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Hy4Smelt

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1 Executive Summary

Hy4Smelt combines the HYFOR (*hydrogen-based fine ore reduction*) process with a Smelter (electric smelting furnace) to produce green HM (hot metal) from non-agglomerated ultra-fine and low/medium-grade iron ores. The process is designed for integration into existing steelworks, where hot metal can be refined in existing BOFs (Basic oxygen furnaces), while the Smelter slag is developed as a secondary raw material for the cement sector. Construction of the industrial-scale demonstration plant in Linz began in 2025, with first production targeted by end of 2027.

The market case is substantial but must be defined realistically. EU crude steel production reached 125.8 Mt in 2025, of which 54.2% - approximately 68.2 Mt - was produced through the basic oxygen route. Globally, around 70% of steel production remains based on BF-BOF technology. This establishes a large long-term replacement pool for low-emission primary ironmaking. Hy4Smelt is not a universal replacement for every production site; its strongest market is integrated plants that wish to retain valuable BOF, casting and rolling assets, lack access to abundant direct-reduction-grade pellets, or need a liquid hot-metal input for demanding steel grades.

The principal competing low-emission route is shaft-furnace direct reduction, particularly MIDREX, followed by EAF or electric smelting. MIDREX is commercially mature and dominant in shaft-furnace DRI production, but it typically uses pellets or lump ore. Hy4Smelt differentiates itself through direct use of fine ores without pelletising, flexible ore quality, hot-metal production and existing steel mill integration. Its commercial opportunity therefore lies in complementing, rather than simply replacing, conventional shaft-furnace DRI: the full HYFOR-Smelter route serves ore-fines of all grades, while the Smelter can also process DRI from other reduction routes.

The exploitation strategy follows the three-stage transfer pathway:

- identify and protect key exploitable results,
- validate benefits, target customers, barriers and ownership,
- and convert the validated results into market uptake, licensing, engineering, steel production, slag products, standards and follow-on research.

PTAT leads commercialisation of HYFOR and Smelter technology; VAS provides the industrial reference and operational pathway; K1-MET coordinates exploitation and market analysis; LOESCHE, BUW and CEMEX develop slag processing and qualification; ESTEP and the scientific partners support market outreach, policy, standardisation and knowledge transfer.

2 Introduction

2.1 Purpose of this Document

This report sets out the market potential and exploitation strategy for the results generated by Hy4Smelt. Hy4Smelt addresses a specific industrial problem, decarbonising ore-based steel production requires a replacement for the coal-based blast furnace, but much of the available iron ore is not suitable for conventional shaft-furnace direct reduction without beneficiation and agglomeration. At the same time, integrated steelworks contain high-value BOF, casting and rolling assets that may remain useful after blast-furnace closure. The HYFOR-Smelter combination is intended to bridge these constraints by reducing iron ore fines with hydrogen, before melting and completing reduction in an electric Smelter, thus delivering HM downstream to the existing steel plant.

The demonstration plant is the foundation of the exploitation strategy. Its role is to establish a reliable operating window across varying ore qualities, confirm DRI and hot-metal quality, demonstrate continuous integration of HYFOR and Smelter, quantify resource consumption, and generate slag for cement testing and certification. These outputs convert a promising process concept into evidence that customers, financiers, regulators and standardisation bodies can use.

2.2 Abbreviations, Acronyms, Units,

Table 1: Abbreviations

Abbreviation	Meaning
ARENA	Australian Renewable Energy Agency
BF	Blast furnace
BF-BOF	Blast furnace-basic oxygen furnace route
BOF	Basic oxygen furnace
BUW	Bauhaus-Universität Weimar
CBAM	Carbon Border Adjustment Mechanism
CEGYS	CEMEX España Gestión y Servicios S.L.
CO_2	Carbon dioxide
DR	Direct reduction
DRI	Direct-reduced iron
EAF	Electric arc furnace
ESF	Electric smelting furnace i.e. Smelter
ESTEP	European Steel Technology Platform
ETS	Emissions Trading System
EU	European Union
EU ETS	European Union Emissions Trading System
FEED	Front-end engineering design

GHG	Greenhouse gas
H_2	Hydrogen
HBI	Hot-briquetted iron
HM	Hot metal
HYFOR	Hydrogen-based fine-ore reduction
Hy4Smelt	Hydrogen-based fluidised-bed direct reduction of ultra-fine iron ores and smelting to green hot metal
IDOS	German Institute of Development and Sustainability
IEA	International Energy Agency
IP	Intellectual property
IRENA	International Renewable Energy Agency
K1-MET	Competence Center for Excellent Technologies in Advanced Metallurgical and Environmental Process Development
LCA	Life-cycle assessment
LCC	Life-cycle costing
MIDREX	MIDREX direct-reduction process
PPA	Power purchase agreement
PTAT	Primetals Technologies Austria GmbH
RFCS	Research Fund for Coal and Steel
SCM	Supplementary cementitious material
SSSA	Scuola Superiore Sant'Anna
UNIDO	United Nations Industrial Development Organization
UNILE	Università del Salento
VAS	voestalpine Stahl GmbH
WP	Work package

Table 2: Units

Unit	**Meaning**
°C	Temperature in Celsius
%	Percent
°C	Degree Celsius
A$	Australian dollar
€	Euro
EUR	Euro (currency code)
GW	Gigawatt
kg	Kilogram
Mt	Million tonnes

Mt/a	Million tonnes per annum
MWh	Megawatt-hour
t	Tonne
€/kg	Euro per kilogram
€/MWh	Euro per megawatt-hour
€/t	Euro per tonne
€/t CO_2	Euro per tonne of carbon dioxide
€/t HM	Euro per tonne of hot metal

3 Market potential of Hy4Smelt

The market potential of Hy4Smelt is directly linked to the scale of steel sector decarbonisation. In 2025, approximately 126 Mt of crude steel were produced across 22 EU member states at around 500 production sites, with 55% of production originating from the BF-BOF route [1]. The replacement of this production capacity represents one of the largest industrial transformation challenges currently facing European industry.

Unlike incremental efficiency improvements, climate neutrality requires the progressive substitution of fossil carbon-based ironmaking with alternative production routes. Consequently, future demand is not limited to niche applications or individual demonstration plants but extends to a substantial proportion of existing primary steel production capacity.

The commercial relevance of Hy4Smelt derives from its ability to address several deployment constraints simultaneously, as summarised in Table 3. This is particularly relevant in the context of increasing demand for low-CO_2 iron, tightening GHG regulations, growing competition for direct-reduction-grade ores, and declining availability of blast furnace-derived supplementary cementitious materials.

Table 3 Market needs addressed by the Hy4Smelt value proposition

Economic value driver	**Mechanism**	**Economic relevance**
Low-carbon iron production	Hydrogen-based reduction substantially reduces direct CO_2 emissions relative to conventional BF-BOF production.	HYFOR- and ESF-based production routes indicate CO_2 avoidance costs in the range of approximately 150-250 € per tonne of avoided CO_2. Increasing EU ETS prices therefore directly improve the competitiveness of low-CO_2 iron production relative to conventional BF-based routes.
Iron ore flexibility	A broad range of iron ore grades, including lower-grade and ultra-fine materials unsuitable for many hydrogen-based direct reduction routes can be utilized.	Reduces dependence on direct-reduction-grade ores, associated beneficiation and pelletisation requirements. This becomes increasingly important as demand for hydrogen-based ironmaking expands and competition for premium iron ore feedstocks intensifies.
By-product valorisation	Controlled slag chemistry enables the production of slag streams suitable for use as SCMs (*supplementary cementitious materials*).	Maintains SCM availability following the phase-out of BF production and supports the cement sector's clinker substitution strategy. Continued utilisation of slag-processing infrastructure creates an estimated equipment adaptation and renewal market of approximately €400 million over 25 years, including approximately €30 million within the EU.

3.1 Commercial viability

The economic case for Hy4Smelt is supported by process-level cost assessments performed for industrial-scale operation, as seen in Table 4. The calculations assume a 2035 market environment characterised by an EU ETS price of 141 €/t CO_2 [2], green hydrogen costs of 2-5 €/kg [3–5], electricity costs of 82 €/MWh, and a green steel premium of 150 €/t [6–9].

Hy4Smelt resource inputs amount to approximately 693 €/t hot metal before product revenue: €173 for ore fines, €270 for hydrogen, €205 for power and €45 for green carbon. A conventional BF case is estimated at 640 €/t hot metal, including 254 €/t for CO_2 certificates. Applying an assumed 150 €/t green-steel premium gives a net Hy4Smelt value of 543 €/t hot metal. Comparison with the conventional blast furnace route indicates a cost advantage of approximately 15% per tonne of hot metal, demonstrating that hydrogen-based reduction and smelting can become economically competitive within the expected regulatory and energy market framework of the next decade.

Table 4 Hy4Smelt economic viability per tonne of hot metal (HM) as example for central Europe expected

Hy4Smelt industrial plant				**BF process**			
	Input/t HM	Unit rates (€)	€/t HM		Input/t HM	Unit rates (€)	€/t HM
Iron ore fines	1.6 t	108	173	BF iron ore mix*	1.6 t	143	229
H_2	60 kg	4.5	270	Coke	470 kg	0.3	141
Power	2.5 MWh	82	205	Power	0.2 MWh	82	16
Green Carbon	100 kg	0.45	45	CO_2 cert.	1.8 t	141	254
Green steel premium			- 150				
Costs			**543**				**640**

*50 % sinter, 20 % lump, 30 % pellets

This comparison does not constitute a complete investment case, as capital recovery, fixed operating costs, financing and first-of-a-kind risks are not fully represented. It nevertheless illustrates the principal commercial mechanisms that could close the cost gap, including potentially lower ore-preparation costs, avoided carbon costs, low-emission product premiums and future by-product revenues.

Public market evidence supports both the opportunity and the caution required. The IEA estimates that early commercial plants using 100% hydrogen DRI can currently cost 50-140% more than BF-BOF, depending on region, and reports only about 10 Mt of near-zero-emission iron capacity expected by 2030 [10,11]. Hy4Smelt therefore cannot rely on decarbonisation demand alone. It must demonstrate lower total cost at selected sites through feed flexibility, asset reuse and integration, while obtaining long-term power, hydrogen and low-CO_2 steel offtake arrangements.

The regulatory environment strengthens the long-term case. CBAM entered its definitive regime on the 1st of January 2026 and is phased in alongside the reduction of free EU ETS allocation through 2034 [12]. The EU Clean Industrial Deal also promotes lead markets, carbon-intensity labelling, public-procurement criteria and additional financing for industrial decarbonisation [13]. These measures improve market conditions for low-emission steel, but do not remove the need for competitive energy prices and customer contracts.

The result highlights the importance of carbon pricing and hydrogen cost reduction for the commercial deployment of low-carbon ironmaking technologies. Under the assumed 2035 conditions, avoided CO_2 emissions and reduced exposure to emissions trading costs offset a substantial portion of the additional costs associated with renewable hydrogen and electricity consumption. Consequently, competitiveness is achieved without relying solely on technological performance improvements, but through the combined effects of process optimisation, energy system development, and increasingly stringent GHG regulation.

3.2 Deployment scale

The global market for fluidised-bed-based direct-reduction capacity is expected to reach up to 200 Mt/a by 2050, including approximately 10 Mt/a within the next decade. Under the Hy4Smelt proposal scenario, HYFOR technology is assumed to address approximately 25% of this future market. This corresponds to around 50 Mt/a of HYFOR capacity. Full-scale HYFOR plants are expected to produce approximately 1–2 Mt/a of DRI and to consist of modules with capacities of approximately 0.5–1.0 Mt/a. Depending on the selected plant capacity, the addressable HYFOR market would therefore correspond to approximately 25–50 full-scale installations globally, including up to 25 installations in Europe. Broader steel-sector transition scenarios similarly anticipate substantial growth in DRI-based steelmaking through 2050 [2,14].

Demand for low-carbon smelting capacity is expected to exceed 200 Mt/a by 2050 because Smelters can process DRI and other iron-bearing feeds produced by HYFOR as well as by alternative reduction technologies. At an assumed industrial Smelter capacity of approximately 1.2 Mt/a, an initial demand of 200 Mt/a would require around 167 installations. As demand continues increasing beyond 200 Mt/a, the global installed base could rise toward approximately 200 Smelters, corresponding to around 240 Mt/a of capacity. Hy4Smelt-developed Smelter technology is expected to address up to 50% of this market, with approximately 42 installations projected in Europe under the proposed scenario.

Based on indicative capital investments €800 million for HYFOR capacity and €350 million for Smelter capacity of 1 Mta hot metal, the overall addressable plant-building revenue is estimated at €32–34 billion through 2050 and beyond. These values are indicative market-scale estimates rather than complete project-cost calculations.

3.3 Exploitation strategy

The strategy begins with identification of results and target users, continues through validation of benefits, barriers and ownership, and concludes with market uptake, standardisation, licensing and continued operation of the demonstrator. The exploitation working group led by K1-MET, with PTAT and VAS at its core, should maintain this sequence throughout WP5.

Table 5 Overview of Key exploitable results

Key exploitable result	**Commercial use**
Demonstrated HYFOR-Smelter process and plant configuration	Reference design for commercial engineering, licensing, customer studies and future plants.
Flexible hydrogen reduction of non-agglomerated fine ores	Access to ore resources that are not readily usable in conventional shaft furnaces and avoidance of pelletising.
Steelworks integration concept	Replacement of fossil ironmaking while retaining BOF, casting, rolling and site infrastructure.

Operating data, process models and digital tools	Performance guarantees, scale-up, operator training, process optimisation and lifecycle services.
DRI, hot-metal and slag quality data	Customer qualification, steel-grade validation, feed specifications and commercial product definitions.
Certified Smelter slag applications	Sale or beneficial use of slag in cement and concrete, supported by standards and end-of-waste/product-status pathways.
Environmental and economic evidence	LCA, LCC, ETS benchmarking, funding applications, customer investment decisions and low-carbon product claims.

The exploitation strategy of Hy4Smelt is based on a clear division of responsibilities between the industrial, research and dissemination partners. Rather than treating project results as a single commercial product, the consortium will exploit a portfolio of complementary outcomes, including process technology, plant-engineering know-how, operational experience, validated material data, environmental and economic assessments, slag-processing solutions and market-transfer activities. This structure reflects the different capabilities and commercial interests of the partners and supports both direct industrial deployment and broader knowledge transfer.

The principal commercial route is expected to arise from the scale-up and licensing of the HYFOR and Smelter technologies, supported by the demonstrator as the first industrial reference. At the same time, the operational results generated at VAS will provide evidence on flexible ore use, hydrogen-based reduction, hot-metal production and integration into an existing steelworks. Additional value will be created through slag re-use in cement-sector applications, which strengthen the circular-economy case and open further service and material markets. Research partners will support replication, life-cycle and cost assessment, modelling and training, while ESTEP will facilitate communication with European steelmakers, policy actors and standardisation bodies. Table 5 summarises the partner-specific exploitation routes.

Table 6 Partner-specific exploitation routes

Partner/group	**Primary exploitation route**
PTAT	Own and commercialise HYFOR and Smelter foreground IP; design and engineer commercial plants; license technology; supply automation, digital and lifecycle services; develop customer-specific concepts.
VAS	Operate the demonstration plant; validate flexible-ore operation and production of H2-based DRI and hot metal; provide the first industrial reference and integrate the route into an existing steelworks.
K1-MET	Lead the exploitation group and market assessment; develop scaling and replication scenarios; quantify technical, environmental and economic impacts; support customer and funding cases.
LOESCHE	Develop processing and grinding routes for Smelter slag; translate slag characteristics into equipment and plant adaptations; support slag certification and future service opportunities.
CEMEX/CEGYS	Test Smelter slag as a secondary cement raw material and clinker substitute; qualify cement and concrete performance; approach cement associations, authorities and standards bodies.

BUW, SSSA, UNILE and other scientific partners	Exploit knowledge through research, teaching, modelling, LCA/LCC, publications, training and follow-up projects while respecting protected industrial IP.
ESTEP	Use the European steel network to communicate results, engage industry and policy actors, support standardisation and facilitate further technology-transfer opportunities.

Commercial development should begin before the demonstrator has completed all campaigns. Early customer engagement can establish the site data, feed materials, utilities and product requirements needed for rapid follow-up studies. However, binding performance guarantees and final commercial designs should be based on demonstrated results. This balance prevents the project from waiting until its end to create a market while avoiding unsupported commitments.

Table 7 Expected route from demonstration to repeat commercial deployment

Stage	**Main output**	**Exploitation result**
1. Demonstration and evidence	Stable campaigns across agreed ore qualities; validated material and energy balances; DRI, hot metal and slag quality; operating and maintenance data	Credible performance envelope and scale-up basis
2. Product and IP definition	Protected foreground, agreed access rights, process package, feed specifications, slag product specification and environmental evidence	Clear offer that can be discussed with customers without compromising partner IP
3. Customer and site development	European site screening, pre-feasibility studies, energy and hydrogen concepts, ore/logistics studies and cement-sector partnerships	Qualified pipeline of first commercial applications
4. First commercial reference	FEED study, financing and offtake agreements, performance guarantees, permitting and supply contracts	Bankable first commercial installation
5. Replication and service business	Standardised modules, licensing, plant supply, digital services, maintenance, operator training and slag-processing packages	Repeatable global commercial business

3.4 Market engagement and standards

Pre-existing patents and know-how relating to HYFOR and Smelter technology are identified as PTAT background IP, while all Foreground IP relating to HYFOR and Smelter technology generated within Hy4Smelt is the sole property of PTAT. Other results are owned by the partner generating them. Where results are jointly generated and the respective contributions cannot be established, the results are jointly owned, with the allocation and terms of exercise of the joint ownership to be agreed by the joint owners. This allocation supports a practical commercial model in which PTAT can offer an integrated process and plant package, while other partners may exploit the results they own or for which they hold agreed access rights, including results concerning slag processing, cement applications, assessment, modelling and scientific research. Scientific partners are granted the right to use project results for their own research and teaching. The exploitation group should maintain a live register of agreed background, Foreground IP and other exploitable results, ownership, access rights, patentability, confidentiality and publication clearance.

Slag standardisation is a separate market-enabling activity rather than a secondary research topic. Granulated blast-furnace slag is an established clinker substitute [15], but its availability is expected to decline as blast-furnace production is progressively replaced by low-carbon ironmaking routes [16]. This creates a need for alternative supplementary cementitious materials with suitable and consistent technical and environmental properties. Hy4Smelt must therefore demonstrate the hydraulic performance, durability, environmental compliance, consistency and processing requirements of Smelter slag. Based on these results, the relevant project partners should engage cement associations, the European Slag Association, building authorities and standards bodies to define the applicable product-status, certification and standardisation pathways [17].

Market engagement should be tailored to the requirements of the respective decision-makers. Steelmakers require evidence concerning process performance, plant integration, feed flexibility, product quality and total production cost. Ore producers require defined feed-acceptance criteria and evidence of the value of ore fines and lower-grade resources. Cement producers require verified and consistent material performance, environmental compliance and a reliable supply of qualified slag. Financiers require transparent risk allocation, credible performance assumptions and contracted revenue streams[10], while steel customers require reliable and verifiable carbon-intensity information[18]. Policymakers and public funding bodies require evidence of contributions to industrial competitiveness, resource security, circularity and climate targets. ESTEP, industry associations and the scientific partners provide suitable channels for wider market, policy and standardisation engagement[19], while commercially sensitive negotiations remain the responsibility of the relevant industrial partners.

4 Expected impact of Hy4Smelt

4.1 Industrial and economic impacts

The first impact is a new plant and technology market. Under the proposed scenario, HYFOR and Smelter deployment creates engineering, equipment, licensing, automation, service and maintenance revenues of approximately 29-31 € billion through 2050 and beyond. Because the Smelter can process DRI from multiple sources, its market can extend beyond HYFOR installations [20].

The second impact is protection of existing industrial capital. Hy4Smelt can retain BOF, casting, rolling, laboratories, logistics and workforce capabilities. This can reduce the scope and disruption of the transformation compared with replacing the full integrated route at once [20]. The value is especially relevant in Europe, where weak capacity utilisation and import competition make large capital decisions difficult [21].

The third impact is wider raw-material access. HYFOR can directly process ultra-fine iron-ore of different qualities without sintering or pelletising [22,23]. Processing suitable ultra-fine and lower-grade ores can therefore reduce dependence on high-grade direct-reduction pellets, open markets for mine fines and domestic resources, and create new business between ore suppliers, technology providers and steelmakers. This is particularly relevant because conventional hydrogen-based shaft-furnace DRI generally requires high-grade pellet feed, while high-grade pellets account for only a small proportion of internationally traded iron ore [24,25].

4.2 Environmental and circular-economy impacts

The environmental value proposition must remain technically precise. Hy4Smelt can substantially reduce direct emissions by more than 90% in Scope 1 emissions, by replacing coke-based reduction with hydrogen and electrified smelting, but the final carbon intensity depends on electricity and hydrogen production, ore preparation and transport, carbonate decomposition, the quantity and origin of carbon used for final reduction and carburisation, and the treatment of slag and off-gases. The demonstration phase must verify the resource balance and avoid presenting zero direct process emissions as zero lifecycle emissions.

Hy4Smelt also avoids or reduces several fossil- and energy-intensive steps associated with the conventional integrated route, including coke production, sintering and, for suitable ores, pelletising. HYFOR directly processes ultra-fine iron ore without prior agglomeration, while the combined HYFOR–Smelter route replaces the coke, ore agglomeration and blast-furnace-based ironmaking stage [26,27]. Its ore flexibility increases resource efficiency, while the use of secondary carbon carriers can further reduce fossil-carbon demand in the Smelter [26].

The slag pathway links steel and cement decarbonisation. Blast-furnace slag is widely used to replace clinker, but its supply will decrease as the BF route contracts. A qualified Smelter slag could preserve part of this circular material flow. The environmental benefit depends on the actual clinker replacement ratio, slag-processing energy, transport distance and consistent allocation of environmental impacts between steel and cement; these factors ought to be addressed in the project LCA and subsequent environmental product declarations [28,29].

4.3 Strategic, policy and societal impacts

Hy4Smelt strengthens European industrial capability in a part of the steel value chain that is still at an early stage of global commercialisation. Its strategic value lies in combining technology ownership, plant engineering, steelworks operation, hydrogen infrastructure, ore expertise and slag qualification within one development pathway. The European Commission's INCITE platform lists Hy4Smelt as an ironmaking technique under development and testing with an expected TRL of 8, recognising both decarbonisation and circular-economy relevance.

Resource resilience is another strategic impact. A validated capability to use a broader range of fines reduces dependence on a narrow market for direct-reduction-grade pellets and allows ore suppliers to develop lower-emission metallics from resources that are difficult to use in conventional shaft furnaces. The benefit is not automatic import substitution; it is greater freedom to combine European, imported and mine-linked feedstocks according to cost, quality, carbon intensity and supply risk. Furthermore, the Smelter enables recycling of iron rich residues in a similar capacity as the BF ensuring continued use of recycling products (slags, dusts, scales) that may not be used in EAFs.

The societal transition concerns people and operating practices as much as equipment. Hydrogen systems, fluidised-bed reduction, electric smelting and digital operation require new safety, maintenance and control competences. The proposed HAZOP work, cold and hot testing, digital-twin training and operator qualification should be converted into reusable training modules and competence profiles for replication sites. This supports skilled employment while reducing the operational risk of first deployment.

Public confidence also depends on a clear boundary between open evidence and commercially sensitive information. Public performance reporting should communicate validated environmental and product results, while feed-specific know-how, detailed process settings, cost models, customer data and performance-guarantee bases remain under the agreed IP and confidentiality regime. This balance allows the project to support policy, permitting and investment decisions without weakening the commercial position of the result owners.

5 Conditions for successful market uptake

Hydrogen remains the most important external constraint. The IEA reported in June 2026 that low-emission hydrogen still represented only slightly more than 1% of global hydrogen production and that the announced 2030 project pipeline had diminished because of delays and cancellations [30]. At the same time, IRENA, UNIDO and IDOS identify green hydrogen as a potential driver of sustainable industrial development, particularly in developing countries with strong renewable energy resources [31]. These two findings are not contradictory: renewable-resource abundance creates opportunity, but it does not automatically provide low-cost delivered hydrogen. Financing cost, grid and port infrastructure, water supply, electrolyser utilisation and reliable industrial offtake determine whether the resource advantage becomes a competitive implementation.

Table 8 Principal conditions and actions for commercial uptake

Condition	Required response
Reliable demonstration performance	Complete representative campaigns, document availability and downtime, confirm material and energy balances, and convert the results into a defined commercial performance envelope.
Competitive renewable electricity and hydrogen	Develop site-specific generation and supply concepts, long-term PPAs, hydrogen storage and flexible operation. Prioritise locations where complementary renewable resources can support high plant utilisation.
Ore qualification and secure feed supply	Define accepted chemical and physical ranges, reduction and smelting behaviour, productivity, energy demand, slag volume and customer qualification procedures.
Integrated site and logistics concept	Confirm land, grid connection, port or rail access, gas systems, material handling, hot-metal or HBI logistics and the ability to reuse existing BOF and downstream assets where applicable.
Water, environmental and social licence	Assess water sourcing, recycling and desalination, biodiversity, land use, community benefits and occupational safety. New renewable-hydrogen hubs must not weaken local energy or water access.
First commercial financing and risk sharing	Use demonstrator evidence to support EU and national instruments, development banks and private finance; combine customer offtake with clear allocation of construction, scale-up and performance risks.
Slag product status and local market	Complete technical and environmental testing, ensure consistency, identify the standards pathway and secure cement-sector qualification and an outlet before commercial operation.
Customer confidence and guarantees	Develop transparent design bases, feed specifications, mass and energy balances, availability assumptions and guarantee boundaries supported by the demonstrator.
IP and competition compliance	Protect patentable results, maintain publication clearance, define licences and access rights, and apply competition-compliance procedures to joint market analysis and customer engagement.
Qualified international project pipeline	Screen integrated steelworks, mine-mouth green-iron hubs and port-based sites. Develop a limited number of high-probability cases with named stakeholders, energy concepts, feed sources and product routes.

Successful uptake should be assessed through concrete site fit rather than through a uniform global hydrogen-price assumption or a top-down market-share figure. Hy4Smelt is most attractive where four conditions coincide:

- suitable fine or low/medium-grade iron ore,
- scalable low-emission electricity and hydrogen,
- industrial and logistics infrastructure,
- a market for green iron, hot metal and the resulting slag.

5.1 Global deployment

The international market can be organised around three deployment models. The first is steelworks conversion, in which HYFOR and the Smelter replace sintering, coke making and the blast furnace while the BOF, casting and rolling assets remain in service. This is the principal European application and is also relevant to India and other countries with young integrated assets. The second is a mine-mouth or port-based green-iron hub in a resource-rich country, where ore fines, renewable electricity and hydrogen are converted into transportable HBI or pig iron for export, or into steel where local downstream demand exists such as Australia, and Brazil. The third is a port-based Smelter market in fast-growing steel regions that may lack sufficient local ore or renewable hydrogen; such sites can import HYFOR DRI/HBI or other DRI and use an electric Smelter to produce clean hot metal for local steelmaking.

Table 9 Indicative global deployment regions for Hy4Smelt, including market drivers, potential applications and principal implementation constraints

Region and deployment case	**Market signal and resource basis**	**Fit with Hy4Smelt**	**Main constraints**
Australia - Pilbara, Western Australia and Whyalla	Australia holds the world's largest identified economic iron-ore resources and is the leading producer; almost 90% of identified resources are in Western Australia [32]. The government has established a A$1 billion Green Iron Investment Fund, including a national stream for early-mover projects and support for Whyalla [33]. Rio Tinto is already a direct Hy4Smelt value-chain partner and will supply 70% of the demonstrator ore [34].	HYFOR directly addresses the challenge of using fine, mainstream Australian hematite/goethite ores without conventional pelletising. Deployment could take the form of mine-mouth HYFOR-HBI production, an integrated HYFOR-Smelter green-iron export hub, or integration at Whyalla. Abundant solar and wind energy and existing ore, rail and port systems strengthen the case.	Large new renewable generation, transmission, hydrogen storage, water/desalination and a bankable export market are required. The competitiveness of HBI, pig iron and finished steel must be compared with continued ore exports.
Brazil - Minas Gerais, Espirito Santo and coastal industrial hubs	Brazil combined major iron-ore production and port infrastructure with an electricity matrix that was 86.8% renewable in 2025 [35]. The federal low-carbon hydrogen strategy explicitly identifies green steel as a value-added use [36], and Vale, one of the world's leading iron ore producers, has pursued green industrial hubs and renewable-	Hy4Smelt could convert mine fines and lower-grade streams into HBI or hot metal close to mines or export terminals. The renewable-heavy grid lowers the initial carbon intensity of electric smelting, while wind and solar expansion can supply dedicated hydrogen. Existing mining, steel and cement value chains provide potential users for iron products and slag.	Transmission expansion, firm low-cost power, hydrogen scale-up, permitting and product certification remain necessary. Hydrological variability and the distance between mines, renewable projects and ports must be

	hydrogen HBI concepts with steel-sector partners [37].		addressed in site design.
India - Odisha, Chhattisgarh and integrated coastal clusters	India has more than 33 billion tonnes of reported iron-ore resources and produced 257 Mt in 2022-23 [38]. By May 2026, cumulative solar capacity exceeded 162 GW [39]. The Ministry of Steel has introduced a Green Steel Initiative, a green-steel taxonomy and hydrogen pilot projects under the National Green Hydrogen Mission.	India combines rapid steel-demand growth, abundant fines and low/medium-grade ores, existing BF-BOF assets and a large DRI sector. Hy4Smelt could support integrated steelworks hot-metal production, greenfield mine-linked projects or a standalone Smelter processing DRI from HYFOR, or other domestic reduction routes.	The present power mix remains carbon intensive in many states, and hydrogen costs, grid reinforcement, water, land and financing are major constraints. The first target should be sites with captive renewables, port access or a strong policy-supported hydrogen cluster.
Vietnam and selected Southeast Asian port-based steel clusters	Southeast Asia has rapidly growing steel demand and significant solar, wind, hydro and geothermal potential, although resource quality and power systems differ widely. Vietnam has requested support for green hydrogen and steel-sector decarbonisation, is developing industrial decarbonisation measures, and has policy discussions on mechanisms for green-steel investment [40].	The most credible initial application is a port-based Smelter or integrated plant supplied with imported HYFOR DRI/HBI, Australian or regional ore, and progressively cleaner electricity and hydrogen. This creates a route for growing steel markets to reduce dependence on coal-based blast furnaces while using established ports and nearby cement markets.	Many power systems remain coal dominated and local DR-grade ore is limited. Renewable integration, imported feed security, hydrogen infrastructure and carbon-accounting rules must improve before a full HYFOR-Smelter route becomes competitive.

The following sections examine the deployment potential in Australia, Brazil, India and Southeast Asia in greater detail, focusing on the regional resource base, industrial context, potential Hy4Smelt configurations and remaining barriers to implementation.

5.1.1 Australia

Australia is the clearest non-European replication case because it combines very large iron ore resources, established mining and export infrastructure, excellent solar and wind potential, and an explicit national policy to develop green iron. Its connection to Hy4Smelt is further strengthened by Rio Tinto, which, although not a beneficiary in the funded RFCS consortium, is a formal industrial project partner under a separate cooperation agreement. Rio Tinto will supply 70% of the iron ore required for the Hy4Smelt demonstration plant, contribute technical expertise on ore quality and preparation, and support the development and future commercialisation of the HYFOR and Smelter technologies. The main technical issue for Australia is that much of the mainstream Pilbara export mix is not naturally suited to conventional hydrogen shaft-furnace DRI without beneficiation and pelletising. HYFOR's fine-ore route and the Smelter's ability to complete reduction and separate gangue therefore respond to a nationally recognised market problem. ARENA is already supporting research and demonstration work on fine-ore hydrogen ironmaking and low-emission processing compatible with Australian ores [41].
A commercial Australian pathway could begin with mine-mouth production of HBI or green pig iron for export to Asian steelmakers, followed by local steel production where downstream scale is justified. Western Australia offers the largest ore and port base, while Whyalla offers an integrated steelworks case and a policy-supported transition pathway. The Superpower Institute webinars

analysed for this report argue that green iron could become a very large Australian export industry and discuss hydrogen DRI and electric smelting routes suited to Australian ores [42,43]. Their A$400 billion opportunity estimate should be presented as an advocacy and scenario result rather than a confirmed market forecast, but it is useful evidence of growing policy and investor attention.

5.1.2 Brazil

Brazil offers a second strong resource-co-location case. Its established ore mines and export ports are combined with one of the world's most renewable electricity systems: renewable sources supplied 86.8% of electricity in 2025 [35]. This does not guarantee a constant low industrial tariff, but it means that an electric Smelter can begin from a substantially lower-carbon power base than in many competing iron-producing regions. Brazil's low-carbon hydrogen policy explicitly frames green steel as a higher-value domestic use of hydrogen rather than treating hydrogen only as an export commodity [36].

For Hy4Smelt, the most plausible Brazilian configurations are a mine-linked HYFOR plant producing HBI, a coastal integrated green-iron hub, or a Smelter linked to existing steelmaking. Vale's, one of the world's leading iron ore producers, work on renewable-hydrogen industrial hubs and low-CO_2 HBI confirms active commercial interest in adding value to Brazilian ore [37]. A Hy4Smelt offer would differentiate itself through direct fine-ore use and the option to produce hot metal, while Brazilian cement production creates a potential local synergy for qualified Smelter slag.

5.1.3 India and Southeast Asia

India provides a different market archetype: it combines a very large and growing domestic steel market with abundant ore fines, extensive BF-BOF and DRI assets, expanding renewable capacity and an increasingly explicit green-steel policy. Hy4Smelt could therefore be deployed both as a complete integrated route or as a standalone Smelter that complements other domestic DRI production. The Ministry of Steel's green-steel taxonomy, roadmap and hydrogen pilot programme show an official intention to move beyond general net-zero statements toward technology testing and product classification [38].

In Southeast Asia, the first opportunity is more likely to be port-based than mine-mouth. Vietnam, Malaysia and Indonesia have fast-growing steel demand and renewable-resource potential, but many sites remain dependent on coal and may not have sufficient suitable iron ore. A standalone Smelter supplied by imported HYFOR DRI/HBI or by DRI from another route could therefore be the initial product. Vietnam's work with UNIDO and the World Bank on steel-sector decarbonisation, green hydrogen and green industrial policy provides a credible policy signal [40]. The market should be approached selectively, prioritising ports with clean-power expansion, an existing steel cluster and a cement-sector outlet for slag.

6 Conclusion

Hy4Smelt has a clear exploitation logic. It is designed to convert suitable fine and lower-grade ores into low-GHG-emission hot metal, avoid the need for ore agglomeration in the HYFOR route, retain valuable BOF-based steelmaking assets, and develop Smelter slag for potential use as a cementitious material. These features distinguish it from both the fossil-based BF-BOF route and conventional shaft-furnace DRI.

The market potential is substantial: 68.2 Mt of EU steel was produced through the basic-oxygen route in 2025, while BF-BOF remains the dominant global production route. The project proposal identifies a long-term global market of up to 200 Mt/a of fluidised-bed-based direct-reduction capacity and more than 200 Mt/a of low-carbon smelting capacity, creating a multi-billion-euro plant-building opportunity until 2050 and beyond. Geographic opportunities are not limited to Europe. Australia and Brazil illustrate mine-linked green-iron hubs built around ore and renewable resources; India combines brownfield assets, ore fines and rapid steel-demand growth; and selected Southeast Asian ports could provide markets for imported DRI/HBI and standalone Smelters. Real market capture will depend on converting this potential into a limited number of high-quality replication cases with suitable ore, energy, infrastructure, customers and slag outlets.

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