for either

imported DRI/HBI followed by electric smelting or, under sufficiently favourable energy conditions, a complete HYFOR-Smelter route. The value of the stand-alone Smelter is particularly relevant because it would allow the metallic supply to change without requiring the reduction plant to be located at the steelworks itself.

The main limitation is the regional energy system. Indonesia, Malaysia and Vietnam have adopted hydrogen strategies and the Southeast Asian low-emission hydrogen project pipeline approaches 480 kt/a to 2030, but only about 6% of this capacity had reached final investment decision according to the IEA's 2025 assessment. Renewable electricity deployment also remains insufficient in several major steel-producing markets for immediate large-scale hydrogen ironmaking. A complete HYFOR installation would therefore require site-specific confirmation of electricity, hydrogen, water and ore availability rather than relying on favourable regional averages.

Southeast Asia consequently provides the clearest example of **geographically separated Hy4Smelt deployment**. Reduction can initially take place where ore and renewable energy are most favourable, while DRI/HBI is transported to port-based Smelters close to growing steel markets. As regional renewable power and hydrogen infrastructure develop, selected sites—particularly in Vietnam and Indonesia—could later progress from stand-alone Smelter operation toward complete HYFOR-Smelter or integrated BF-replacement configurations.

5. Commercial Scale-up and Replication Requirements

Commercial replication requires a substantial step from the approximately 2.2 t/h HYFOR and 2.5 t/h Smelter demonstration scale toward continuous industrial production at several tens of tonnes per hour. The project proposal uses approximately 50-100 t/h hot-metal production as a representative industrial scale. Scale-up cannot be treated as proportional enlargement: HYFOR throughput affects gas distribution, fluidisation stability, solids residence time, heat and mass transfer, pressure control, recycle-gas operation and ore behaviour, while larger hot-material flows increase the demands on transfer and charging systems. The Smelter must demonstrate stable bath behaviour, final reduction, slag formation, electrical power input, electrode and refractory performance, carburisation, tapping and off-gas handling under long-duration operation.

The combined process must ultimately operate as one production chain rather than as two independently successful units. Buffer capacity, process control and production scheduling must prevent disturbances in HYFOR, material handling or the Smelter from immediately limiting the downstream steelworks. Commercial engineering therefore depends on validated operating envelopes for feed quality, throughput, hydrogen and electricity consumption, metallic yield, slag generation, hot-metal chemistry, maintenance demand and plant availability.

5.1 Demonstration evidence, modularisation and site conditions

D5.6 uses approximately 0.5-1.0 Mt/a per HYFOR module and around 1.2 Mt/a per Smelter as indicative market-scaling assumptions. These are not final commercial design capacities,

but they show the likely need for modular process trains. Smaller BF replacements may be served by one or a limited number of trains, whereas multi-million-tonne replacements require several parallel modules unless larger commercial units are developed. Modularisation enables staged capacity introduction and redundancy, but increases equipment count, auxiliary systems and the number of material and energy interfaces.

Modularity also changes the availability concept. Parallel trains can allow maintenance on one unit while some ore-based production continues, and they make staged BF replacement possible. The disadvantage is duplication of auxiliaries, gas and solids distribution systems, electrical connections and control interfaces. Commercial design must therefore balance module size against redundancy and site complexity. For a steelworks, annual nameplate capacity alone is not sufficient: the number of trains must also reflect converter campaigns, planned maintenance, acceptable interruption duration and the amount of hot-metal or metallic buffer available elsewhere on the site.

The principal demonstration and site conditions are consolidated below. This replaces separate narrative subsections because the same issues are interdependent: an ore window influences hydrogen and electricity demand; energy-system design affects economics and plant availability; hot-material logistics affect downstream scheduling; and slag qualification affects both environmental performance and site economics.

Table 9 Commercial scale-up and replication requirements

Area	**Evidence / requirement for replication**	**Commercial question to resolve**
HYFOR operating envelope	Stable campaigns across representative qualified ores; metallisation, productivity, H2 utilisation, recycle-gas performance and validated feed limits.	Can the required throughput and feed flexibility be guaranteed at commercial scale?
Hot-material transfer	Reliable handling, buffering and charging of hot DRI fines/HCI at much larger solids flows.	Can interruptions be absorbed without destabilising HYFOR, Smelter or downstream production?
Smelter performance	Stable operation with representative reduced iron, HBI/scrap/carbon additions; reproducible HM chemistry; validated slag, electrode, refractory and off-gas behaviour.	Can long-duration HM quality, metallic yield and availability meet steelworks requirements?
Mass and energy balance	Validated H2, electricity, carbon, off-gas, dust, metallic-yield and slag-production data.	Can indicative D5.1/D5.6 screening values be replaced by guaranteeable design data?
Ore qualification and supply	Defined chemistry, mineralogy, PSD, moisture and reducibility window plus long-term consistent supply.	Does the wider HYFOR feed window create a measurable advantage over conventional DR preparation?
Hydrogen supply	Continuous industrial-scale flow, storage/redundancy concept, carbon intensity and competitive cost.	Can H2 be supplied reliably through on-site electrolysis, pipelines or other regional infrastructure?

Area	Evidence / requirement for replication	Commercial question to resolve
Electricity and grid	Low-carbon continuous supply, connection capacity, reinforcement, power quality and redundancy, including concurrent EAF/electrolyser loads where applicable.	Can the combined site energy system support Smelter, HYFOR auxiliaries and hydrogen production economically?
Site integration / logistics	Land, ore and DRI storage, enclosed hot-material handling, inert gas, HM transport, slag granulation, dust/gas cleaning, water/oxygen and rail/port interfaces.	Can the plant be integrated into an operating site without unacceptable constraints on availability or construction?
Downstream route	Verified HM and steel quality plus a defined value case for BOF retention, metallic-input quality and production scheduling.	Does retaining a liquid-hot-metal route create enough value relative to full EAF conversion?
Slag qualification	Consistent chemistry/glass content, granulation, reactivity/durability/leaching tests, standards/product status and realistic local market.	Can slag become a qualified co-product rather than a disposal burden?
Economics / regulation	Full-system CAPEX/OPEX, H2 and power prices, carbon costs, raw-material premiums, finance, permitting and customer demand for low-CO2 steel.	Does the complete Hy4Smelt system compete with alternative transition routes over the required investment horizon?
Skills, safety and operability	HAZOP, commissioning experience, H2 handling, fluidised-bed operation, high-power systems, Smelter procedures, maintenance and abnormal-operation strategies.	Can first-of-a-kind operating knowledge be transferred into repeatable industrial procedures and training?

The table emphasises that technical suitability alone is insufficient. Recent European projects demonstrate that even technically credible hydrogen-based routes can be delayed or cancelled when electricity, hydrogen, financing or market conditions are unfavourable. Conversely, existing high-capacity electrical infrastructure, secure ore logistics, valuable downstream assets and a realistic slag market can materially improve a site's replication case. Detailed feasibility must therefore evaluate the complete production and energy system rather than individual HYFOR or Smelter units in isolation.

Hydrogen and electricity are particularly important because nominal annual availability does not guarantee continuous ironmaking. A commercial plant requires adequate instantaneous flow, storage or backup, and a grid connection capable of supporting major continuous loads while also serving EAFs, electrolysers and other site consumers. Long-term PPAs or dedicated renewable generation can improve cost and carbon intensity but do not remove the need for reliable balancing and redundancy. The relevant feasibility question is therefore the performance of the complete site energy system under normal operation, maintenance and supply interruptions.

Economic and regulatory assessment must likewise capture system effects. Potential benefits - avoided pelletising, wider ore selection, retained downstream assets, reduced direct CO2 emissions and possible slag value - must be compared with hydrogen and electricity demand, new infrastructure, financing, integration and first-of-a-kind risk. Safety and operability data

from the demonstrator are part of this evidence base: HAZOP results, commissioning experience, hydrogen procedures, refractory and electrode performance, maintenance practice and abnormal-operation scenarios should be converted into design guidance and training that can be transferred to the first commercial installation.

6. Replication Pathway and Outlook

Commercial replication should proceed through four linked stages. First, demonstration campaigns must establish a validated and reproducible operating envelope covering ore quality, metallisation, productivity, hydrogen utilisation, electricity demand, metallic yield, hot-metal chemistry, slag behaviour and plant availability. Second, candidate sites must be assessed using site-specific ore supply, energy infrastructure, required hot-metal capacity, downstream route and logistics. This stage includes ore qualification, mass and energy balancing, capacity matching, utility studies, plot-plan integration and comparison with alternative transition pathways.

Third, the first commercial installation must provide long-duration evidence on availability, maintenance, refractory and electrode performance, operating flexibility and product consistency. Once these parameters are demonstrated, later projects can rely increasingly on standardised HYFOR and Smelter modules, common feed-qualification procedures, transferable process-control concepts and accumulated operating experience. Replication can then shift from first-of-a-kind engineering toward repeatable industrial deployment.

The European screening indicates that Hy4Smelt should remain selective. Its strongest value proposition is not generic blast-furnace replacement, but situations in which fine-ore flexibility, reduced dependence on pelletising, retention of valuable downstream assets, continued hot-metal production or coexistence with EAF capacity create a measurable system advantage. Internationally, the same flexibility enables different layouts, including mine-linked green-iron hubs and geographically separated reduction and smelting. Across all cases, the decisive next step is to convert the technological flexibility identified in D5.1 into validated, warranted industrial performance using WP4 demonstration results and the subsequent WP5 technical, environmental and economic assessments.

PART II
Preliminary LCA

7. LCA methodology

LCA is a standardized methodology used to quantify the potential environmental impacts associated with products, processes, or services throughout their entire life cycle. According to ISO 14040 [76] , LCA is defined as the "c*ompilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*." More specifically, inputs include the consumption of materials and energy as well as natural resources from the environment, whereas outputs consist of emissions released to air, water, and soil, together with other environmental exchanges generated during the life cycle.

The object of analysis in an LCA study is the product system, which is defined by ISO 14040 [76] as a "*collection of unit processes with elementary and product flows, performing one or more specified functions, and which models the life cycle of a product*". Each unit process represents *"the smallest element considered in the life cycle inventory analysis for which input and output data are quantified*" [76] .

The life cycle perspective adopted in LCA extends beyond the direct environmental burdens generated during manufacturing by considering all stages that contribute to the provision of the product or service. Depending on the goal and scope of the study, the assessment may encompass raw material extraction, material processing, manufacturing, distribution, use, maintenance, recycling, and end-of-life management, thereby providing a cradle-to-grave representation of the analysed system. This holistic perspective is founded on the principles of Life Cycle Thinking, which promotes the evaluation of environmental performance across the entire value chain rather than focusing exclusively on individual production stages. Consequently, environmental burdens associated with activities such as product design, raw material procurement, logistics, manufacturing, use, and final disposal are considered simultaneously (Figure 1).

Figure 2: Life cycle stages of a generic product or process [77] .

Environmental performance is quantified through a set of impact categories, each representing a specific environmental issue at either the global, regional, or local scale. Examples include climate change, ozone depletion, acidification, eutrophication, resource depletion, ecotoxicity, and water use. For each category, characterization models convert inventory flows into environmental impact indicators, allowing the contribution of the different life cycle stages to be quantified and compared.

The LCA methodology follows the internationally recognized framework established by ISO 14040 and ISO 14044 (5, 12) which consists of four interconnected phases (also illustrated in Figure 2):

1. Goal and scope definition, in which the objectives of the study, the functional unit, the system boundaries, and the methodological assumptions are established.
2. LCI, involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
3. LCIA, aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
4. Life Cycle Interpretation, in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

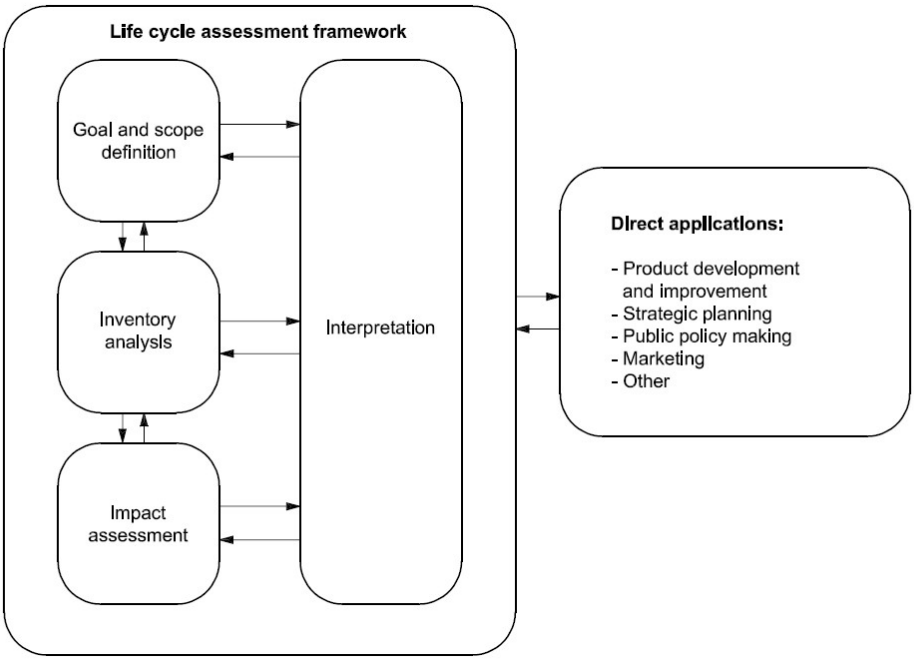

Figure 3: Stages of an LCA according to the ISO 14040 standard (5).

7.1 Goal and scope definition

The goal definition constitutes the first phase of the goal and scope definition. It establishes the intended application, the reasons for carrying out the study, the intended audience, and the intended use of the results (5). Since all subsequent methodological choices depend on these objectives, the goal definition provides the foundation for the entire LCA study.

The scope definition translates these objectives into a detailed methodological framework by specifying how the assessment will be performed. It identifies the product system under investigation, defines the function delivered by the system, establishes the functional unit (i.e., the quantified performance of a product system for use as a reference unit), and determines the corresponding reference flow, namely the measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit (5). In addition, the scope specifies the system boundaries, the life cycle stages to be included, the assumptions adopted, and any methodological limitations relevant to the study (5).

A key element of the scope definition is the establishment of the system boundaries, which determine the processes and exchanges considered within the assessment. These boundaries distinguish the product system from both the surrounding economy (technosphere) and the natural environment (ecosphere), thereby identifying which unit processes, material flows, and elementary flows are included or excluded from the analysis. To ensure transparency, the system boundaries are represented graphically, illustrating the unit processes considered in the model together with the relationships among them.

Another important methodological choice concerns the modelling of recycling. Several approaches have been developed for metals, each relying on different assumptions regarding the allocation of environmental burdens and benefits associated with recycled materials [78] .

The cut-off approach allocates the environmental impact of recycling to the users of secondary resources and attributes no environmental burdens to the materials embodied in secondary resources entering the system. On the other hand, no environmental burdens and credits are assigned to recycling at the end of life [79] .

Conversely, the avoided burden (or substitution) approach allocates the environmental impact of recycling to the producer of the waste. This implies that the environmental impact of recycling is allocated to the waste generated in the process and at the end of life of the products, considering that the recovered secondary materials substitute the production of primary materials in the market as environmental credits [79] . On the other hand, the avoided burden approach attributes the environmental impact of embodied virgin materials to the secondary materials consumed in the process.

A third option is represented by the Circular Footprint Formula (CFF), developed within the Product Environmental Footprint (PEF) method to balance the environmental responsibilities between the producer and the user of recycled materials. However, for intermediate products such as liquid steel, the CFF provides results equivalent to those obtained using the cut-off approach (9, 10).

7.2 Life Cycle Inventory (LCI)

The LCI constitutes the second phase of the LCA framework and consists of compiling and quantifying all material and energy flows associated with the product system. The objective of this phase is to develop a comprehensive inventory of the resources consumed and the emissions and waste generated throughout the life cycle, considering every process included within the defined system boundaries.

The inventory is built by collecting both primary and secondary data. Primary data are obtained directly from industrial stakeholders or technology developers, typically through questionnaires, technical documentation, process monitoring, or direct communication with

the companies involved. When primary information is unavailable or incomplete, secondary data are retrieved from scientific literature, technical reports, or other reliable sources.

The data collection process enables the quantification of all input and output flows associated with the processes directly modelled in the study, commonly referred to as the foreground system. However, LCA also requires the inclusion of all upstream and downstream processes that support the foreground activities. These processes, which form the background system, include, for example, raw material extraction and processing, electricity and fuel production, transportation, and waste treatment. Their environmental profiles are generally modelled using established LCI databases, which provide life cycle inventories describing the exchanges of materials and energy between the technosphere and the ecosphere.

7.3 Life Cycle Impact Assessment (LCIA)

The third phase is the LCIA, which assigns impact values to all elementary flows gathered during the LCI analysis for each impact category. This process, known as characterisation, involves various methodologies that use different characterisation factors. One of the most commonly used impact assessment methods is the EF 3.1 v1.05 developed by the Joint Research Centre of the European Commission [80] . After characterisation, the method enables the assessment of normalised and weighted results, allowing for comparisons between impact category values and different products. Normalisation involves expressing characterised environmental impacts in terms of normalised values, usually relative to the average impact of the population in that region for that category. Weighting, on the other hand, assigns a weight to these normalised values based on the relative importance of each impact category, determined through qualitative judgment.

The EF 3.1 LCIA method developed by the European Commission [80] assesses environmental performance through 16 midpoint impact categories, each representing a specific environmental issue associated with the life cycle of a product or system:

1. **Climate Change** *(kg CO_2 eq)*: Assesses the contribution of greenhouse gas emissions to global warming over a 100-year time horizon.
2. **Ozone Depletion** *(kg CFC-11 eq)*: Evaluates emissions of substances that deplete the stratospheric ozone layer, increasing harmful ultraviolet (UV) radiation reaching the Earth's surface.
3. **Ionising Radiation** *(kBq U-235 eq)*: Quantifies the potential impact of ionising radiation on human health resulting from radionuclide emissions associated with electricity generation and other processes.
4. **Photochemical Ozone Formation** *(kg NMVOC eq)*: Measures the formation of ground-level ozone (summer smog) due to emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x), which can affect both human health and vegetation.
5. **Particulate Matter** *(Disease incidence)*: Assesses the health impacts associated with emissions of primary and secondary particulate matter, which contribute to respiratory and cardiovascular diseases.
6. **Acidification** *(mol H^+ eq)*: Evaluates the acidifying effects of emissions such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) on terrestrial and freshwater ecosystems.

7. **Eutrophication, Freshwater** *(kg P eq)*: Measures nutrient enrichment of freshwater ecosystems, mainly caused by phosphorus emissions, leading to excessive algal growth and oxygen depletion.
8. **Eutrophication, Marine** *(kg N eq)*: Assesses nutrient enrichment of marine environments due primarily to nitrogen emissions.
9. **Eutrophication, Terrestrial** *(mol N eq)*: Evaluates the deposition of reactive nitrogen compounds that alter nutrient balances and biodiversity in terrestrial ecosystems.
10. **Ecotoxicity, Freshwater** *(Comparative Toxic Unit for ecosystems, CTUe)*: Estimates the potential toxic effects of chemical emissions on freshwater aquatic organisms.
11. **Human Toxicity, Cancer** *(Comparative Toxic Unit for humans, CTUh)*: Assesses the potential increase in cancer risk resulting from human exposure to toxic substances emitted throughout the life cycle.
12. **Human Toxicity, Non-cancer** *(Comparative Toxic Unit for humans, CTUh)*: Evaluates potential non-carcinogenic health effects caused by exposure to hazardous substances.
13. **Land Use** *(Dimensionless soil quality index, Pt)*: Quantifies the impacts of land occupation and transformation on soil quality and ecosystem services.
14. **Water Use** *(m^3 world eq deprived)*: Assesses the potential environmental impacts associated with freshwater consumption, taking into account regional water scarcity.
15. **Resource Use, Fossils** *(MJ)*: Measures the depletion of fossil energy resources, including coal, oil, and natural gas.
16. **Resource Use, Minerals and Metals** *(kg Sb eq)*: Evaluates the depletion of mineral and metal resources based on their long-term availability and extraction requirements.

During normalization, each impact category is divided by its corresponding normalization factor. Subsequently, the normalized results are multiplied by the weighting factors defined for the EF 3.1 method. The normalization and weighting factors of the EF3.1 v1.05 LCIA method are reported in Table 10.

The resulting weighted impacts are expressed in eco-points (Pt), a dimensionless unit representing the relative contribution of a product system to the overall environmental burden after normalization and weighting. One eco-point does not correspond to a physical quantity; rather, it is an index that facilitates the aggregation and comparison of environmental impacts across different categories.

The single score is obtained by summing the weighted results of all 16 impact categories. It provides an overall indicator of the potential environmental performance of the assessed product system and is particularly useful for comparing alternative scenarios or identifying preferable options.

Table 10: Normalization and weighting factors adopted in the Environmental Footprint (EF 3.1) method for the 16 midpoint impact categories v1.05 [80] .

Impact category	Normalization factor	Weighting factor
Acidification	1.80E−02	6.20E−02

Climate change	1.32E−04	2.11E−01
Freshwater ecotoxicity	1.76E+02	1.92E−02
Particulate matter	1.68E−04	8.96E−02
Marine eutrophication	5.12E−03	2.96E−02
Freshwater eutrophication	6.22E−05	2.80E−02
Terrestrial eutrophication	5.66E−02	3.71E−02
Human toxicity, cancer	5.80E−06	2.13E−02
Human toxicity, non-cancer	7.77E−05	1.84E−02
Ionising radiation	2.37E+02	5.01E−02
Land use	1.22E+04	7.94E−02
Ozone depletion	1.91E−07	6.31E−02
Photochemical ozone formation	2.45E−02	4.78E−02
Resource use, fossils	1.54E+04	8.32E−02
Resource use, minerals and metals	1.57E−01	7.55E−02
Water use	8.72E+03	8.51E−02

7.4 Life Cycle Interpretation

The life cycle interpretation phase represents the final stage of the LCA framework. Its objective is to analyse and integrate the findings of the LCI and LCIA to draw conclusions that are consistent with the goal and scope of the study. This phase focuses on identifying the most relevant environmental issues, including the inventory flows, impact categories, life cycle stages, and unit processes that contribute most significantly to the overall environmental performance of the product system (5). In accordance with ISO 14040 and ISO 14044, the life cycle interpretation phase also includes an evaluation of the robustness and reliability of the assessment through completeness, sensitivity, and consistency checks. The completeness check verifies that all relevant information required to support the conclusions has been collected and that no significant data or processes have been omitted. The sensitivity check investigates the influence of methodological choices, modelling assumptions, allocation procedures, and input data on the final results, thereby assessing the robustness of the conclusions. The consistency check ensures that the methods, assumptions, data sources, and modelling choices adopted throughout the study are coherent with the objectives and scope initially defined [81] . Depending on the objectives of the study, additional analyses may be performed to support the interpretation of the results and to improve their robustness. These analyses facilitate the identification of environmental hotspots, quantify the influence of uncertainties, and evaluate the effects of alternative modelling assumptions. Contribution analysis is used to identify the processes, life cycle stages, or elementary flows that make the largest contributions to the selected environmental indicators, thereby highlighting the main drivers of environmental impacts. Uncertainty analysis assesses the extent to which variability and uncertainty in input data, parameters, and modelling assumptions affect the reliability of the results. Finally, sensitivity analysis evaluates how changes in methodological choices or

input parameters influence the environmental outcomes, providing insight into the robustness of the conclusions and identifying those assumptions that have the greatest effect on the overall assessment.

8. Preliminary LCA

This section describes the application of the LCA methodology to the three steelmaking routes defined in Section 8.1, which are considered baseline production routes within the Hy4Smelt project. These routes, labelled Routes A, B and C, will serve as benchmarks for the future LCA of the Hy4Smelt technology currently under development.

8.1 Goal and scope definition

The goal of this preliminary LCA is to assess the environmental performance of three steelmaking routes: (i) Route A, ii) Route B, and iii) Route C. The function of the assessed systems is the production of liquid steel from primary resources. Accordingly, the functional unit is defined as the production of 1 ton of liquid steel. The system boundaries are cradle-to-gate, covering all the unit processes composing the three production routes. In addition, the system boundaries also include direct GHG emissions and the waste management of steelmaking residues (i.e., slag, dust) and waste and wastewater flows generated along with the process. The scientific literature classifies slag either as waste or as a by-product depending on the specific context [82] .

As a reference case, slag is considered as waste requiring disposal. This choice is motivated by the fact that this is a precautionary assumption which results in higher environmental impacts than considering slag as waste for recycling or as a by-product. However, as discussed in 9.5, a sensitivity analysis is conducted to quantify the implications of three alternative classifications: slag as waste for disposal (Scenario 1), slag as waste for recycling (Scenario 2), and slag as a by-product (Scenario 3). The system boundaries are illustrated in Figure 4. As illustrated in Figure 4, Routes A, B, and C are all composed of 4 tiers, and the reference flow is liquid steel for all production routes. Tier 1 represents the conversion of HM into liquid steel, which takes place in the BOF. Tier 2 includes the production of HM from iron-bearing materials. In Route A, this transformation is carried out in the BF, whereas in Routes B and C it takes place in the ESF. Tier 3 comprises the production of the iron-bearing materials fed into the HM production stage. Specifically, it includes the sintering process in Route A, the MIDREX direct reduction process in Route B, and the HYFOR hydrogen-based direct reduction process in Route C. Finally, Tier 4 groups the upstream raw material preparation processes required by each steelmaking route. These include coke production in Route A, iron ore beneficiation and pellet production in Route B, and iron ore preparation in Route C.

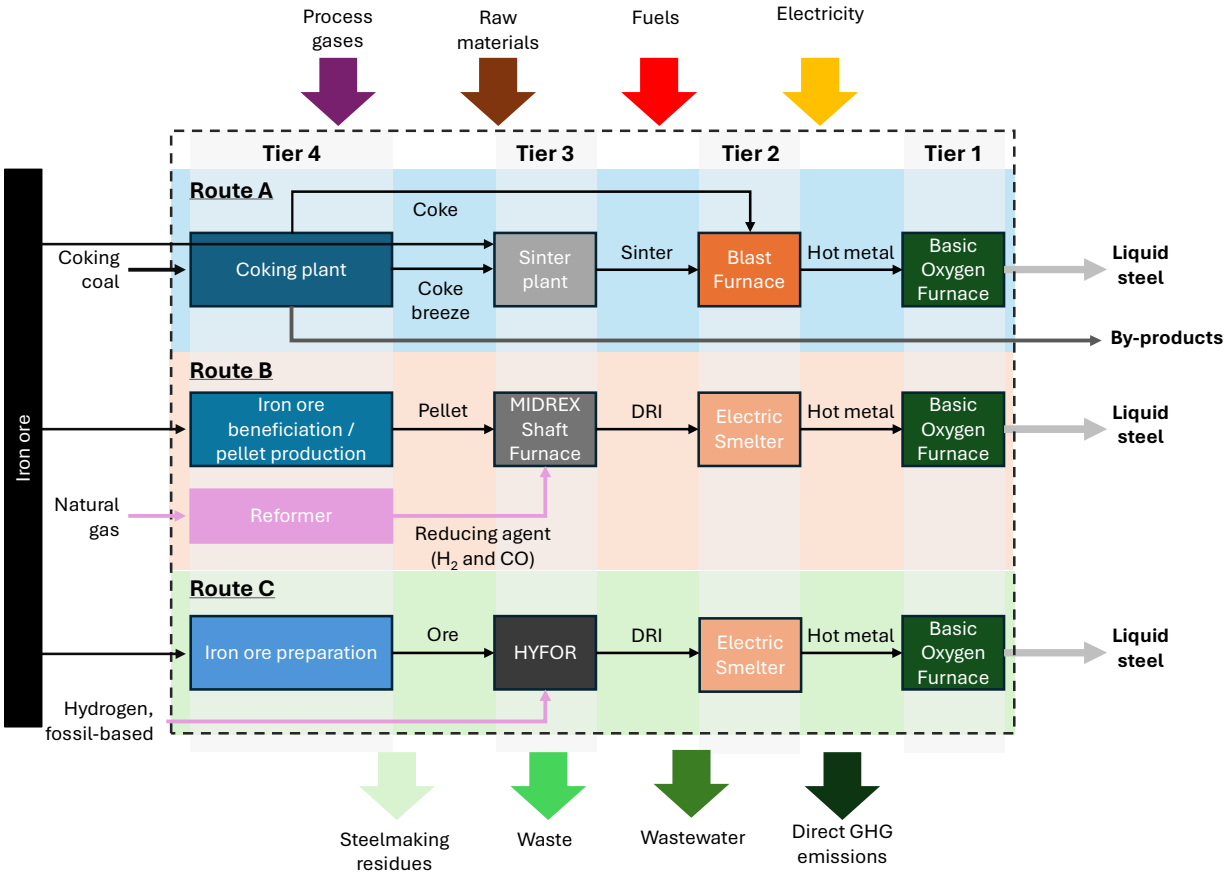

Figure 4: System boundaries of the three liquid steel production routes considered in this preliminary LCA study: Route A represents the BF-BOF route, Route B represents the MIDREX–ESF–BOF route, Route C the HYFOR–ESF–BOF route

The conventional route (Route A) includes a coking plant (Tier 4), a sinter plant (Tier 3), a BF (Tier 2), and a BOF (Tier 1). These sequential processes produce liquid steel while generating crude tar, light oil, sulfuric acid, and quenching sludge/slurry as by-products of the coking plant.

The MIDREX-based route (Route B) starts with iron ore beneficiation and pellet production (Tier 4). The pellets are converted into DRI through a MIDREX shaft furnace (Tier 3) using a natural gas-based reducing gas whose production is internal to the system boundaries. The DRI is subsequently processed in an ESF (Tier 2) to produce HM, which is finally converted into liquid steel in the BOF (Tier 1).

Similarly, Route C produces liquid steel through the ESF–BOF route but differs from Route B in the direct-reduction stage. HYFOR (Tier 3) is supplied directly with iron-ore fines after a preparation step (Tier 4) that does not require conventional beneficiation or pelletisation. For this preliminary LCA, HYFOR is modelled using externally supplied grey hydrogen from natural-gas reforming. This provides a reference baseline against which the environmental benefit of green hydrogen can later be quantified.

The Hy4Smelt demonstration plant itself is designed to operate with **green hydrogen from the H2FUTURE PEM electrolyser at the voestalpine Stahl site in Linz**. The complete environmental assessment will be reported in **Deliverable D5.4 – Results of LCA and LCC**, using the Hy4Smelt process data and the green-hydrogen configuration.

Across all three production routes, the main inputs include raw materials (e.g. iron ore, scrap, carbon sources, binders, and additives), process gases (e.g. coke oven gas and enriched blast furnace gas), fuels (primarily natural gas), and electricity. The outputs include liquid steel, solid waste (e.g. slag, dust, wastewater, sludge, and inert waste), and direct atmospheric emissions. A limitation of this preliminary study is that, owing to data availability limitations, only direct CO_2 emissions have been included in the LCI. This data gap will be filled in the complete LCA analysis that will be carried out during the Hy4Smelt project.

Regarding recycling modelling, the study adopts the cut-off approach; accordingly, the environmental burdens associated with recycling are allocated to the consumption of secondary materials. On the other hand, no credits or burdens are assigned to end-of-life recycling. For instance, input scrap has the environmental impact of sorting and pressing activities. On the other hand, the recovery of secondary resources (e.g., process gases) is cut off because it is considered burden-free. This approach is consistent with the recommendations of the Environmental Product Declaration (EPD) framework [83] and the PEF method for intermediate products (9, 10).

Regarding the treatment of multifunctionality in Route A, arising from the generation of several co-products in the coking plant, ISO 14044 [81] establishes a hierarchy in which the preferred approaches are subdivision as the first option, followed by system expansion. Subdivision resolves multifunctionality by dividing a multifunctional process into two or more subprocesses for which separate input and output data can be collected. System expansion, instead, consists of expanding the product system to include the additional functions associated with the co-products and is conceptually consistent with the avoided burden approach. Neither approach is applicable in the present study. The coking process cannot be meaningfully subdivided into subprocesses associated with the individual co-products, while system expansion is difficult to implement because the co-products of the coking plant have multiple potential applications, making it challenging to identify appropriate substituted products [78] . Consequently, allocation cannot be avoided. Following the hierarchy established by ISO 14044, the inputs and outputs of the coking process are partitioned according to the underlying physical relationship among the co-products. Specifically, a mass-based physical allocation is applied to distribute the environmental burdens of the coking process among coke, the main product, and the associated co-products in proportion to their mass. According to this approach, allocation factors were determined for all products as follows: 95.3% for coke (the main product), 3.3% for crude tar, 1,0% for light oil, 0,4% for sulfuric acid, and less than 0,1% for quenching sludge/slurry i.e., the co-products).

8.2 Life Cycle Inventory

This section describes the LCI of the three steelmaking routes assessed in this preliminary LCA. The LCI of Route A represents a conventional BF-BOF steelmaking process, while the LCIs of Routes B and C are representative of realistic operational data for the MIDREX-ESF-BOF and HYFOR-ESF-BOF steelmaking routes, respectively. All LCIs were developed with the support of the project partners K1-MET and Voestalpine. In addition, secondary data from scientific literature have been used to fill the data gaps when needed [84] .

The data composing the LCI of the three steelmaking routes refers to the amount of process gases, raw materials, fuels, and electricity consumed by Route A, Route B, and Route C, as well as the waste, by-products, and direct emissions generated in these plants. These flows compose the so-called foreground LCI, whereas the background LCI is based on the ecoinvent

3.12 – cut-off version database [85] . This database is fundamental to consider in the product system all the upstream and downstream unit processes such as the raw materials extraction, processing, and transporting, and the waste management of steelmaking residues. Accordingly, the LCI of the three production routes is extensively reported in Appendix 1. More specifically, the LCI of Route A is documented in Tables A1 – A4 (Appendix 1.1), the LCI of Route B in Tables A5 – A8 (Appendix 1.2), and the LCI of Route C in Tables A9 – A12 (Appendix 1.3).

The selection of datasets for iron-bearing materials is particularly important for the LCI of the three steelmaking routes. To ensure a consistent comparison, the same iron ore grade was adopted for Routes A, B, and C. This choice makes it possible to explicitly highlight the different levels of upstream processing required by each route. In particular, the conventional BF-BOF route (Route A) requires the iron ore to undergo a sintering process before entering the BF. Route B requires the iron ore to be beneficiated and pelletised prior to direct reduction in the MIDREX process, whereas Route C only requires limited pre-treatment before being processed in the HYFOR reactor. Accordingly, the common reference ecoinvent dataset selected for iron ore was "*Iron ore, crude ore, 46% Fe {GLO}* | *market for iron ore, crude ore, 46% Fe* | *Cut-off, U*".

Several simplifications were introduced in this preliminary LCI modelling. For all routes, the BOF requires the addition of ferroalloys, whose composition may vary depending on the steel grade being produced. Following the recommendations of the industrial partners, ferrosilicon was selected as the representative ferroalloy because it is the most commonly used in typical BOF operations. The corresponding ecoinvent dataset chosen is "*Ferrosilicon {GLO}* | *market for ferrosilicon* | *Cut-off, U*". A strong simplification in the LCI is that, due to the lack of data for all the processes, other direct emissions of pollutants, other than GHG emissions, are not accounted for. In addition, all GHG emissions of Route A have been entirely allocated to Tier 4 since data were available in aggregated form, but it does not reflect the actual distribution of direct GHG emissions across the tiers of Route A.

In addition, the ESF used in Routes B and C requires carbon sources. To simplify the modelling, all generic carbon inputs were represented by the dataset "*Hard coal {AT}* | *market for hard coal* | *Cut-off, U*". Nevertheless, alternative carbon sources, such as coke, anthracite, or biochar, may also be employed in industrial practice and should be considered in future, more detailed assessments. Finally, the ESF also requires the addition of fluxes to control slag chemistry and facilitate impurity removal. Dolomite was selected as the representative flux and modelled using the dataset "*Dolomite {RER}* | *dolomite production* | *Cut-off, U*". However, in a full LCA analysis that will be conducted by the end of the project, circular economy strategies like slag and dust recovery will be accounted for.

These assumptions were necessary to fill data gaps that are common in preliminary LCA studies. They ensure a complete and internally consistent inventory while providing a robust baseline for the more detailed LCA that will be developed as additional process-specific data become available during the project.

8.3 Life Cycle Impact Assessment

The LCIA phase of this preliminary LCA, the LCIA method EF3.1 [80] version 1.05 as implemented in the SimaPro v10.4 software, has been used to calculate 16 environmental

impact indicators. The EF3.1 method developed by the European Commission assesses environmental performance through 16 midpoint impact categories, each representing a specific environmental issue associated with the life cycle of a product or system. Together, these 16 midpoint indicators provide a comprehensive assessment of the environmental performance of products and systems by covering climate change, ecosystem quality, human health, natural resource depletion, and water use, thereby supporting robust environmental decision-making within the EF methods. In addition, consistent with the PEF method, this deliverable also presents normalized and weighted results which allow for a more general comparison based on the single score environmental impact.

8.4 Life Cycle Interpretation

The life cycle interpretation of this preliminary LCA focuses on comparing the three steelmaking routes assessed in this study and identifying the main environmental hotspots within their production processes. A process-based contribution analysis [86] is presented to quantify the contribution of individual unit processes to the environmental impacts of Routes A, B, and C. In addition, a "first-tier contribution analysis" [86] approach is applied subsequently to all the 4 tiers of the steelmaking routes. This approach facilitates the interpretation of the environmental performance of the three steelmaking routes by identifying the main environmental hotspots within each production tier. For instance, it distinguishes the direct and indirect contributions associated with the BOF (Tier 1), explains the different environmental performance of the BF and the ESF (Tier 2), highlights the impacts associated with hydrogen- and natural gas-derived reducing agents for DRI production (Tier 3), and identifies the environmental burdens related to the processing of iron-bearing materials (Tier 4). Based on these results, contribution analysis provides valuable guidance for technology developers by highlighting opportunities to reduce the environmental footprint of steel production through process optimization and more efficient resource use.

As part of the life cycle interpretation, this study includes a sensitivity analysis to address uncertainty associated with the LCI modelling approach of BF, BOF, and ESF slags. The scientific literature remains fragmented on this topic, as slags may be classified either as waste or as by-products of steelmaking, depending on the study context and the adopted slag-management route [82] . To assess the influence of this modelling choice on the results, a sensitivity analysis is conducted considering three alternative approaches:

- **Scenario 1:** This precautionary scenario considers slag as a waste requiring disposal in a landfill
- **Scenario 2:** Slag is considered a recyclable waste. In accordance with the cut-off approach, recycled slag leaves the product system without receiving any upstream environmental burdens from the steelmaking process
- **Scenario 3**: Slag is considered a by-product of the steelmaking process. In line with the approach selected for addressing multifunctionality, environmental burdens are allocated between the steel products and slag based on their respective masses, consistently with the treatment of by-products from the coking plant.

The differences among these scenarios and their influence on the LCA results are assessed and discussed.

9. Results and discussion

This section presents the results of the preliminary LCA study. In accordance with the ISO standards and the PEF framework, the environmental impacts are first reported at the characterization level and subsequently expressed as normalized and weighted impact categories (Section 9.1). A contribution analysis is then provided for Routes A, B, and C in Sections 9.2, 9.3, and 9.4, respectively.

9.1 LCIA results

The characterized LCIA results are reported for the 16 environmental impact categories illustrated in Figure 5. Overall, the results indicate that Route A (blue bars) exhibits the highest environmental impacts for the majority of the assessed impact categories. Notable exceptions are *Particulate matter*, *Ozone depletion*, and *Resource use, fossils*, for which Route B (orange bars) is associated with the highest environmental burdens. Conversely, Route C (green bars) shows the greatest impacts for *Ionising radiation* and *Resource use, minerals and metals*.

For some impact categories, however, the differences among the three steelmaking routes are relatively limited, i.e., below 10% difference [83]. This is particularly evident for *Human toxicity, non-cancer*, *Land use*, and *Resource use, fossils*, where the environmental impacts of Routes A, B, and C are of comparable magnitude.

These observations are confirmed by the numerical results reported in Table 11, which summarize the characterized LCIA results for all 16 environmental impact categories, referring to the functional unit, i.e., the production of 1 ton of liquid steel.

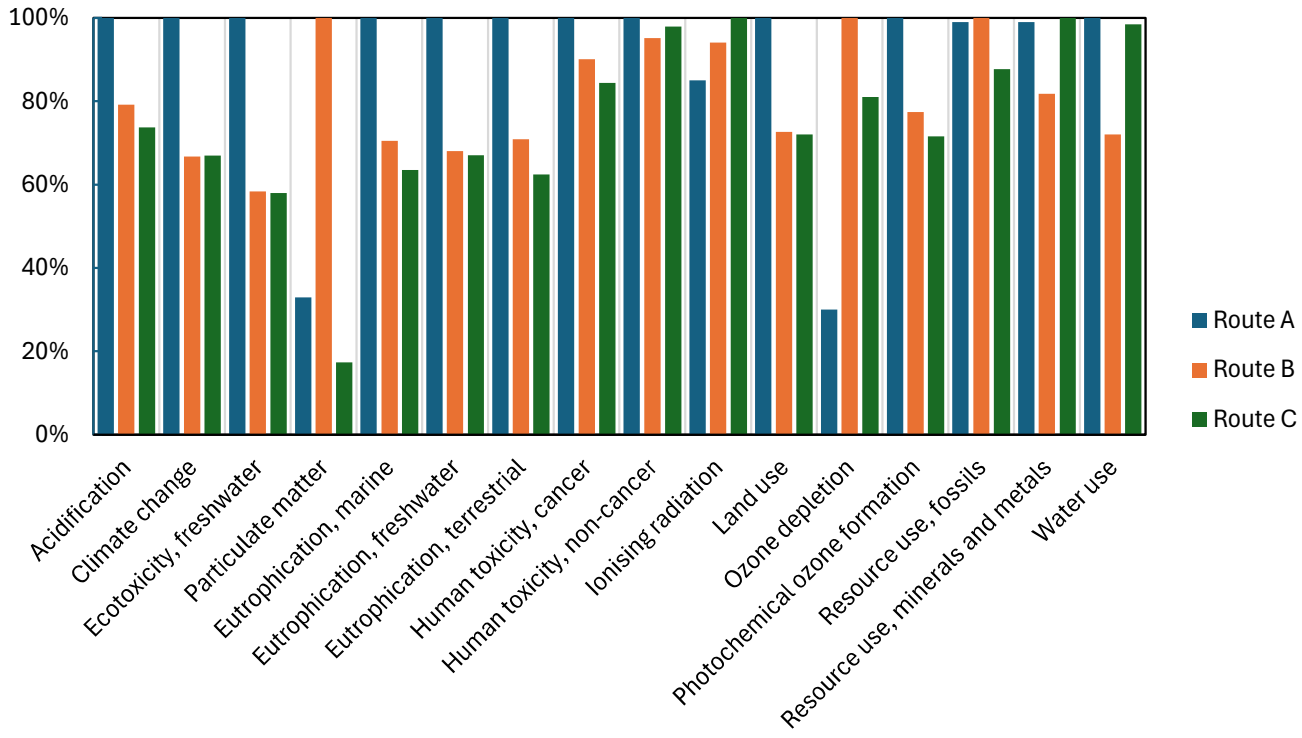

Figure 5: Characterised LCIA results for the 16 environmental impact categories considered in the LCIA with the EF3.1 impact assessment method. Results are expressed relative to the highest impact value for each impact category (100%), enabling a comparison of the

environmental performance of Routes A, B, and C independently of the different units of measurement.

Table 11: Characterized LCIA results for the 16 impact categories assessed for Routes A, B, and C. Results are reported per functional unit, corresponding to the production of 1 ton of liquid steel.

Impact category	Route A	Route B	Route C	Unit
Acidification	3,26E+00	2,58E+00	2,40E+00	mol H+ eq / ton liquid steel
Climate change	2,33E+03	1,55E+03	1,56E+03	kg CO_2 eq / ton liquid steel
Ecotoxicity, freshwater	3,65E+03	2,13E+03	2,12E+03	CTUe / ton liquid steel
Particulate matter	4,14E-05	1,26E-04	2,19E-05	disease inc. / ton liquid steel
Eutrophication, marine	1,05E+00	7,43E-01	6,68E-01	kg N eq / ton liquid steel
Eutrophication, freshwater	1,39E+00	9,49E-01	9,35E-01	kg P eq / ton liquid steel
Eutrophication, terrestrial	1,04E+01	7,39E+00	6,52E+00	mol N eq / ton liquid steel
Human toxicity, cancer	4,44E-07	4,00E-07	3,75E-07	CTUh / ton liquid steel
Human toxicity, non-cancer	4,56E-06	4,34E-06	4,46E-06	CTUh / ton liquid steel
Ionising radiation	8,69E+01	9,61E+01	1,02E+02	kBq U-235 eq / ton liquid steel
Land use	3,49E+03	2,54E+03	2,52E+03	Pt / ton liquid steel
Ozone depletion	1,23E-05	4,08E-05	3,31E-05	kg CFC11 eq / ton liquid steel
Photochemical ozone formation	3,00E+00	2,32E+00	2,15E+00	kg NMVOC eq / ton liquid steel
Resource use, fossils	1,88E+04	1,90E+04	1,67E+04	MJ / ton liquid steel
Resource use, minerals and metals	2,37E-03	1,96E-03	2,39E-03	kg Sb eq / ton liquid steel
Water use	1,92E+02	1,38E+02	1,89E+02	m^3 depriv. / ton liquid steel

As shown above, Route A exhibits the highest environmental impacts for the majority of the assessed impact categories. However, in line with the PEF method [87] , characterized results do not permit determination of the overall environmental performance of the three steelmaking routes. To enable comparisons across impact categories, the characterized results shall be subsequently normalized and weighted, allowing them to be aggregated into a single score indicator [87] .

The single score results for the three production routes are presented in Figure 6 and are expressed as millipoints (mPt) per ton of liquid steel, where 1 eco-point (Pt), defined in Section 7.3, corresponds to 1000 mPt. The results confirm that Route A has the highest single score environmental impact, whereas Route C represents the most environmentally sustainable option among the three alternatives considered. As expected, Route B exhibits an intermediate environmental performance, lying between Routes A and C.

The numerical results of the normalized and weighted midpoint environmental impact categories are reported in Table 12. The first row presents the overall single score, while the subsequent rows report the contribution of each individual impact category to the total environmental impact. The results indicate that among the 16 *impact categories* included in the EF 3.1 method, *Climate change*, *Freshwater eutrophication*, and *Resource use, fossils* are the dominant contributors to the overall environmental impacts of all three steelmaking routes.

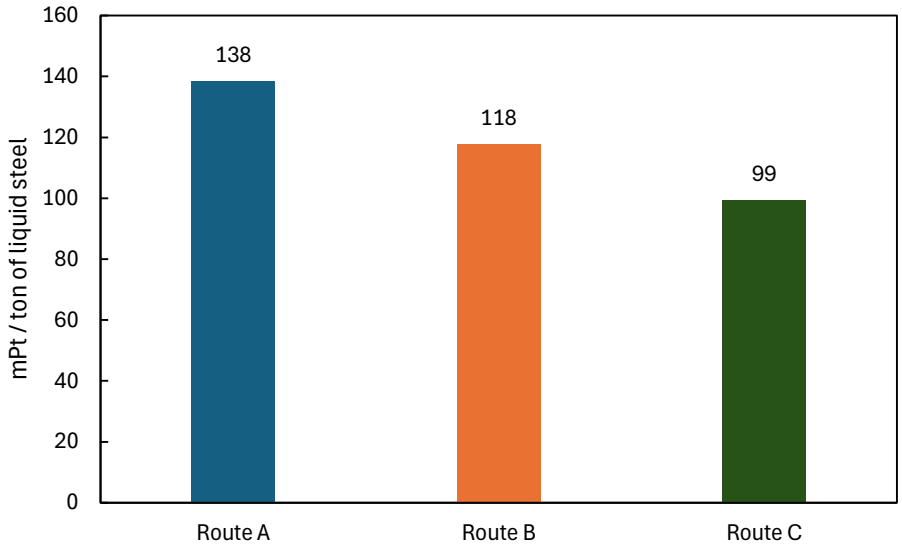

Figure 6: Single score results obtained after normalization and weighting of the characterized LCIA results according to the EF 3.1 method. Results are expressed as millipoints (mPt) per functional unit, corresponding to the production of 1 ton of liquid steel.

Table 12: Normalized and weighted LCIA results for Routes A, B, and C. The first row reports the overall single score, while the remaining rows show the contribution of each impact category to the total environmental impact. Results are expressed as millipoints (mPt) per functional unit, corresponding to the production of 1 ton of liquid steel.

Impact category	**Route A**	**Route B**	**Route C**	**Unit**
Single score	*1,38E+02*	*1,18E+02*	*9,95E+01*	*mPt / ton of liquid steel*
Acidification	3,64E+00	2,88E+00	2,68E+00	mPt / ton of liquid steel
Climate change	6,49E+01	4,33E+01	4,34E+01	mPt / ton of liquid steel
Ecotoxicity, freshwater	1,23E+00	7,21E-01	7,16E-01	mPt / ton of liquid steel
Particulate matter	6,23E+00	1,89E+01	3,30E+00	mPt / ton of liquid steel
Eutrophication, marine	1,59E+00	1,12E+00	1,01E+00	mPt / ton of liquid steel
Eutrophication, freshwater	2,43E+01	1,65E+01	1,63E+01	mPt / ton of liquid steel
Eutrophication, terrestrial	2,19E+00	1,55E+00	1,37E+00	mPt / ton of liquid steel
Human toxicity, cancer	5,48E-01	4,94E-01	4,63E-01	mPt / ton of liquid steel
Human toxicity, non-cancer	6,52E-01	6,20E-01	6,38E-01	mPt / ton of liquid steel
Ionising radiation	1,03E+00	1,14E+00	1,21E+00	mPt / ton of liquid steel
Land use	3,38E-01	2,46E-01	2,44E-01	mPt / ton of liquid steel
Ozone depletion	1,48E-02	4,92E-02	3,98E-02	mPt / ton of liquid steel
Photochemical ozone formation	3,51E+00	2,72E+00	2,51E+00	mPt / ton of liquid steel
Resource use, fossils	2,41E+01	2,43E+01	2,13E+01	mPt / ton of liquid steel

Resource use, minerals and metals	2,81E+00	2,32E+00	2,84E+00	mPt / ton of liquid steel
Water use	1,42E+00	1,02E+00	1,40E+00	mPt / ton of liquid steel

9.2 Contribution analysis – Route A

A process-based contribution analysis is reported in Figure 7. Unlike the approach proposed by [86] for this type of contribution analysis, in Route A, the direct GHG emissions across the plant have been grouped in the "Direct GHG" emissions group. This was necessary because, since data on direct GHG emissions were available as aggregated Scope 1 emissions from a product carbon footprint of the entire process, it was not possible to attribute the overall emissions of the steelmaking route to each tier of the process. Therefore, the contributions *to* the environmental impact categories *from* all unit processes included do not account for direct emissions and are only indirect contributions deriving *from* resource use and waste treatment processes.

Figure 7 shows that the main environmental contributor *to* Route A is the BF. The BF contribution *to* the impact categories ranges from 25% (for *Climate change*) to 80% (for *Ozone depletion*). This evidence is very relevant for the project because it stresses the importance of replacing BF with an ESF, thus electrifying primary steelmaking routes.

Moreover, another impactful tier of Route A is the coking plant. The contribution *to* all environmental impact categories *from* coke production is also crucial in Hy4Smelt because, through the steelmaking Routes B and C, it is possible to avoid the presence of a coking plant, which is necessary in a BF-BOF route.

The direct GHG emissions also represent a major environmental impact *to* the category *Climate change* since almost 50% of this category derives *from* the direct emissions associated with the steelmaking process. This evidence stresses the need to incorporate in the analysis a wider range of direct emissions in addition to GHG; for instance, direct impacts

from the emissions of particulate matter and NOx can be substantially relevant *to* the indicators *Particulate matter* and *Acidification* impact categories.

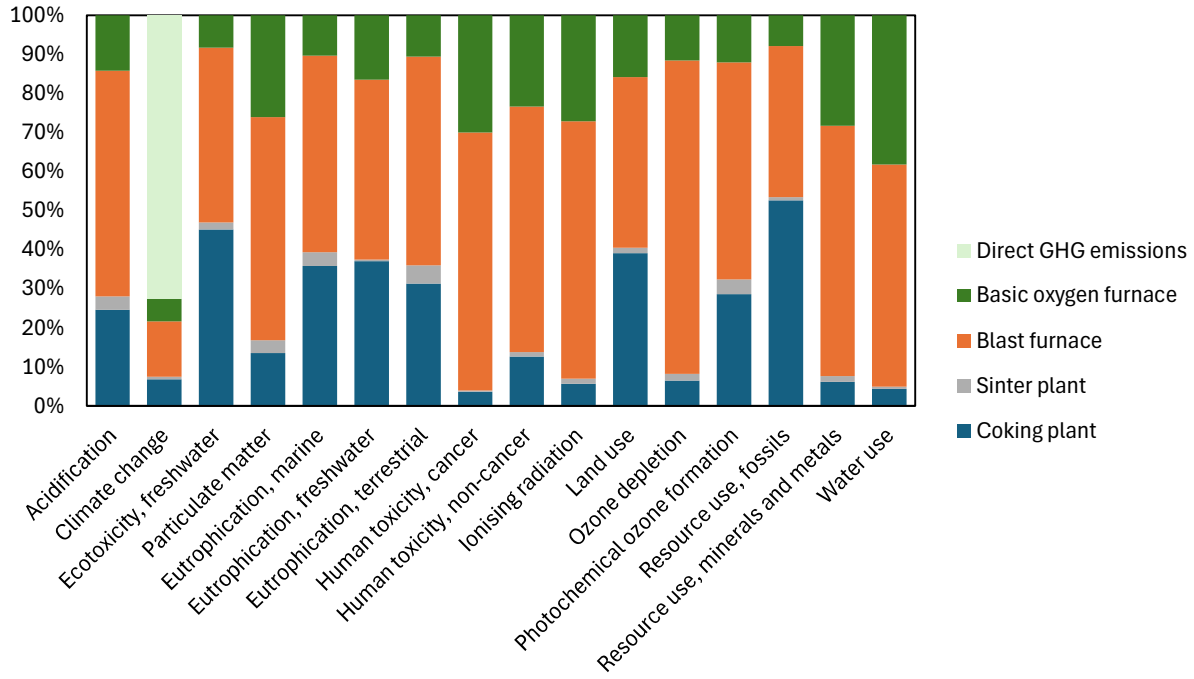

Figure 7: Process-based contribution analysis of Route A across the 16 impact categories. Results are expressed as the percentage contribution of each production tier to the characterized LCIA results. Direct GHG emissions are reported as a separate contribution because they were available only as aggregated Scope 1 emissions and could not be allocated to the individual production tiers.

A "first-tier contribution analysis" [86] of Route A is presented below, covering all production tiers from Tier 1 – BOF (Figure 8) to Tier 4 – Coking plant (Figure 11). We underline that due to the impossibility of splitting direct GHG emissions by Tier, their contribution has been excluded from the tier-specific contribution analysis illustrated in Figures 8-11.

Overall, the analysis shows that the environmental impacts of the BOF (Figure 8) are largely derived *from* the indirect contribution of the upstream production of HM in the BF. Except for the HM, some non-negligible contributions to the impact categories *Particulate matter*, *Human toxicity, cancer*, and *Water use* derive from the indirect contributions of alloys, the waste treatment of BOF slag, and Oxygen.

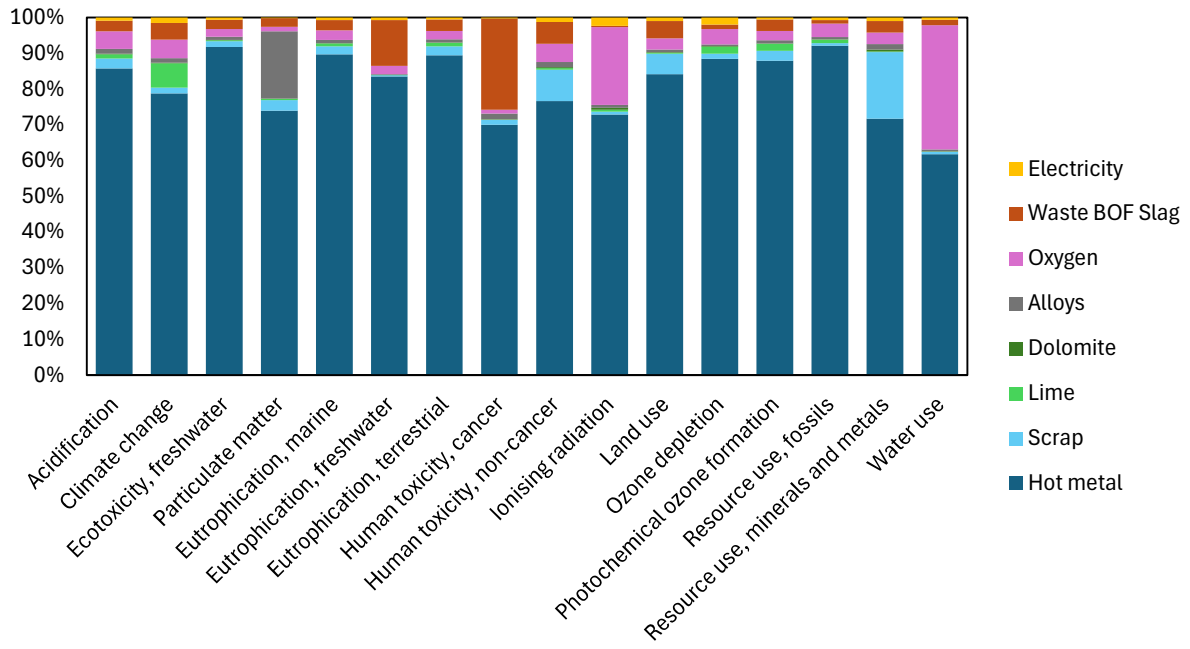

Figure 8: Contribution analysis of the BOF (Tier 1) in Route A. Results are expressed as the percentage contribution of the unit processes supplying the BOF to the characterized LCIA results.

The main contributors *to* the environmental impacts of the BF are highlighted in the analysis of Tier 2 (Figure 9). Several input flows contribute *to* the impacts of the BF: in addition to the indirect contribution *from* the consumption of coke in Tier 4 (i.e. grey bars in Figure 9), the consumption of iron-bearing materials represents another environmental hotspot for most impact categories. The iron-bearing materials used in the BF are the iron sinter produced in the sintering plant (i.e. Tier 2), the lump ore, and iron pellets.

Other relevant contributors *to* the environmental burdens of Tier 2 derive from the production of blast air, and the management of BF slag generated during steelmaking. This is especially true for the impact category *Human toxicity, cancer*. Blast air is another main contributor *to* some specific categories, such as *Human toxicity, non-cancer*, *Ionising radiation*, and *Resource use, minerals and metals*. The indirect impacts of oxygen and nitrogen are critical *to* the *Water use* category and the *Ionising radiation* category. Also, electricity consumption and the indirect impact of sinter *from* the previous Tier (Tier 3) are non-negligible contributors *to* the majority of the environmental impact indicators.

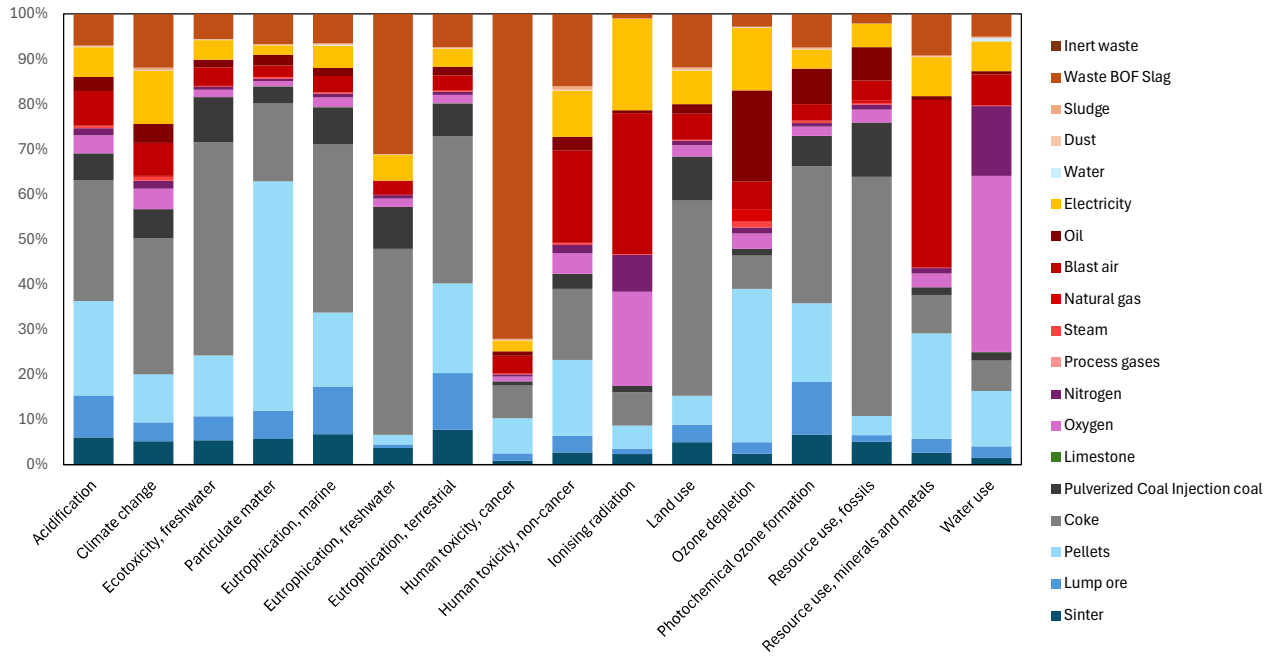

Figure 9: Contribution analysis of the BF (Tier 2) in Route A. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

The contribution analysis of the sintering process (Figure 10), which produces the sinter used in the BF, indicates that the indirect impacts *from* the production of coke breeze supplied by the coking plant are the main source of environmental impacts. Additional relevant indirect contributors *to* the majority of impact categories derive *from* the consumption of fine iron ore and the electricity demanded for the sintering process. Indirect impacts *from* electricity are particularly relevant to the impact categories *Ionising radiation* and *Ozone depletion*. The environmental burdens *from* iron ore supply are major contributors to several environmental impact categories, such as *Particulate matter*, *Eutrophication, terrestrial*, and *Acidification*.

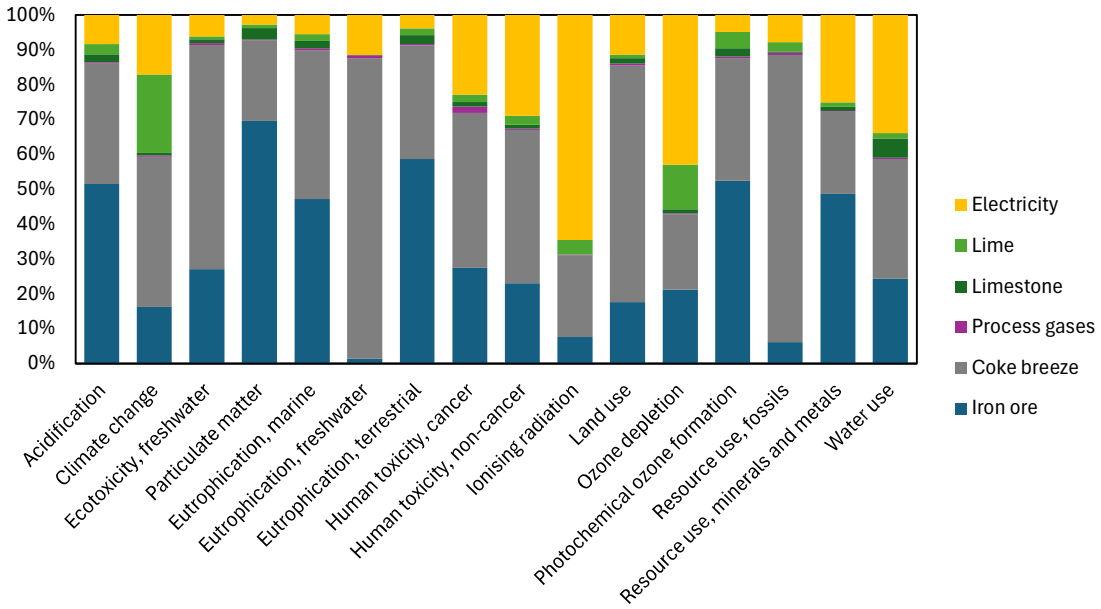

Figure 10: Contribution analysis of the sintering plant (Tier 3) in Route A. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

Finally, the detailed analysis of the coking plant (Figure 11), identified as the second largest environmental contributor *to* the impacts of Route A according to the process-based contribution analysis in Figure 7, shows that the consumption of coking coal, from which coke is produced, dominates the environmental impacts of Tier 4.

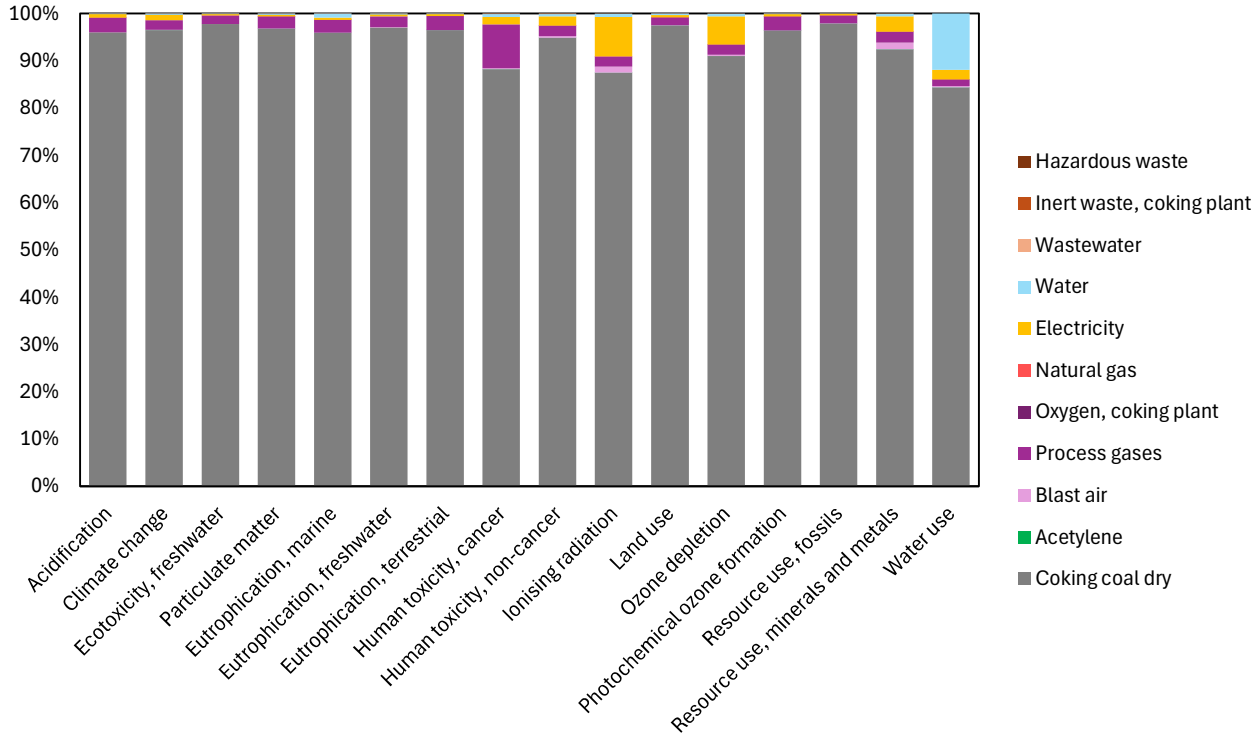

Figure 11: Contribution analysis of the coking plant (Tier 4) in Route A. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

9.3 Contribution analysis – Route B

A process-based contribution analysis for Route B is presented in Figure 12. As discussed in relation to Figure 7, the BF and the coking plant represent the main environmental hotspots of Route A. By replacing the BF with an ESF and eliminating the need for a coking plant, the environmental impacts associated with primary steel production are substantially reduced. This improvement is clearly demonstrated by comparing the contribution of the ESF in Figure 12 with that of the BF in Figure 7; based on these charts, the contribution of the BF is considerably higher across most impact categories compared to that of the ESF.

However, for certain impact categories, Figure 12 also shows that part of the environmental burden of Route B is shifted from the BF and the coking plants to the DRI production. In particular, the MIDREX process is the dominant contributor *to* the *Ozone depletion* indicator, accounting for approximately 80% of the impacts in this category. Moreover, a major contribution *to* the impact categories, especially *Particulate matter*, derives *from* the iron ore beneficiation and pellet production. In addition, both the MIDREX process and iron ore beneficiation and pellet production contribute substantially *to* the category *Resource use, fossils*. These findings explain why Route B exhibits higher environmental impact contributions than the other production routes *to* Ozone *depletion*, *Particulate matter*, and *Resource use, fossils* categories, as shown in Figure 12.

The contribution analysis demonstrates that, although replacing the BF with an ESF significantly reduces the environmental burden of the steelmaking process itself, upstream activities associated with DRI production become the dominant environmental hotspots. This finding highlights the importance of improving the direct reduction stage and the preparation of iron-bearing materials, thereby providing the rationale for the HYFOR-based Route C, which eliminates pellet production and replaces the natural gas-derived reducing gas with hydrogen.

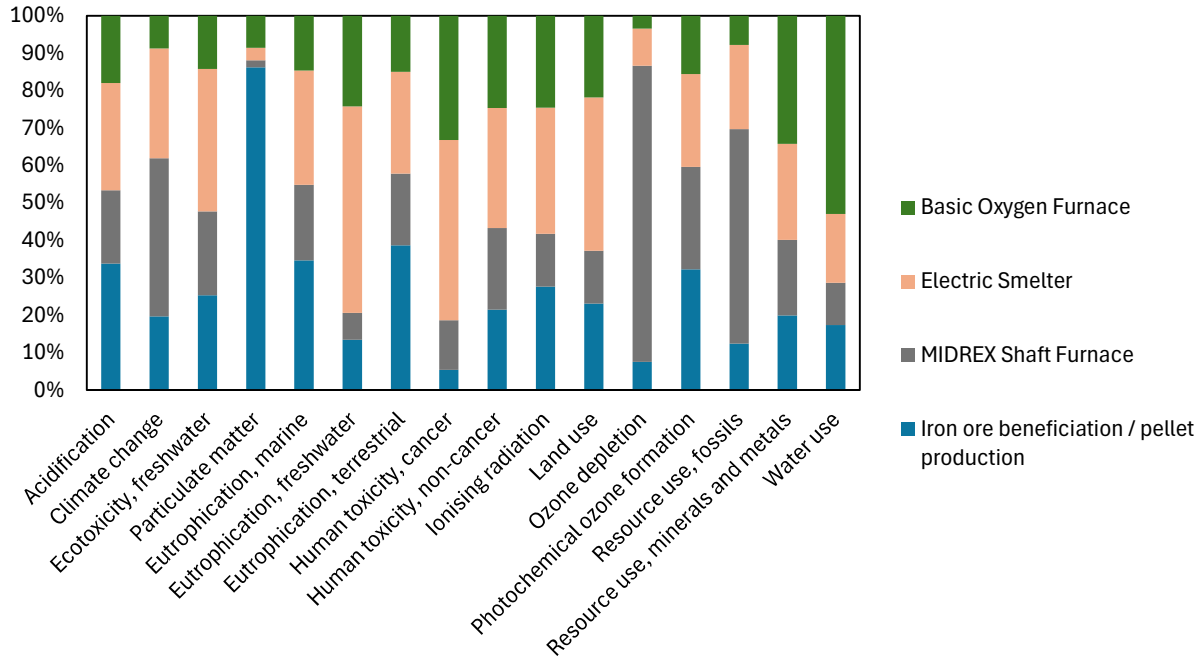

Figure 12: Process-based contribution analysis of Route B for the 16 impact categories. Values represent the relative contribution of each production tier to the characterized LCIA

results, highlighting the environmental contributions of iron ore beneficiation and pellet production, the MIDREX shaft furnace, the ESF, and the BOF.

A contribution analysis for each production tier of Route B is presented from Figure 13 (BOF, Tier 1) to Figure 16 (Iron ore beneficiation/pellet production, Tier 4).

Similar to Route A, the contribution analysis of Tier 1 indicates that the environmental impacts associated with the BOF mostly derive *from* the indirect contribution *to* the majority of impact categories of the HM outlet from the ESF (Figure 13), which carries the environmental burdens accumulated throughout the unit processes in previous tiers. Again, some consistent environmental impact percentage contributions are derived from oxygen and waste management of BOF slag to some specific categories like *Human toxicity, cancer* and *Water use*.

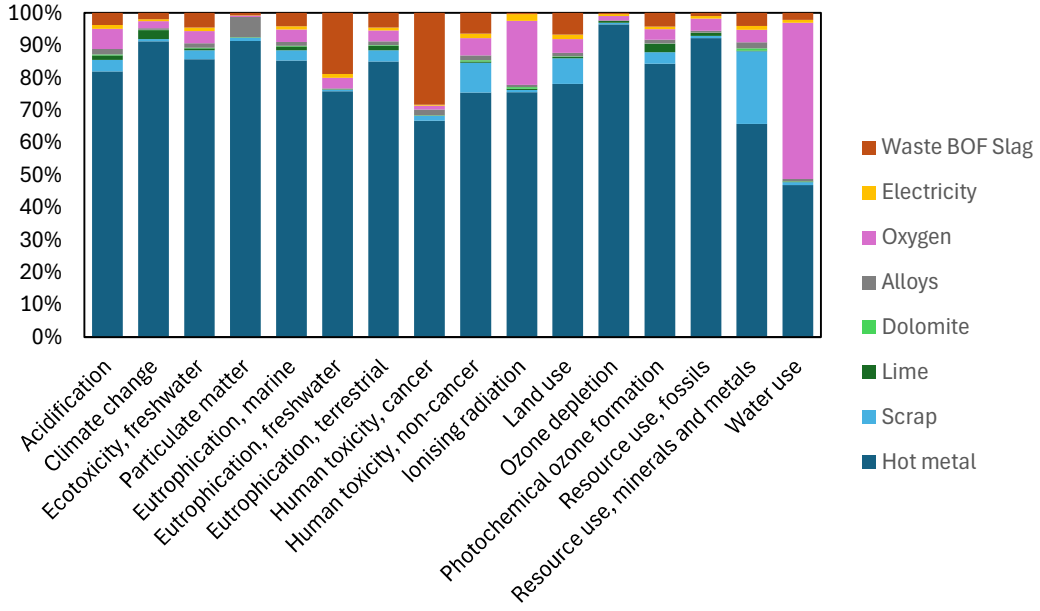

Figure 13: Contribution analysis of the BOF (Tier 1) in Route B. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

The contribution analysis of Tier 2 (i.e. the ESF operation) is illustrated in Figure 14 and shows that among all the inputs of the process, the production of DRI in the Tier 3 is the main environmental hotspot for all environmental impact categories, except for *Eutrophication, freshwater,* and *Human toxicity, cancer*. Investigating Tier 3, the MIDREX shaft furnace, is therefore important to evaluate the impact of the process. However, other important contributors include the electricity consumption of the ESF (especially *to Ionising radiation*, *Resource use, minerals and metals*, and Water use), the management of ESF slag (especially contributing *to Human toxicity, cancer,* and *Eutrophication, freshwater*), all of which contribute significantly to the overall environmental impacts.

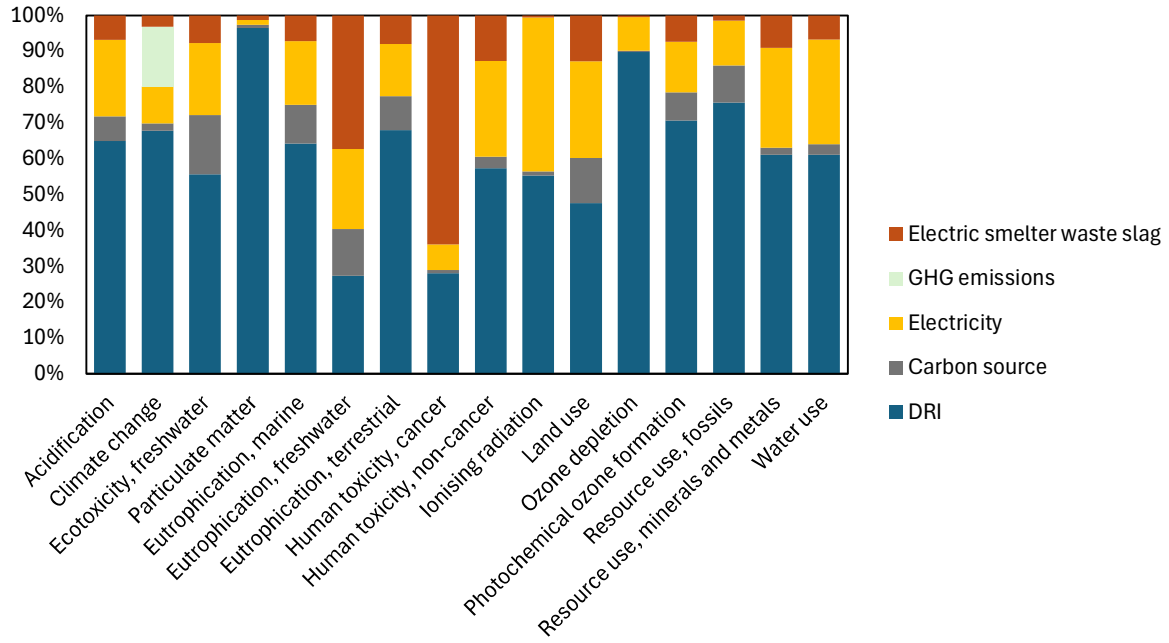

Figure 14: Contribution analysis of the ESF (Tier 2) in Route B. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

A detailed contribution analysis of Tier 3 (MIDREX shaft furnace) explains why the indirect impacts *from* DRI overall represent a major environmental hotspot. Figure 15 highlights that the environmental impacts of DRI production are primarily derived *from* the iron pellets supplied from Tier 4 (Figure 15). For example, iron pellet production accounts for almost 95% of the impacts *on* the *Particulate matter* category. In addition, the impacts *from* consumption of natural gas for the reducing agent production represent another major environmental hotspot across all categories, particularly *to* Ozone *depletion* and *Resource use, fossils*. Direct contributions *from* GHG emissions are also responsible for a substantial share of the impacts in *Climate change*, while the environmental burdens *from* the electricity consumed in the MIDREX process and the natural gas reformer provide a non-negligible contribution *to* most of the impact categories (e.g *Ecotoxicity, freshwater*, and *Ionising radiation*). Again, it is important to investigate Tier 4, which represents an environmental hotspot for the DRI production.

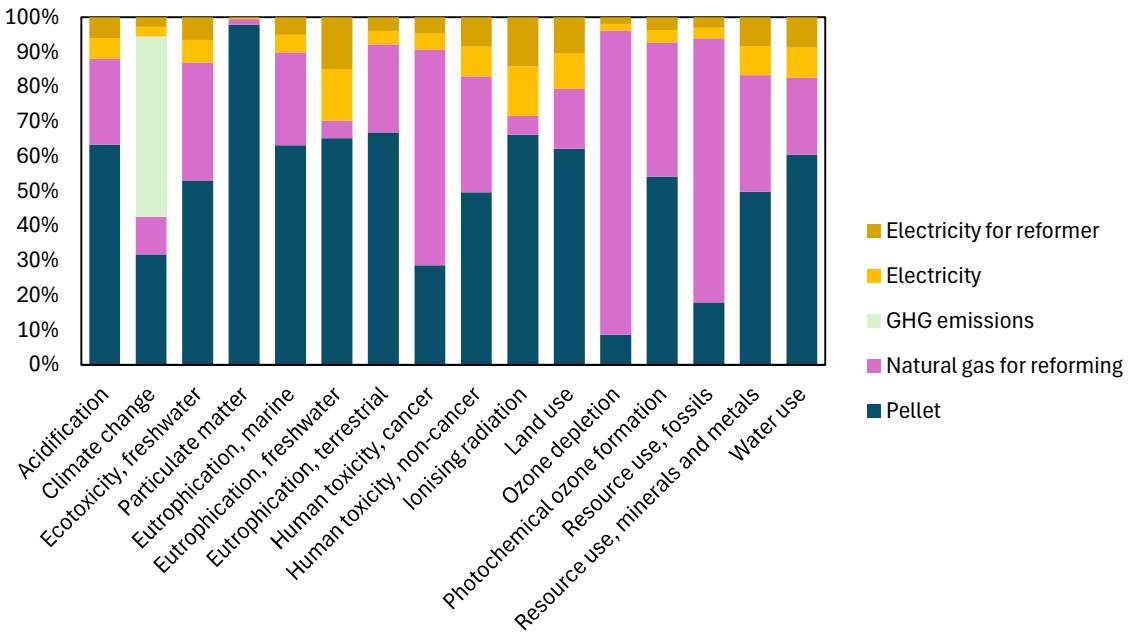

Figure 15: Contribution analysis of the MIDREX shaft furnace (Tier 3) in Route B. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

The contribution analysis of iron ore beneficiation and pellet production (Figure 16) shows that the environmental burdens *from* electricity consumption are the primary contributors *to* the large majority of the environmental impact indicators associated with Tier 4. All preparation steps that aim to increase the iron content of the pellet compared to the mineral consume a massive amount of electricity and additives.

Other relevant contributors indeed include the production of process additives such as bentonite and dolomite, dominating the category *Particulate* matter for which the percentage contribution is higher than 90%. However, for all the impact categories, the contribution of these additives ranges from 20% to 50%. After electricity and additives, the supply of virgin iron ore represents the third main contributor *to* the impact categories, and it is especially relevant for *Acidification*, *Eutrophication, marine* and *terrestrial*, as well as *Photochemical ozone formation*. In the specific case of *Climate change*, direct contributions are also consistent since direct GHG emissions account for almost 50% of the impacts to this category.

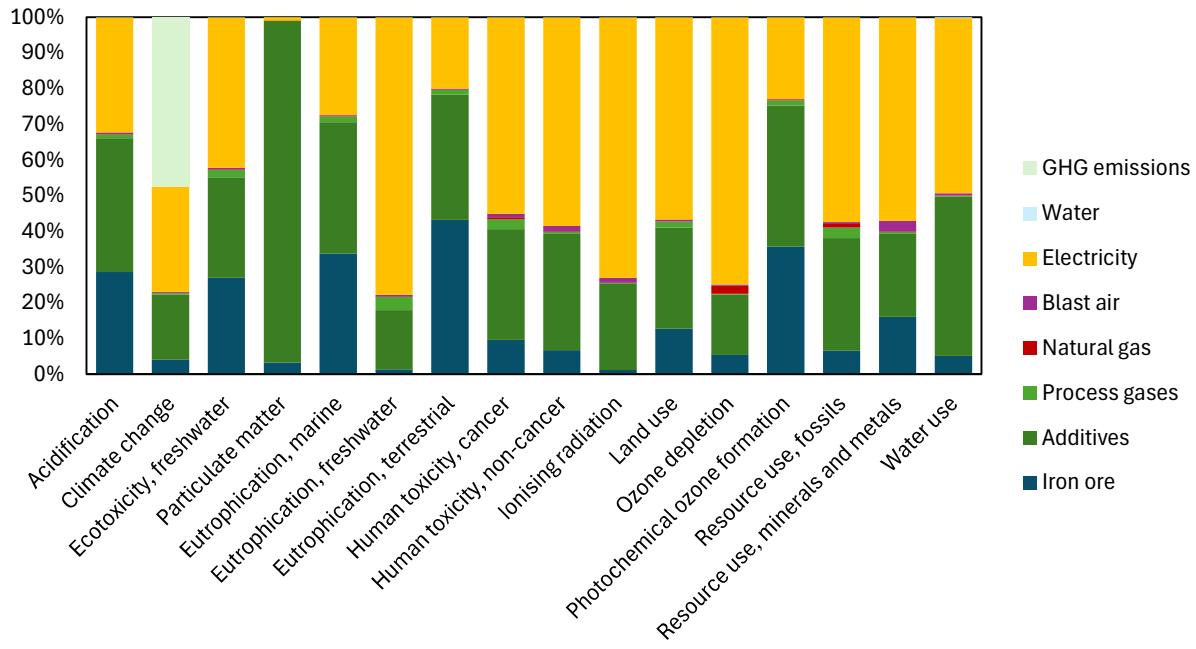

Figure 16: Contribution analysis of the iron ore beneficiation and pellet production process (Tier 4) in Route B. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

9.4 Contribution analysis – Route C

Figure 17 presents a process-based contribution analysis of Route C, highlighting the unit processes that represent the main environmental hotspots across the 16 impact categories. As shown in the figure, the BOF, ESF, and HYFOR unit processes constitute the major contributors *to* the environmental impacts of the steelmaking route. In contrast, the contribution *from* the iron ore preparation stage *to* all the impact categories is considerably lower than that of iron pellet production observed for Route B (Figure 12).

This difference largely explains the improved environmental performance of Route C compared with Route B for most impact categories, as well as for the single score. The results therefore confirm the environmental advantages of the HYFOR technology, which enables the production of DRI directly from pretreated iron ore fines, avoiding the energy- and resource-intensive pelletization step required by the MIDREX process, which is one of the targets of Hy4Smelt

Although Route C exhibits the lowest overall environmental impacts among the three steelmaking routes, the HYFOR process itself remains a significant contributor across nearly all impact categories. A first-tier contribution analysis will show that this is largely due to the grey hydrogen makeup, which demonstrates the high potential of Hy4Smelt in reducing the environmental burdens of Route C via the replacement of grey hydrogen with green hydrogen in the direct reduction process.

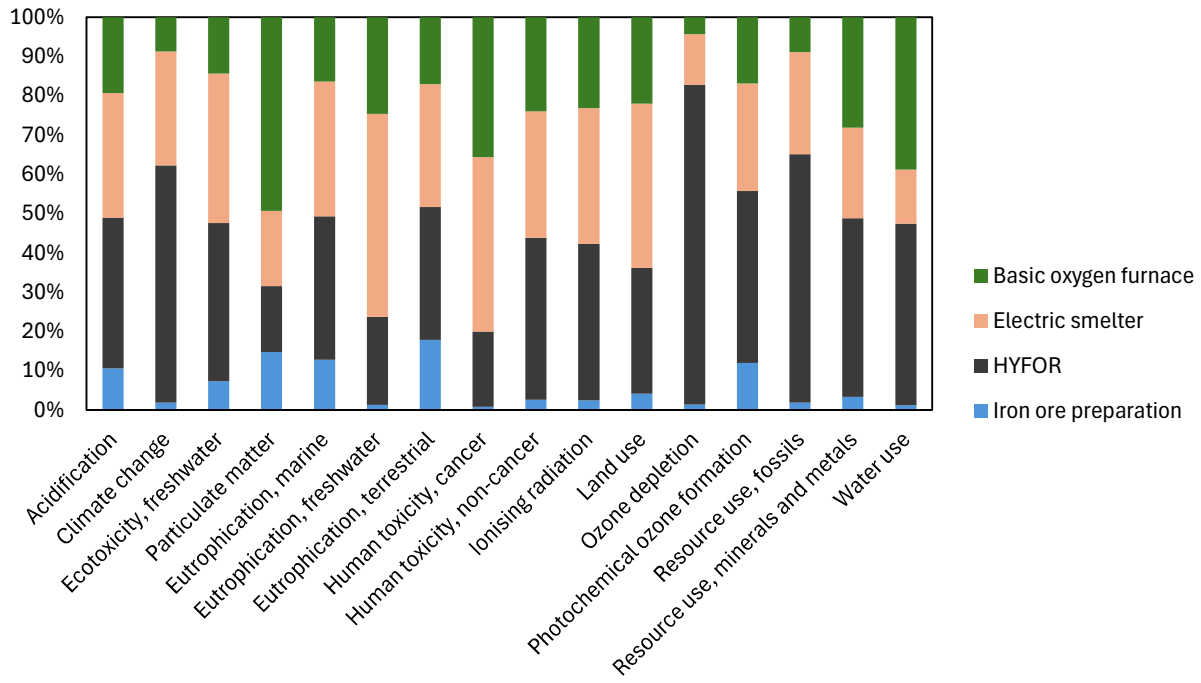

Figure 17: Process-based contribution analysis of Route C across the 16 impact categories. Results are expressed as the percentage contribution of each production tier to the characterized LCIA results.

The contribution analysis of each production tier is presented from Figure 18 (referred to the BOF, Tier 1) to Figure 21 (Iron ore preparation, Tier 4).

As expected, the Tier 1 analysis confirms that the environmental impact contributions associated with liquid steel production in the BOF *to* all characterized indicators are primarily derived *from* the indirect contribution of the HM supplied from the previous tier (Figure 18). This outcome is not surprising because the HM embodies the environmental burdens associated with all the previous unit processes (ESF, HYFOR, and iron ore preparation). Like for previous steelmaking routes, it is therefore important moving forward to the previous tiers and assess the main environmental hotspots associated with upstream unit processes.

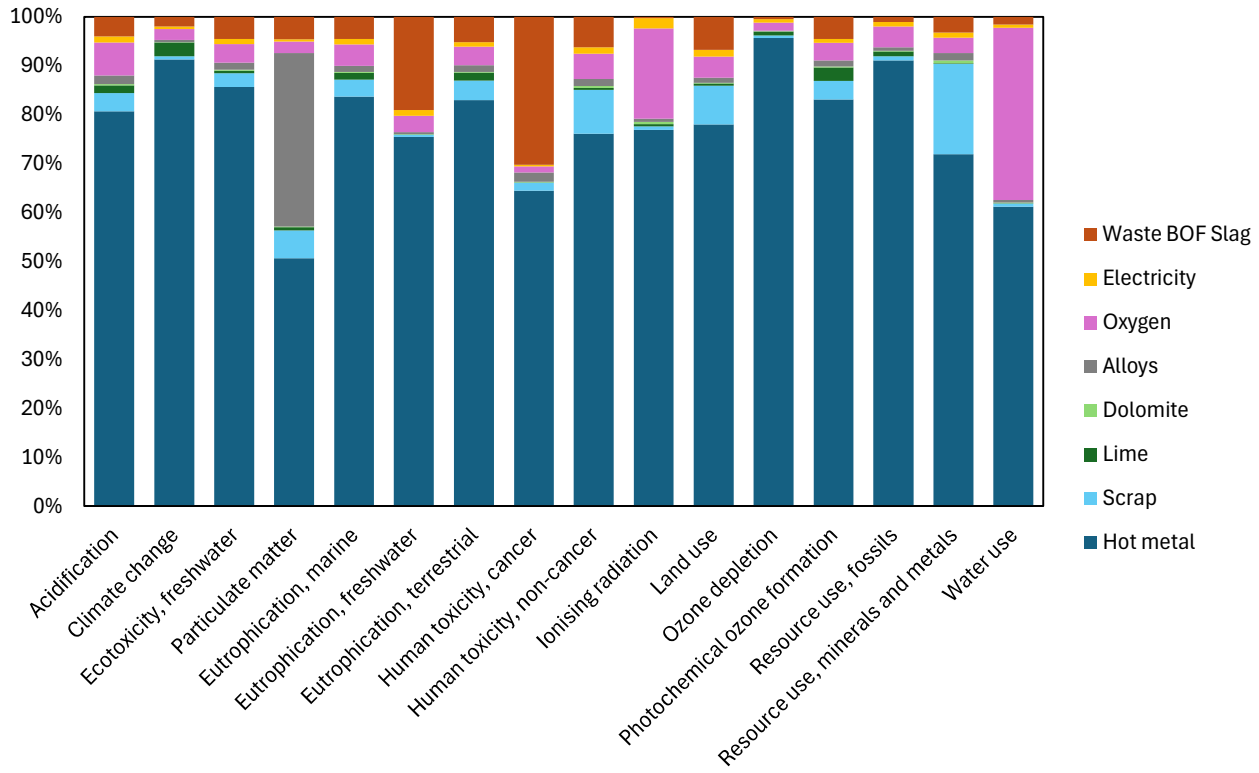

Figure 18: Contribution analysis of the BOF (Tier 1) in Route C. Results are expressed as the percentage contribution of the unit processes supplying the BOF to the characterized LCIA results.

In Figure 19, a contribution analysis of Tier 2, which is the ESF. Interestingly, despite having replaced the MIDREX process with the HYFOR in Route C, according to Figure 19, DRI production remains the dominant environmental hotspot for all the impact categories except for *Human toxicity, cancer*, for which the waste management of ESF slag represents the main contributor. Similarly to the case of the ESF in Route B, other important contributors across the impact categories include electricity consumption in the ESF and the direct emissions of GHG for the *Climate change* category.

However, since the DRI is produced through the HYFOR process, the environmental performance of Tier 2 is largely determined by the upstream processes occurring in Tier 3. A further tier-based contribution analysis to Tier 3 is therefore necessary.

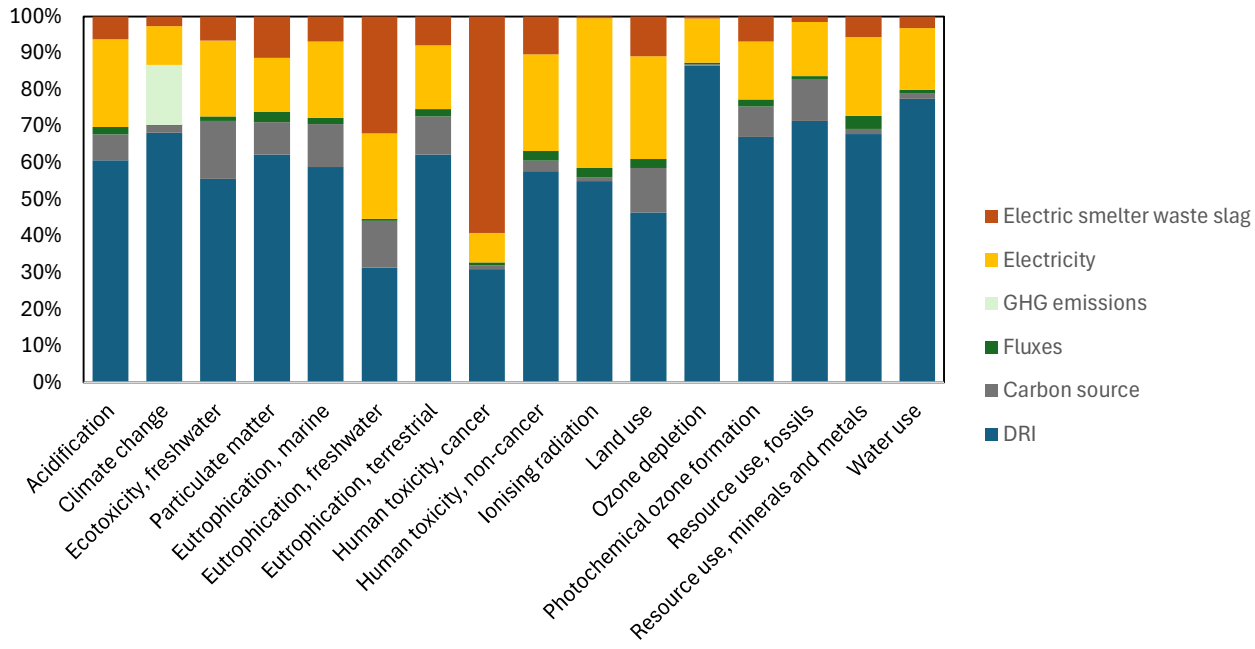

Figure 19: Contribution analysis of the ESF (Tier 2) in Route C. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

The contribution analysis of the HYFOR process (Tier 3), reported in Figure 20, identifies two major environmental hotspots. The first is the electricity consumption required for the direct reduction process, which accounts for more than 90% of the impacts in *Freshwater eutrophication* and *Ionising radiation*. The second is the hydrogen makeup, which represents a substantial contributor across most of the impact categories. Although its contribution is relatively limited for *Freshwater eutrophication*, *Ionising radiation*, and *Land use*, it generally exceeds 30% for the remaining impact categories and reaches approximately 65% for *Ozone depletion, Water use,* and *Resource use, fossils*.

These results clearly demonstrate the potential for further improving the environmental performance of Route C. Assuming that, in accordance with the objectives of the Hy4Smelt project, grey hydrogen is replaced by green hydrogen produced via water electrolysis, whose carbon intensity is considerably lower [88] , a substantial reduction in the environmental impacts associated with the HYFOR process can be achieved, and thus of Route C. This potential improvement is proportional to the magnitude of the purple segment illustrated in Figure 20.

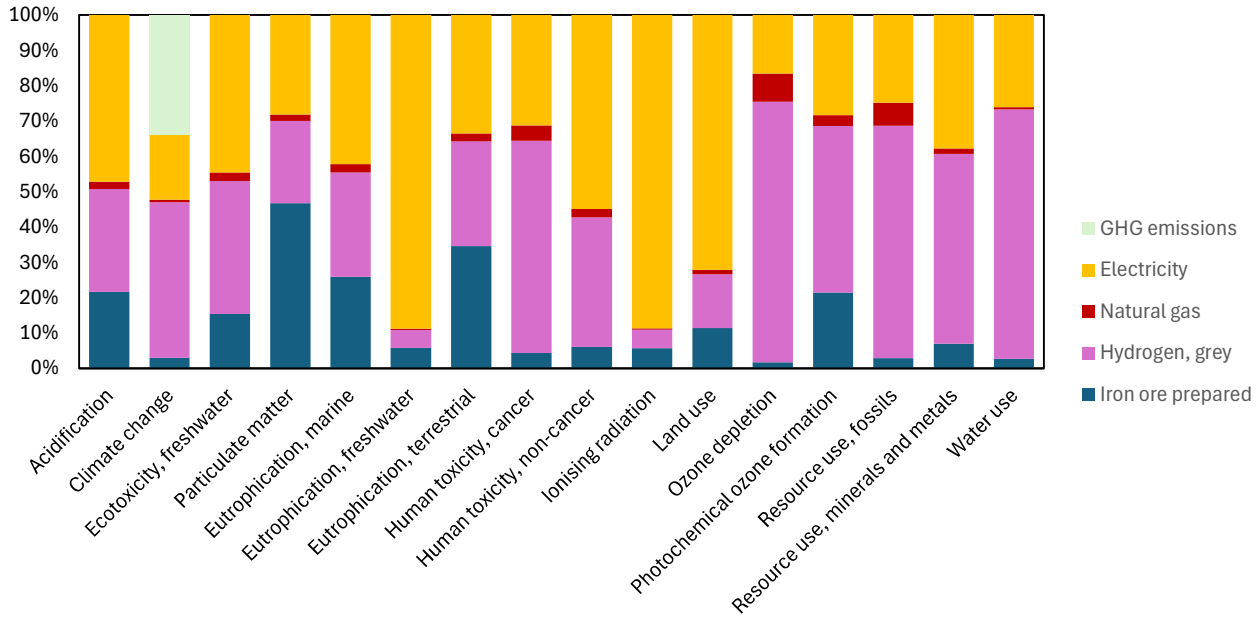

Figure 20: Contribution analysis of the HYFOR process (Tier 3) in Route C. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

Finally, the contribution analysis of Tier 4, regarding iron ore preparation (Figure 21), indicates that iron ore mining is the primary environmental hotspot of this production stage. Electricity consumption also represents a significant contributor, particularly for *Freshwater ecotoxicity* and *Ionising radiation*. Compared with the pellet production stage in Route B, however, the environmental burdens associated with iron ore preparation are considerably lower, further confirming the environmental benefits of directly processing iron ore fines through the HYFOR technology.

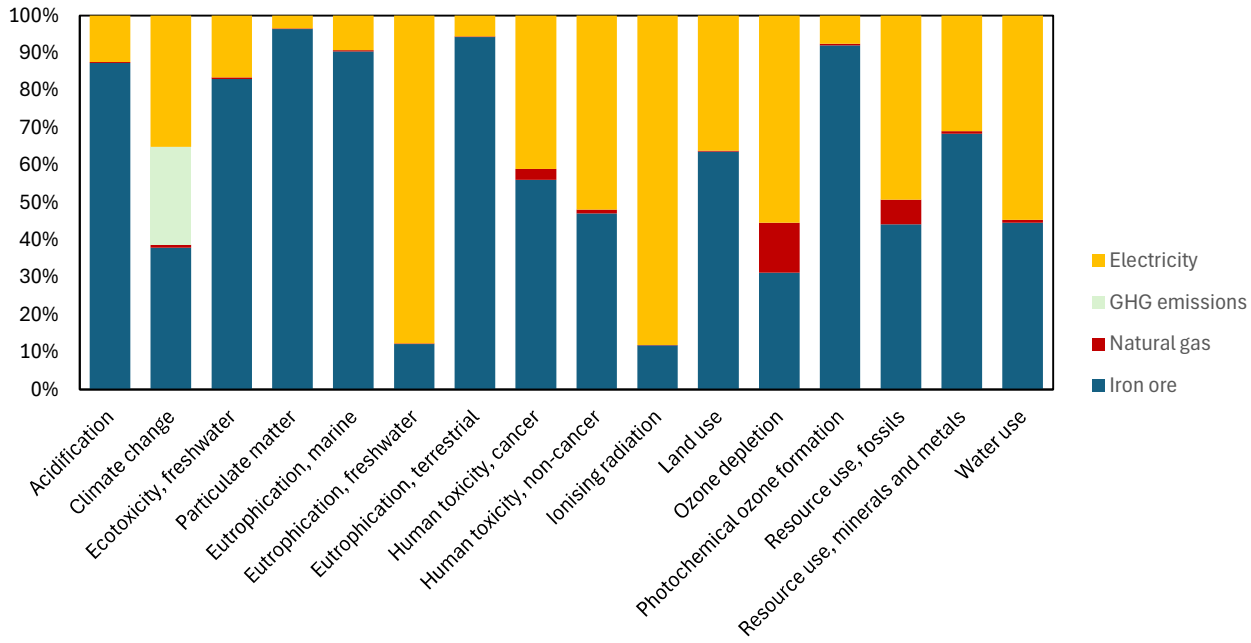

Figure 21: Contribution analysis of the iron ore preparation process (Tier 4) in Route C. Results are expressed as the percentage contribution of the input flows to the characterized LCIA results.

9.5 Sensitivity analysis

The results presented in the previous sections are influenced by the assumption that slags are waste managed via disposal. This section quantifies the variation in results across three scenarios, in which slags are modelled as waste sent to disposal (Scenario 1), waste sent to recycling (Scenario 2), or by-products of the steelmaking processes (Scenario 3). The characterised results calculated for all the considered scenarios, are reported in *Table 13*.

Table 13: Characterized LCIA results for the 16 impact categories assessed for Routes A, B, and C in Scenarios 1, 2 ,3. Results are reported per functional unit, corresponding to the production of 1 ton of liquid steel.

Impact category	**Route A**			**Route B**			**Route C**			**Unit**
	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 1*	*Scenario 2*	*Scenario 3*	
Acidification	3,26E+00	2,97E+00	2,16E+00	2,58E+00	2,34E+00	1,82E+00	2,40E+00	2,19E+00	1.74E+00	mol H+ eq
Climate change	2,33E+03	2,24E+03	1,93E+03	1,55E+03	1,48E+03	1,13E+03	1,56E+03	1,49E+03	1.17E+03	kg CO2 eq
Ecotoxicity, freshwater	3,65E+03	3,36E+03	2,41E+03	2,13E+03	1,89E+03	1,46E+03	2,12E+03	1,90E+03	1.50E+03	CTUe
Particulate matter	4,14E-05	3,84E-05	2,90E-05	1,26E-04	1,23E-04	9,43E-05	2,19E-05	1,97E-05	1.65E-05	disease inc.

Eutrophication, marine	1,05E+00	9,61E-01	6,92E-01	7,43E-01	6,67E-01	5,15E-01	6,68E-01	6,00E-01	4.75E-01	kg N eq
Eutrophication, freshwater	1,39E+00	8,53E-01	6,10E-01	9,49E-01	5,02E-01	3,86E-01	9,35E-01	5,31E-01	4.18E-01	kg P eq
Eutrophication, terrestrial	1,04E+01	9,41E+00	6,78E+00	7,39E+00	6,55E+00	5,06E+00	6,52E+00	5,76E+00	4.56E+00	mol N eq
Human toxicity, cancer	4,44E-07	1,01E-07	7,49E-08	4,00E-07	1,16E-07	9,07E-08	3,75E-07	1,19E-07	9.44E-08	CTUh
Human toxicity, non-cancer	4,56E-06	3,72E-06	2,78E-06	4,34E-06	3,65E-06	2,87E-06	4,46E-06	3,84E-06	3.07E-06	CTUh
Ionising radiation	8,69E+01	8,60E+01	6,51E+01	9,61E+01	9,54E+01	7,54E+01	1,02E+02	1,02E+02	8.16E+01	kBq U-235 eq
Land use	3,49E+03	2,98E+03	2,17E+03	2,54E+03	2,11E+03	1,65E+03	2,52E+03	2,13E+03	1.70E+03	Pt
Ozone depletion	1,23E-05	1,18E-05	8,55E-06	4,08E-05	4,04E-05	3,07E-05	3,31E-05	3,27E-05	2.55E-05	kg CFC11 eq+
Photochemical ozone formation	3,00E+00	2,71E+00	1,96E+00	2,32E+00	2,08E+00	1,61E+00	2,15E+00	1,93E+00	1.53E+00	kg NMVOC eq
Resource use, fossils	1,88E+04	1,83E+04	1,31E+04	1,90E+04	1,86E+04	1,42E+04	1,67E+04	1,63E+04	1.28E+04	MJ
Resource use, minerals and metals	2,37E-03	2,13E-03	1,62E-03	1,96E-03	1,76E-03	1,42E-03	2,39E-03	2,22E-03	1.79E-03	kg Sb eq
Water use	1,92E+02	1,83E+02	1,43E+02	1,38E+02	1,31E+02	1,09E+02	1,89E+02	1,82E+02	1.50E+02	m3 depriv.

Table 13 shows that all the environmental impact categories of the analyzed steelmaking routes decrease progressively from Scenario 1 to Scenario 2 and then to Scenario 3. Scenario 1 is confirmed as the most impactful because it includes the environmental burdens associated with slag disposal, which can be particularly relevant for certain impact categories, as shown by the contribution analyses presented in 9.2-9.4. In Scenario 2, all slags are assumed to be fully recycled, which implies that their waste management is considered burden-free in accordance with the cut-off approach. Scenario 3 produces the lowest impacts for steel because a share of the environmental burdens of the steelmaking processes is allocated to the slags. Depending on the process, the mass-based allocation factor assigned to slags ranges from approximately 10% to 20%, with the highest values observed for BF and ESF slags.

The influence of slag modelling on the results varies across impact categories. In particular, the contribution analysis indicates that slag disposal represents a relevant environmental hotspot for some impact categories such as *Human toxicity, cancer*. Consequently, the results for these categories decrease particularly markedly when slags are modelled as recyclable waste or by-products rather than as wastes sent to disposal.

Figure 22 also shows that the single-score environmental impact decreases from Scenario 1 to Scenario 3. Nevertheless, the ranking of the three routes remains unchanged across all scenarios. Regardless of the LCI modelling approach adopted for slags, Route C has the lowest environmental burden, followed by Route B and Route A.

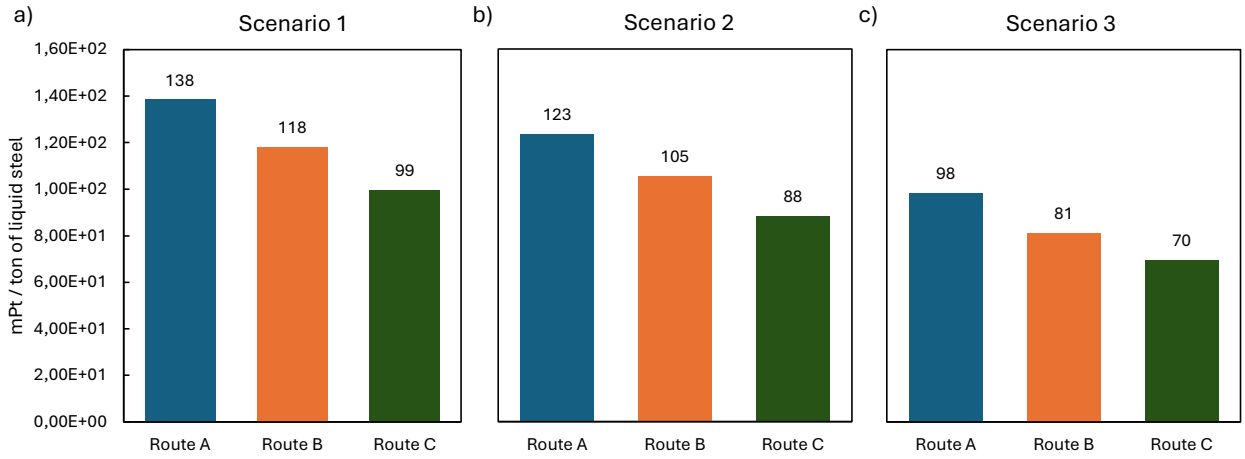

Figure 22: Single score results obtained after normalization and weighting of the characterized LCIA results according to the EF 3.1 method for a) Scenario 1, b) Scenario 2, and c) Scenario 3. Results are expressed as millipoints (mPt) per functional unit, corresponding to the production of 1 ton of liquid steel.

In the Deliverable 5.4 of the Hy4Smelt project, once complete data on the use and end-of-life management of the slags become available, the most appropriate LCI modelling approach for slag will be selected. The resulting impacts will then be benchmarked against the corresponding scenario assessed in this preliminary LCA.

10. Conclusions

Deliverable D5.1 presented a preliminary LCA of three steelmaking routes selected as benchmark scenarios for the Hy4Smelt project. The assessment provides the environmental baseline against which the final HYFOR–ESF–BOF route powered by green hydrogen will be evaluated in the subsequent phases of the project.

The comparative analysis shows that replacing the conventional BF with an ESF substantially reduces the environmental impacts associated with primary steel production. The additional replacement of the MIDREX process with the HYFOR technology further improves environmental performance by avoiding the beneficiation and pelletization stages required for conventional DRI production. As a result, Route C achieves the lowest overall environmental impacts among the three benchmark routes considered based on the single score result.

The contribution analyses provide valuable insight into the environmental hotspots of each production route. While the BF represents the dominant contributor in the conventional route, the environmental burden progressively shifts toward upstream DRI production in Routes B and C. In particular, the HYFOR contribution analysis highlights that hydrogen production and electricity consumption are the main drivers of the remaining environmental impacts. These findings clearly indicate that the transition from grey hydrogen to green hydrogen represents one of the largest opportunities for further reducing the environmental footprint of primary steel production.

The sensitivity analysis conducted on the LCI modelling of BF, BOF, and ESF slags confirms the robustness of the main conclusions. Three alternative scenarios were assessed, considering slags as wastes sent to disposal, recyclable wastes, or by-products subject to mass-based allocation. Although the selected approach affects the magnitude of the results, particularly for impact categories strongly influenced by slag disposal, the ranking of the routes remains unchanged. Route C consistently exhibits the lowest overall environmental burden, followed by Route B and Route A.

Although several assumptions were required because of the preliminary nature of the assessment, the adopted methodology provides a consistent and scientifically robust basis for future work. As additional primary industrial data become available and the Hy4Smelt technology evolves, the LCA will be progressively refined. The final environmental assessment, to be reported in Deliverable D5.4, will quantify the environmental benefits of the complete HYFOR–ESF–BOF route powered by renewable hydrogen and evaluate its potential contribution toward the decarbonization of the European steel sector.

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12. Appendix 1 – Life Cycle Inventories

12.1 Appendix 1.1 – Route A

Table A1: LCI of the coking plant for Route A.

Coking Plant				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Coking coal dry	1250	kg	Hard coal {AT}| market for hard coal | Cut-off, U
	Process gases	3615	MJ	Coal gas {DE}| coke production | Cut-off, U (25%) + Blast furnace gas {GLO}| market for blast furnace gas | Cut-off, U (75%)
	Water	15	m^3	Water, decarbonised {DE}| market for water, decarbonised | Cut-off, U
	Natural gas	3E-03	Nm^3	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U
	Electricity	24	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Blast air	8	m^3	Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, U
	Oxygen	7E-04		Oxygen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U
	Acetylene	2E-04		Acetylene {RER}| market for acetylene | Cut-off, U
output	**Coke**	**1000**	**kg**	Main product
	Crude tar	**35**	**kg**	Co-product
	Light oil	**10**	**kg**	Co-product
	Sulfuric acid	**4**	**kg**	Co-product
	Quenching sludge/slurry	**1E-02**	**kg**	Co-product
	Inert waste	8E-02	kg	Inert waste, for final disposal {RoW}| market for inert waste, for final disposal | Cut-off, U
	Wastewater	3E-01	m^3	Wastewater from pig iron production {Europe without Switzerland}| market for wastewater from pig iron production | Cut-off, U

Table A.2: LCI of the sinter plant for Route A.

Sinter Plant				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Iron ore	959	kg	Iron ore, crude ore, 46% Fe {GLO}| market for iron ore, crude ore, 46% Fe | Cut-off, U
	Coke	44	kg	Coke {RoW}| market for coke | Cut-off, U
	Limestone	131	kg	Limestone, unprocessed {RoW}| market for limestone, unprocessed | Cut-off, U
	Process gases	67	MJ	Coal gas {DE}| coke production | Cut-off, U (25%) + Blast furnace gas {GLO}| market for blast furnace gas | Cut-off, U (75%)
	Electricity	33	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Lime	10	kg	Quicklime, in pieces, loose {CH}| market for quicklime, in pieces, loose | Cut-off, U
output	**Sinter**	**1000**	**kg**	

Table A.3: LCI of the Blast Furnace for Route A.

Blast Furnace				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Sinter	615	kg	Table A.2
	Lump ore	298	kg	Iron ore concentrate {GLO}| market for iron ore concentrate | Cut-off, U
	Pellets	669	kg	Iron pellet {GLO}| market for iron pellet | Cut-off, U
	Recycled BOF slag	17	kg	Blast furnace slag {GLO}| blast furnace slag, Recycled Content cut-off | Cut-off, U
	Coke dry	348	kg	Table A.1
	Waste plastics	18	MJ	Waste plastic, mixed, for recycling, unsorted {GLO}| waste plastic, mixed, for recycling, unsorted, Recycled Content cut-off | Cut-off, U
	Pulverized Coal Injection coal	96	kg	Hard coal {AT}| market for hard coal | Cut-off, U
	Process gases	1,2	MJ	Coal gas {DE}| coke production | Cut-off, U (25%) + Blast furnace gas {GLO}| market for blast furnace gas | Cut-off, U (75%)
	Oxygen	44	Nm^3	Oxygen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U (density assumed 1,311 kg / m3)
	Blast air + O2	879	Nm^3	Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, U
	Limestone	26	kg	Limestone, unprocessed {RoW}| market for limestone, unprocessed | Cut-off, U
	Natural gas	2,2	kg	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U (0,735 kg/m^3)
	Oil	30	kg	Light fuel oil {Europe without Switzerland}| market for light fuel oil | Cut-off, U
	Nitrogen	46	kg	Nitrogen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U (1,25 kg/m^3)
	Water	3	m^3	Water, decarbonised {DE}| market for water, decarbonised | Cut-off, U (1000 kg/m^3)
	Steam	48	MJ	Heat, from steam, in chemical industry {RER}| market for heat, from steam, in chemical industry | Cut-off, U
output	**Hot metal**	**1000**	**kg**	
	BF-slag	267	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U
	Waste	11	kg	Inert waste, for final disposal {RoW}| market for inert waste, for final disposal | Cut-off, U
	Dust	14	kg	Blast furnace dust {RER}| market for blast furnace dust | Cut-off, U
	Sludge	12	kg	Blast furnace sludge {Europe without Switzerland}| market for blast furnace sludge | Cut-off, U

Table A.4: LCI of the Basic Oxygen Furnace for Route A.

Basic Oxygen Furnace				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Hot metal	814	kg	Table A.3
	Scrap	271	kg	Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, U
	Lime	37	kg	Quicklime, in pieces, loose {CH}| market for quicklime, in pieces, loose | Cut-off, U
	Dolomite	24	kg	Dolomite {RER}| dolomite production | Cut-off, U
	Alloys	1	kg	Ferrosilicon {GLO}| market for ferrosilicon | Cut-off, U
	Oxygen	51	Nm^3	Oxygen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U (density assumed 1,311 kg / m^3)
	Electricity	35	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
output	**Liquid steel**	**1000**	**kg**	
	BOF-slag	107	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U

For the BF-BOF route, aggregated data on GHG emissions across all the steps were validated by industrial partners, i.e., 1690 kg CO_2 eq/ton of liquid steel.

12.2 Appendix 1.2 – Route B

Table A.5: LCI of the Iron ore beneficiation / Pellet Production plant for Route B

Iron ore beneficiation / Pellet Production				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Iron ore	996	kg	Iron ore, crude ore, 46% Fe {GLO}| market for iron ore, crude ore, 46% Fe | Cut-off, U
	Water	1E-1	m^3	Water, decarbonised {DE}| market for water, decarbonised | Cut-off, U
	Electricity	236	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Binders/additives	120	kg	Adapted from binders and additives in "Iron pellet {RoW}| iron pellet production | Cut-off, U"
	Process gases	306	kg	Coal gas {DE}| coke production | Cut-off, U (25%) + Blast furnace gas {GLO}| market for blast furnace gas | Cut-off, U (75%)
	Natural gas	14	MJ	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U (36 MJ/m^3)
	Blast air	10	MJ	Compressed air, 600 kPa gauge {RER}| market for compressed air, 600 kPa gauge | Cut-off, U
output	**Iron pellets**	**1000**	**kg**	
	Direct GHG emissions	104	kg	Emissions to air

Table A.6: LCI of the Reformer / MIDREX Shaft Furnace for Route B.

Reformer / MIDREX Shaft Furnace				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Pellets	1450	kg	Table A.5
	Natural gas for reforming	260	Nm^3	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U
	Electricity for the reformer	100	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Electricity for the shaft furnace	100	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
output	**DRI**	**1000**	**kg**	
	Direct GHG emissions from the reformer	505	kg	Emissions to air
	Direct GHG emissions from the shaft furnace	11,1	kg	Emissions to air

Table A.7: LCI of the Electric Smelter for Route B.

Electric Smelter				
	Flow	*Amount*	*Unit*	*Background dataset*
input	DRI / HDRI	1184	kg	Table A.6
	Electricity	652	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Carbon source	84	kg	Hard coal {AT}| market for hard coal | Cut-off, U
output	**Hot metal**	**1000**	**kg**	
	Slag	198	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U
	Direct GHG emissions	291	kg	Emissions to air

Table A.8: LCI of the Basic Oxygen Furnace for Route B.

Basic Oxygen Furnace				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Hot metal	814	kg	Table A.7
	Scrap	271	kg	Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, U
	Lime	37	kg	Quicklime, in pieces, loose {CH}| market for quicklime, in pieces, loose | Cut-off, U
	Dolomite	24	kg	Dolomite {RER}| dolomite production | Cut-off, U
	Alloys	1	kg	Ferrosilicon {GLO}| market for ferrosilicon | Cut-off, U
	Oxygen	51	Nm^3	Oxygen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U (density assumed 1,311 kg / m3)
	Electricity	35	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
output	**Liquid steel**	**1000**	**kg**	
	BOF-slag	107	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U

12.3 Appendix 1.3 – Route C

Table A.9: LCI of the Iron ore preparation (Drying / Pre-treatment) for Route C.

Iron ore preparation				
	Flow	*Amount*	*Unit*	*Background dataset*
Input	Iron ore fines	1000	kg	Iron ore, crude ore, 63% Fe {GLO}| market for iron ore, crude ore, 63% Fe | Cut-off, U
	Electricity	30	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Natural gas	15	MJ	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U
Output	**Ore, prepared**	**1000**	**kg**	
	Direct GHG emissions	6	kg	Emissions to air

Table A.10: LCI of the HYFOR Reduction Section for Route C.

HYFOR				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Preheated/oxidized ore fines	1380	kg	Table A.9
	Hydrogen makeup	516	Nm^3	Hydrogen, gaseous, low pressure {RER}| hydrogen production, steam methane reforming | Cut-off, U (density assumed 0,09 kg/m^3)
	Electricity	728	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Thermal energy for gas heaters	711	MJ	Natural gas, low pressure {DE}| market for natural gas, low pressure | Cut-off, U (Lower Heating Value assumed 36 MJ / m^3)
output	**DRI**	**1000**	**kg**	
	Direct GHG emissions	366	kg	Emissions to air

Table A.11: LCI of the Electric Smelter for Route C.

Electric Smelter				
	Flow	*Amount*	*Unit*	*Background dataset*
input	DRI	1100	kg	Table A.10
	Electricity	671	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
	Carbon addition	80	kg	Hard coal {AT}| market for hard coal | Cut-off, U
	Fluxes	120	kg	Dolomite {RER}| market for dolomite | Cut-off, U
output	**Hot metal**	**1000**	**kg**	
	Slag	166	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U
	Direct GHG emissions	283	kg	Emissions to air

Table A.12: LCI of the Basic Oxygen Furnace for Route C.

Basic Oxygen Furnace				
	Flow	*Amount*	*Unit*	*Background dataset*
input	Hot metal	814	kg	Table A.11
	Scrap	271	kg	Iron scrap, sorted, pressed {RER}| market for iron scrap, sorted, pressed | Cut-off, U
	Lime	37	kg	Quicklime, in pieces, loose {CH}| market for quicklime, in pieces, loose | Cut-off, U
	Dolomite	24	kg	Dolomite {RER}| dolomite production | Cut-off, U
	Alloys	1	kg	Ferrosilicon {GLO}| market for ferrosilicon | Cut-off, U
	Oxygen	51	Nm^3	Oxygen, liquid {RER}| industrial gases production, cryogenic air separation | Cut-off, U (density assumed 1,311 kg / m3)
	Electricity	35	kWh	Electricity, medium voltage {AT}| market for electricity, medium voltage | Cut-off, U
output	**Liquid steel**	**1000**	**kg**	
	BOF-slag	107	kg	Basic oxygen furnace slag {RER}| market for basic oxygen furnace slag | Cut-off, U