UNLOCKING THE FIRST WAVE OF BREAKTHROUGH STEEL INVESTMENTS

International Opportunities

THE UNITED KINGDOM, SPAIN, FRANCE, AND THE UNITED STATES

Prepared by

Energy Transitions Commission

Supported by

Breakthrough Energy

INSIGHT REPORT / APRIL 2023

AUTHORS & ACKNOWLEDGEMENTS

This report was prepared by the Energy Transitions Commission as part of the Mission Possible Partnership and with the support of Breakthrough Energy.

The report was authored by:

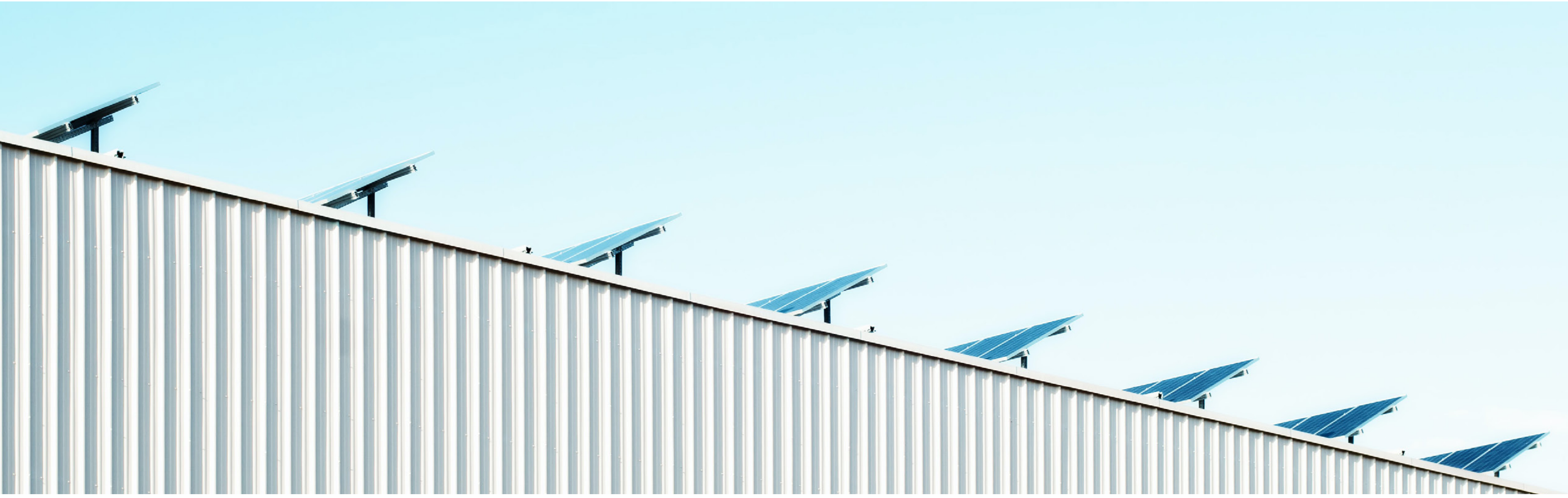
Alasdair Graham (ETC)
Marc Farre Moutinho (ETC)
Rafal Malinowski (ETC)
Stephannie Lins (ETC)

We thank Lord Adair Turner (ETC), Faustine Delasalle (MPP), Eveline Speelman (Systemiq), Rob Campbell-Davis (Systemiq), Julia Reinaud (Breakthrough Energy), Pénélope Le Menestrel (Breakthrough Energy), Alberto Toril (Breakthrough Energy), Abigail Regitsky (Breakthrough Energy), Jessica Terry (RMI), Chathurika Gamage (RMI), Nick Yavorsky (RMI), Rachel Wilmoth (RMI), and other collaborators for their valuable support.

The report was edited and designed by M. Harris & Company.

CONTENTS

EXECUTIVE SUMMARY



Steel is a critical material for the global economy, but producing it is emissions-intensive, accounting for 7% of annual global greenhouse gas emissions. Decarbonising steelmaking is essential for achieving a net-zero economy. There are multiple opportunities for reducing emissions through greater material circularity and expanding secondary (recycled scrap-based) steelmaking, but inherent limits to the future supply of recyclable scrap mean decarbonising primary (iron ore-based) steelmaking is critical for achieving a net-zero steel industry.

'Breakthrough' primary steelmaking technologies, centred around using low-carbon hydrogen to produce direct reduced iron, are gaining traction. A pipeline of +60 million tonnes per annum (Mtpa) of commercial-scale production capacity is planned to become operational by 2030. However, this pipeline falls short of the 190 Mtpa of near-zero emissions primary production capacity (approximately 7% of total steel capacity) that must be operational by that date to ensure the global steel industry is on a 1.5°C-aligned pathway to net zero. Of the pipeline of projects, only three – H2 Green Steel in Boden, Sweden (5 Mtpa), Salzgitter's Flachstahl plant in Germany (2 Mtpa), and ArcelorMittal's Dofasco plant in Hamilton, Canada (2.5 Mtpa) – have broken ground after securing final investment decisions (FIDs) to proceed.

To accelerate the scale-up of near-zero-emissions primary steelmaking, the Energy Transitions Commission (ETC) has sought to assess what it will take to achieve FIDs on breakthrough iron and steel projects in the next five years. To drive this assessment, the ETC conducted a series of regionally focused forums to develop a clearer-eyed understanding of what it will take to reach FID for such projects in the near term, focusing on the United Kingdom, Spain, France, and the United States (which was delivered in partnership with RMI).

The findings of the forums and resulting analysis are promising. A viable investment case for breakthrough iron and steel may already be within reach in the United States and the EU. Cost-competitive and low-carbon industrial electricity, driven by good renewable energy resource availability and supply chains in combination with favourable policy developments (subsidies for renewable hydrogen production in the United States and the forthcoming EU carbon border adjustment mechanism in the cases of Spain and France), create conditions for a viable business case for breakthrough projects in those countries. Crucially, breakthrough iron and steel is possible in all four geographies. Practical interventions such as government support for capital expenditures and forward purchase agreements at an initial premium offer a feasible way to close the financial gap and unlock FIDs in the near term.

With the multiyear lead times involved in planning and building steel mills, there is a narrow window of time available to get steel, the largest emitting industrial sector, on a pathway towards 1.5°C-alignment by 2030. Yet a positive investment case will require strong coordinated intervention on the part of the industry, policy and the wider value chain. It will be imperative that the potentially distortionary effects on highly commoditised and margin-based iron and steel markets are not used as an excuse to slow the necessary transition. Instead, high-ambition international and multilateral efforts will be needed to navigate complex new competitiveness issues inherent in transitions in primary production processes of basic materials like steel.

PART I

THE GLOBAL STATE OF PLAY

1.1 The Global Pipeline

Steel constitutes a fundamental component of most elements of everyday life. From buildings to cars, from chemicals to food, steel underpins a range of industries and processes. At the same time, the global steel industry is the largest emitter of greenhouse gases (GHGs) of all heavy industries, accounting for 7% of annual global GHG emissions.[i] Achieving a sustainable, net-zero economy is only possible by decarbonising steel production.

There are multiple options for decarbonising steel, many of which can be combined but broadly fall into three categories:

1. **Limit demand and increase scrap recycling:** Creating crude steel from recycled scrap avoids the need to produce new units of iron, a process that conventionally relies on fossil fuel feedstocks (primarily coal) and constitutes the most emissions-intensive part of steelmaking.

2. **Capture emissions:** capturing emissions from iron and steel production and sequestering them (either in dedicated, permanent storage or by making effective use of the emitted CO_2 emitted in long-lived products).

3. **Develop and deploy low-emissions steelmaking technologies:** producing iron and steel with breakthrough technologies capable of producing steel with near-zero emissions, such as using low-carbon hydrogen to produce direct reduced iron (DRI) or electrolytic steelmaking processes.

i *Making Net-Zero Steel Possible*, Mission Possible Partnership, September 2022.

However, categories 1 and 2 face certain barriers that make pursuing category 3 indispensable. Steel is already one of the most recycled materials with estimates pointing to an 85%+ recycling rate, suggesting that while there is still room for improvement, it is quite limited given the progress that has already been made. Inherent limits to the future supply of scrap, with the exception of a few geographies, also mean it is unlikely that future global steel demand could be met through recycling alone. In addition, there is a set of contaminants called 'tramp elements' (i.e., copper or zinc), which are not removed during standard metallurgical processing and negatively impact quality of final product. Each recycling loop results in accumulation of these elements in the resulting crude steel, reducing its viability for higher-grade applications such as flat steel products used in automotive manufacturing or aerospace engineering. These contaminants can be diluted if the recyled scrap is supplemented with fresh, ore-based metallics pointing to a continued need for ironmaking even if efforts to improve scrap recycling are strengthened.

In the case of carbon capture technologies, additional research is needed to develop technologies for iron and steel production with a sufficiently high effective capture rate (90%–95%) to enable net-zero-compatible steelmaking. At present, there is only one steel plant using carbon capture at scale (the Al Reyadah project in Abu Dhabi, for which the effective capture rate is less than 50%) and none for which carbon capture is used at a commercial scale on blast furnace-basic oxygen furnace (BF-BOF) production, the most prevalent form of steelmaking today, accounting for 75% of global output. Barriers to scrap recycling and carbon capture mean that 'breakthrough' steelmaking technologies, which avoid emissions and can produce ore-based steel with emissions of less than 0.4 tonnes of CO_2 per tonne of end product (tCO_2/t),[ii] are essential to make the necessary progress in the 2020s.[iii]

Among breakthrough technologies, a front-runner that has seen significant development in recent years involves producing DRI using low-carbon hydrogen (H_2-DRI). DRI production is already a well-established technology. A total of 120 million tonnes (Mt) of steel was produced from DRI made with fossil fuel feedstocks (chiefly natural gas) in 2021,[iv] amounting to 6% of global steel production that year.[v] Switching from fossil fuel feedstocks to low-carbon hydrogen offers a route to producing low-emissions DRI, which can then be fed into conventional steel production processes to enable deeply decarbonised steelmaking. H_2-DRI enjoys a technology readiness level (TRL) rating of 6 and multiple projects centred on this approach have already been announced, with the EU leading the way (Exhibit 1, next page).[vi]

ii This threshold is based on the Scope 1 and 2 emissions threshold set by the International Energy Agency in its definition of 'near zero emission crude steel production with zero scrap use' in ***Achieving Net Zero Heavy Industry Sectors in G7 Members***, May 2022, p. 109.

iii ***Making Net-Zero Steel Possible***, Mission Possible Partnership, September 2022.

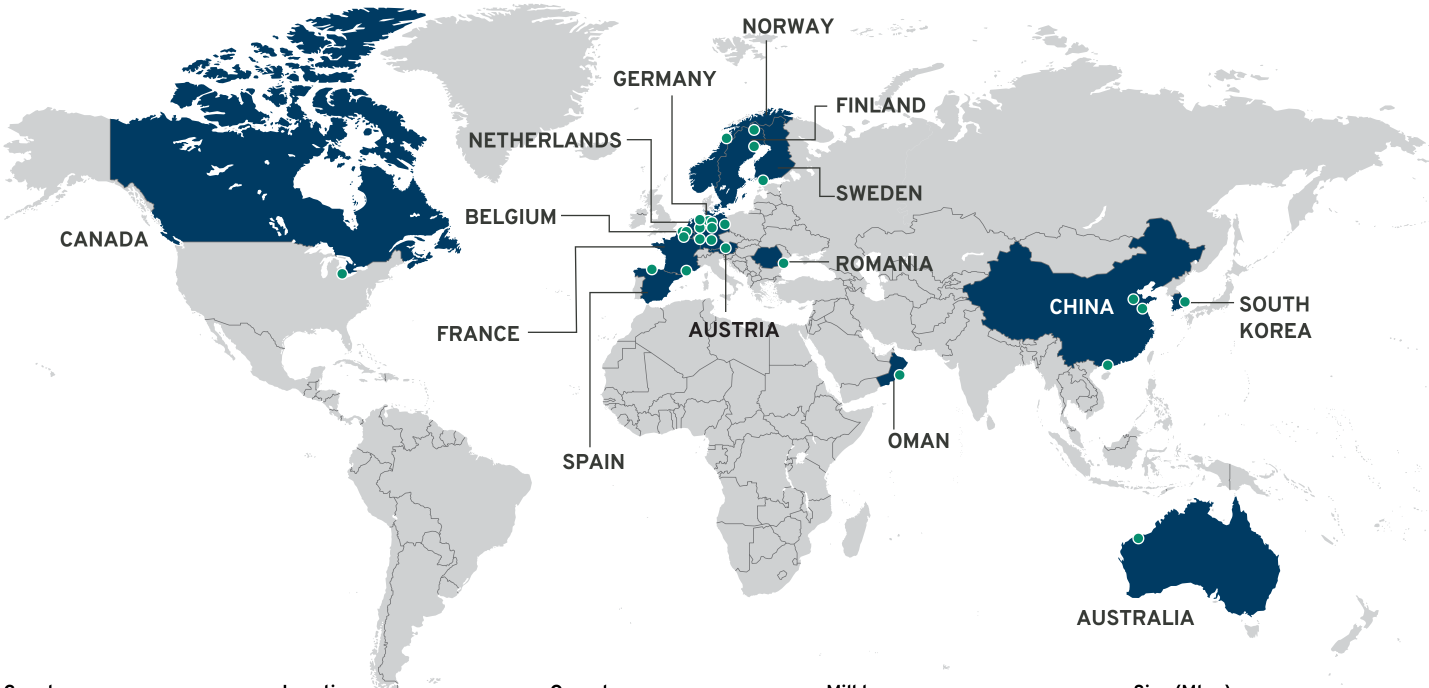
iv "**Global DRI production increased by 14% in 2021**," GMK Center, September 2022.

v Based on 1,951 Mt of crude steel production as reported in ***World Steel in Figures 2022***, worldsteel, April 2022.

vi TRL refers to a method of assessing where a given technology stands in its journey to widespread adoption, commonly reflected by a score between 1 (initial idea) and 9 (commercially available). In the International Energy Agency's ***ETP Clean Energy Technology Guide***, last updated September 2022, H_2-DRI was given a TRL score of 6 (full prototype at scale) and the technology has seen further development since then.

EXHIBIT 1

Global map of announced H2-DRI projects



Country	Location	Operator	Mill type	Size (Mtpa)
Australia		Posco	H_2-DRI	
Austria	Donawitz	Voestalpine	(H_2-DRI-)EAF	1.6
	Linz	Voestalpine	(H_2-)DRI-EAF	1.5
Belgium	Gent	ArcelorMittal	(H_2-) DRI-EAF + CCU	2.5
Canada	Hamilton	ArcelorMittal	(H_2)-DRI-EAF	2.5
China	Rizhao	Rhizao Steel	H_2-DRI	0.5
	Xuanhua	HBIS Group	H_2-DRI	1.2
	Zhanjiang	Baowu	H_2-DRI	1
Finland	Inkoo	Blastr	H_2-DRI-EAF	
France	Dunkirk	ArcelorMittal	(H_2-) DRI-EAF + CCUS	2.7
	Dunkirk	Liberty	(H_2-)DRI	2
	Fos-sur-Mer	GravitHy	H_2-DRI	2
Germany	Bremen	ArcelorMittal	(H_2)-DRI-EAF	3
	Dillingen	Stahl-Holding-Saar	H_2-DRI(-EAF)	3.5
	Duisburg	Thyssenkrupp	(H_2-)DRI-Melter-BOF	1.2
	Eisenhüttenstadt	ArcelorMittal	(H_2)-DRI-EAF	0.5
	Hamburg	ArcelorMittal	H_2-DRI	0.1
	Salzgitter	Salzgitter AG	H_2-DRI(-EAF)	2
	Völklingen	Stahl-Holding-Saar	H_2-DRI(-EAF)	3.5
	Wilhelmshaven	Salzgitter AG	(H_2-DRI-)EAF	2
Norway	Gildeskål	Blastr	H_2-DRI-EAF	
Oman	Duqm	Jindal Shadeed	H_2-DRI-EAF	5
Romania	Galati	Liberty	(H_2-)DRI-EAF	4
South Korea	Pohang	Posco	H_2-DRI	1
Spain	Gijon	ArcelorMittal	(H_2-)DRI-EAF	2.7
	Iberia	H2 Green Steel	H_2-DRI (-EAF)	5
Sweden	Boden	H2 Green Steel	H_2-DRI-EAF	5
	Gallivare	Hybrit, SSAB	(H_2-)DRI	4

The map includes only publicly confirmed projects, ranging from announced proposals to final investment decisions. Where known, project production capacities are noted in square brackets. Project components between regular brackets denote planned but not fully confirmed components, being contingent on various factors (namely, availability of hydrogen for H2-DRI production or the value of attaching steelmaking to planned stand-alone ironmaking investments).

Sources: ETC analysis based on data from: Green Steel Tracker, Leadership Group for Industry Transition (LeadIT), November 2022; Global Steel Transformation Tracker, Agora Energiewende, August 2022; and corporate announcements.

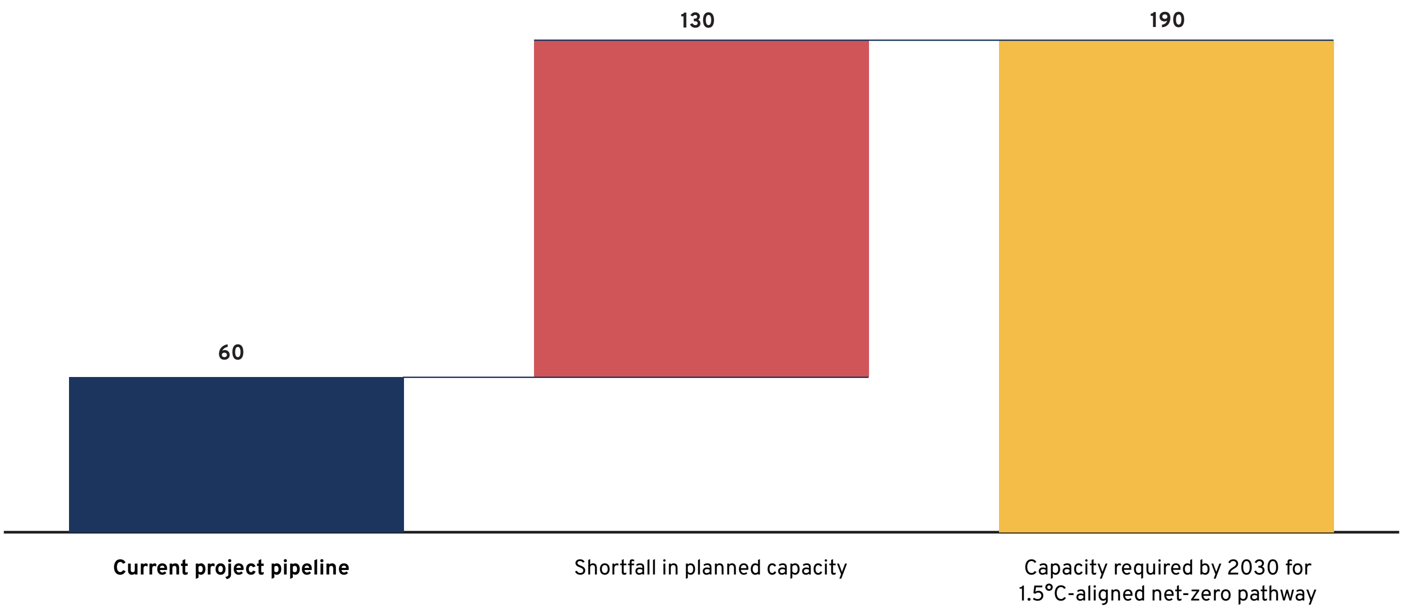
Although the pipeline for breakthrough iron and steel projects continues to grow, planned capacity still falls short of what is needed for the global steel industry to be on a clear path towards a decarbonised future (Exhibit 2). Moreover, from this pipeline, few projects have secured final investment decisions (FIDs), a crucial step in realising such projects in the real world. Steel projects can take around four years to go from FID to fully operational and can involve years of planning before an FID is even reached. Given the timescales involved, the window to scale up the required capacity by 2030 is narrowing, meaning action to advance new projects and accelerate them to FID is needed urgently.

The need to scale breakthrough technology is made more pressing by the long (re)investment cycles associated with primary steel plants, which revolve around the 'relining' (renovation) of blast furnaces and span 20 years on average. With a large share of blast furnaces around the world due for relining in the present decade, failing to transform existing sites with decarbonised alternatives risks locking them in to emissions-intensive production methods for years to come.

EXHIBIT 2

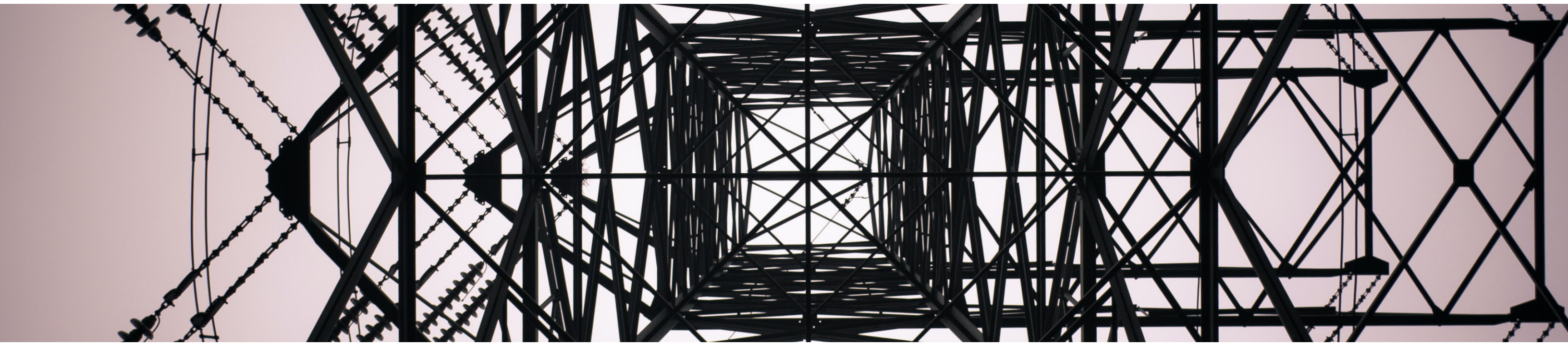
Current shortfall in near-zero emissions steel project pipeline

Nameplate crude steel production capacity *(Mtpa)*



Notes: The chart shows the pipeline of breakthrough iron and steel projects to date versus the required pipeline of near-zero emissions primary capacity to 2030 to put the global steel industry on a path to net zero by 2050 that is aligned with limiting average global temperature rise to 1.5°C (above preindustrial levels). The current project pipeline is an approximation based on the capacity of the projects in Exhibit 1 and estimates for confirmed projects whose capacity has not yet been disclosed.

Source: Making Net-Zero Steel Possible, Mission Possible Partnership, September 2022



1.2 Policy Developments

Breakthrough H_2-DRI projects have been clustered around Europe largely due to the EU's climate ambitions and the resulting policy environment. At the same time, recent policy developments in the United States have markedly improved conditions for breakthrough iron and steel, meaning an acceleration of projects could be expected in the region. Key components of the policy environment in both locations include:

European Union

- **European Union Emissions Trading System (EU ETS):** In place since 2005, the EU ETS requires eligible industrial facilities to purchase allowances for their carbon emissions, establishing a price on carbon that has risen since its inception. Steel plants are currently partially shielded from this cost, as they receive a portion of their allowances for free. Plans are in place to gradually phase out these free allowances, but their full phaseout is expected no earlier than 2032 and more likely by the end of 2034.[vii]

- **Carbon Border Adjustment Mechanism (CBAM):** Planned to commence from 2026,[viii] this measure to avoid carbon (i.e., the relocation of production to jurisdictions with lower environmental regulation) from the EU should further level the playing field for breakthrough iron and steel (and other industries) by extending the carbon price of the EU ETS to iron and steel imported from outside the bloc.

- **Green Deal Industrial Plan:** Announced in 2023 and recently supplemented by the Net-Zero Industry Act, the plan includes several provisions to support industry decarbonisation, including the loosening of restrictions on state aid and access to EU funding, such as funds available under the REPowerEU and Recovery & Resilience Facility programs. The plan also includes a provision to auction fixed premiums for low-carbon hydrogen production. The first auction will be launched in the second half of 2023, funded by €800 million from the EU Innovation.[ix] These provisions can support the cost of constructing and operating breakthrough iron and steel facilities, increasing competitiveness with conventional high-emissions production.

United States

- **Inflation Reduction Act (IRA):** Legislated in 2022, the IRA is a broad piece of legislation covering numerous areas but crucially offering a production tax credit (PTC) for low-carbon hydrogen ($3/kg). This provision is designed to lower the cost of hydrogen and could therefore lower the cost of key feedstock for breakthrough iron and steel.

- **Industrial Demonstrations Program:** Run by the Department of Energy and funded by the IRA and the Infrastructure Investment and Jobs Act, the program allocates approximately $6 billion to direct support to projects designed to decarbonise high-emitting industries, including iron and steel.[x] Funding from the program could be used to improve the financial viability of breakthrough iron and steel projects, particularly ones intended to decarbonise existing primary production in the country.

- **Federal Buy Clean Initiative:** An ongoing effort to direct the federal government's $650 billion worth of purchasing towards low-emissions materials, including iron and steel.[xi] The initiative is poised to offer a valuable lead market for breakthrough iron and steel products and may help cover the relatively higher costs associated with their production.

These policy developments will strengthen the investment case for breakthrough iron and steel in the EU and United States; Part 3 explores how they would impact a range of different hydrogen steelmaking technology archetypes. However, given the scale of the shortfall in planned capacity globally, further action in these regions and beyond is needed to grow the global project pipeline and accelerate projects to FID status.

vii "**Steelmakers win concessions in EU carbon market reform talks**," Euractiv, October 2022.

viii "**Carbon border adjustment mechanism as part of the European green deal**," European Parliament, January 2023.

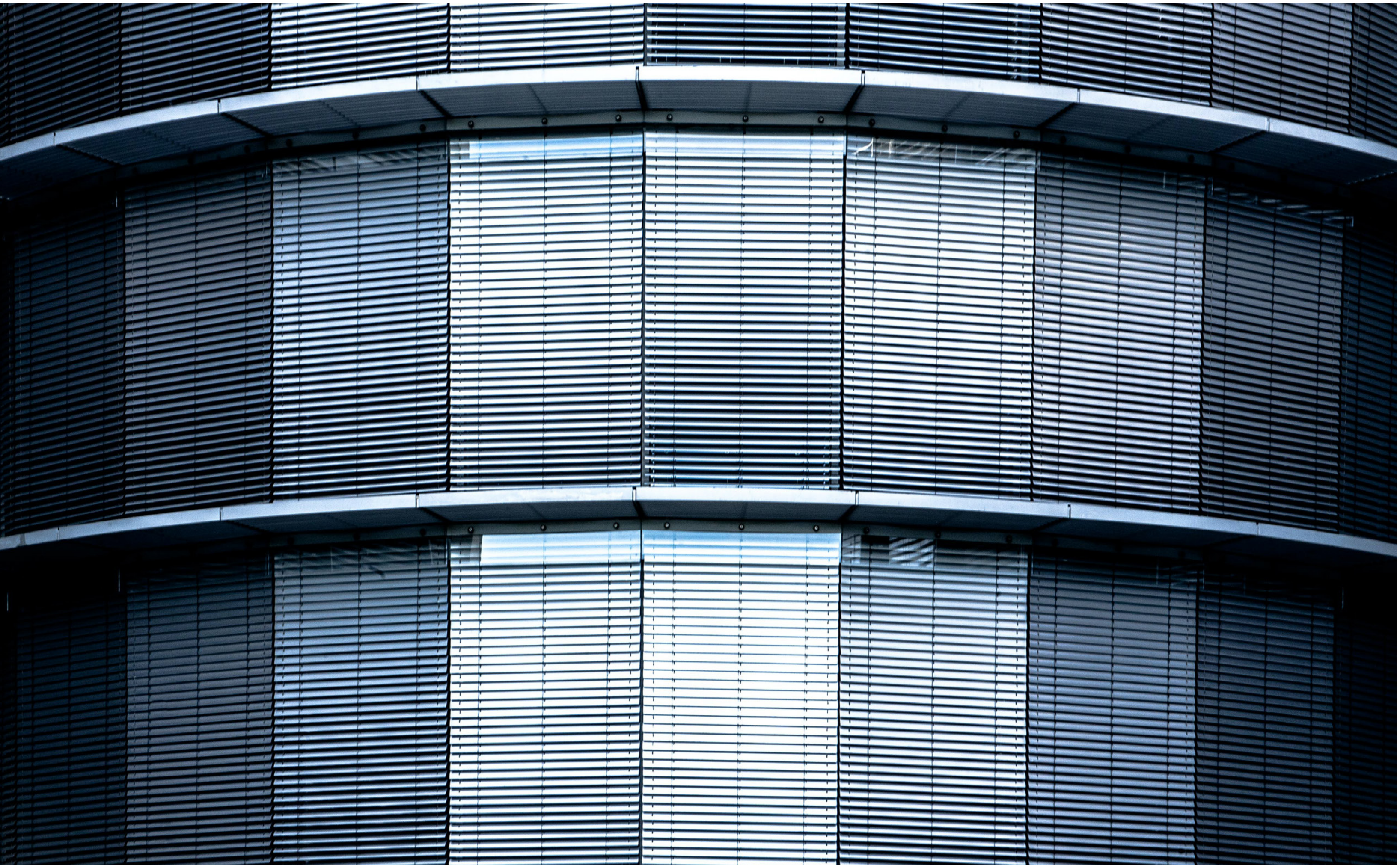
ix ***A Green Deal Industrial Plan for the Net-Zero Age***, European Commission, February 2023.

x ***Biden-Harris Administration Announces $6 Billion To Drastically Reduce Industrial Emissions and Create Healthier Communities***, Department of Energy, March 2023.

xi ***Federal Buy Clean Initiative***, Office of the Federal Chief Sustainability Officer (CSO).

PART 2

THE BREAKTHROUGH STEEL FORUM METHODOLOGY



While economy-wide and sectoral decarbonisation roadmaps, such as the International Energy Agency's *Net Zero by 2050* and the Mission Possible Partnership's *Making Net-Zero Steel Possible*, point to breakthrough technologies for primary steelmaking as essential for achieving net zero, detailed insight into what is needed to achieve FIDs on breakthrough technology deployments has been more limited. To drive this assessment, the ETC conducted a series of regionally focused forums to develop a clearer-eyed understanding of what it will take to reach FID for such projects in the near term.

Given the combination of project announcements and favourable policy developments from Europe and North America, the forum series was centred on these regions as they appear to offer the best prospects for securing FIDs on a first wave of projects in the short term. Within Europe and North America, four subregions were chosen to reflect a variety of locational contexts, each represented by a specific country: the United Kingdom, Spain, France, and the United States (the US forum delivered in partnership with RMI) (Exhibit 3, next page).

EXHIBIT 3

Overview of the current state of the iron and steel industry in selected forum regions

Rationale for inclusion	Existing capacity *(Mtpa)* EAF / BF-BOF	Crude steel production *(Mt 2021)* EAF / BF-BOF	Average Scope 1 emissions *(tCO$_2$/t steel 2021)*	Scrap steel trade balance *(Mt 2021)* Exports / Imports
United Kingdom				
Birthplace of industrial steelmaking with a long history of industry expertise. However, the industry has been shrinking in recent decades, with production falling from 17.8 Mt in 1990 to 7.2 Mt in 2021. Existing primary steel assets face imminent decisions as they reach the end of their current investment cycles, creating a clear window of opportunity to transform them with breakthrough technology.	EAF 3, BF-BOF 8; total 11	EAF 1, BF-BOF 6; total 7	1.9	Exports 8
Spain (Southern Europe)				
Benefitting from an already lower-emissions steel industry based on secondary steelmaking using domestic and imported scrap, Spain can leverage breakthrough iron and steel to extract greater value from its abundant renewable energy resources.	EAF 13, BF-BOF 5; total 18	EAF 10, BF-BOF 5; total 15	0.9	Exports 1; Imports 4
France (Western Europe)				
Part of the heartland of continental European steelmaking, France has pioneered research into steel decarbonisation since the early 2000s but has not yet seen FIDs on commercial-scale projects like in neighbouring Germany. Recent policy developments may help change that in the short term.	EAF 6, BF-BOF 12; total 17	EAF 5, BF-BOF 9; total 14	1.7	Exports 7; Imports 2
United States (North America)				
Representing the majority of steelmaking in the region, the scale of production in the US means it still generates high emissions despite a large proportion of secondary steelmaking. Recent policy developments combined with good renewable energy resources could help accelerate a domestic project pipeline.	EAF 73, BF-BOF 36; total 109	EAF 59, BF-BOF 26; total 86	0.9	Exports 18; Imports 5

Global average Scope 1 emissions intensity (tCO$_2$/tonne of crude steel):	**Electric arc furnace (EAF):** 0.16	**Blast furnace-basic oxygen furnace (BF-BOF):** 2.4

Notes: Total BF-BOF capacity in the EU is approximately 104 Mtpa, while total EAF capacity is approximately 87 Mtpa.

Source: ETC analysis based on data from ***World Steel in Figures 2022***, worldsteel, April 2022; ***Global Steel Plant Tracker***, Global Energy Monitor, March 2022; ***EU ETS Data Viewer***, European Environment Agency, 2022; and ***Making Net-Zero Steel Possible***, Mission Possible Partnership, September 2022.

To underpin forum discussions, the ETC developed an open-source tool that models the financial performance of different breakthrough iron and steel investments.[xii] The architecture and input assumptions of the tool were stress tested and validated with experts and stakeholders in each forum, allowing the tool to reflect the realistic economics of an investment in the corresponding region.

Analysis and discussion within the forums revolved around breakthrough iron and steel project archetypes (Exhibit 4).[xiii] These archetypes were developed to provide a foundation for open discussion on the investment prerequisites while avoiding debate on particular assets. Given the advancements in H2-DRI highlighted in Part 1.1 of this report, the archetypes were centred around this technology, while technologies with lower TRLs (such as carbon capture with effective captures rates above 90%-95%, or molten ore electrolysis) were not included in the scope.

Before committing to an FID, investors consider a wide range of factors in evaluating a prospective investment and use a variety of metrics to do so. Three metrics commonly used to assess the attractiveness of an asset investment are (1) net present value (NPV),[xiv] (2) levelised cost of production (LCOP),[xv] and (3) payback period.[xvi] These metrics are used to measure the performance of breakthrough archetypes in the financial tool and assess the resulting investment case in forum discussions.

EXHIBIT 4

Overview of breakthrough iron and steel archetypes

	INTEGRATED STEELMAKING				SEPARATE IRON AND STEELMAKING	
	Brownfield total conversion	**Brownfield EAF conversion**	**Brownfield melter conversion**	**Greenfield H_2-DRI-EAF**	**Greenfield EAF**	**Greenfield merchant HBI**
Existing technology	BF-BOF	EAF	BF-BOF	n/a	n/a	n/a
Target site technology	DRI-EAF	DRI-EAF	DRI-melter-BOF	DRI-EAF	EAF	DRI
DRI feedstock	100% green H_2	100% green H_2	100% green H_2	100% green H_2	n/a	100% green H_2
Capital expenditure	$0.9 – $1.4 billion	$0.7 – $1.0 billion	$0.9 – $1.1 billion	$1.3 – $2.1 billion	$0.6 – $1.0 billion	$0.8 – $1.2 billion
End-product	Hot-rolled coil	Hot-rolled coil	Hot-rolled coil	Hot-rolled coil	Hot-rolled coil	Hot briquetted iron

Notes: Going forward, hot-rolled coil and hot briquetted iron are referred to by their acronyms, HRC and HBI. Unless otherwise stated, all analysis assumes 2 million tonnes per annum as a reference plant capacity to enable direct comparison between the archetypes. All monetary values in this report are denoted in real 2020 US$ due to the international nature of steel investment and lending portfolios, where finances are assessed in US$ terms.

Source: ETC analysis

xii The tool is publicly available and allows users to modify inputs to explore the impact of changing assumptions on the financials of breakthrough steel projects.

xiii The DRI technology archetypes considered in the forum series are not exhaustive, with variants including the use of submerged arc furnace technology for steelmaking. Several projects and feasibility studies employing alternative technologies were announced over the course of the forum series. It is possible to explore additional variants in the accompanying financial model, provided the techno-economic input assumptions can be sourced.

xiv NPV is the unlevered difference between the present value of cash inflows and the present value of cash outflows over a period of time.

xv LCOP is a form of discounted cash flow analysis that expresses the present value of nonrevenue cash flows per unit of production. In this report, all LCOP values are reported on a post-interest pretax basis. Unlevered NPV values, on the other hand, include tax but do not include interest expenses. For more information on financial methodologies, please see the Technical Appendix to this report.

xvi Payback period refers to the length of time needed by an investment to cover its up-front capital expenditures. Steel investors normally expect to see payback periods of 10 years or fewer on proposed investments.

KEY INSIGHTS

3.1 Energy

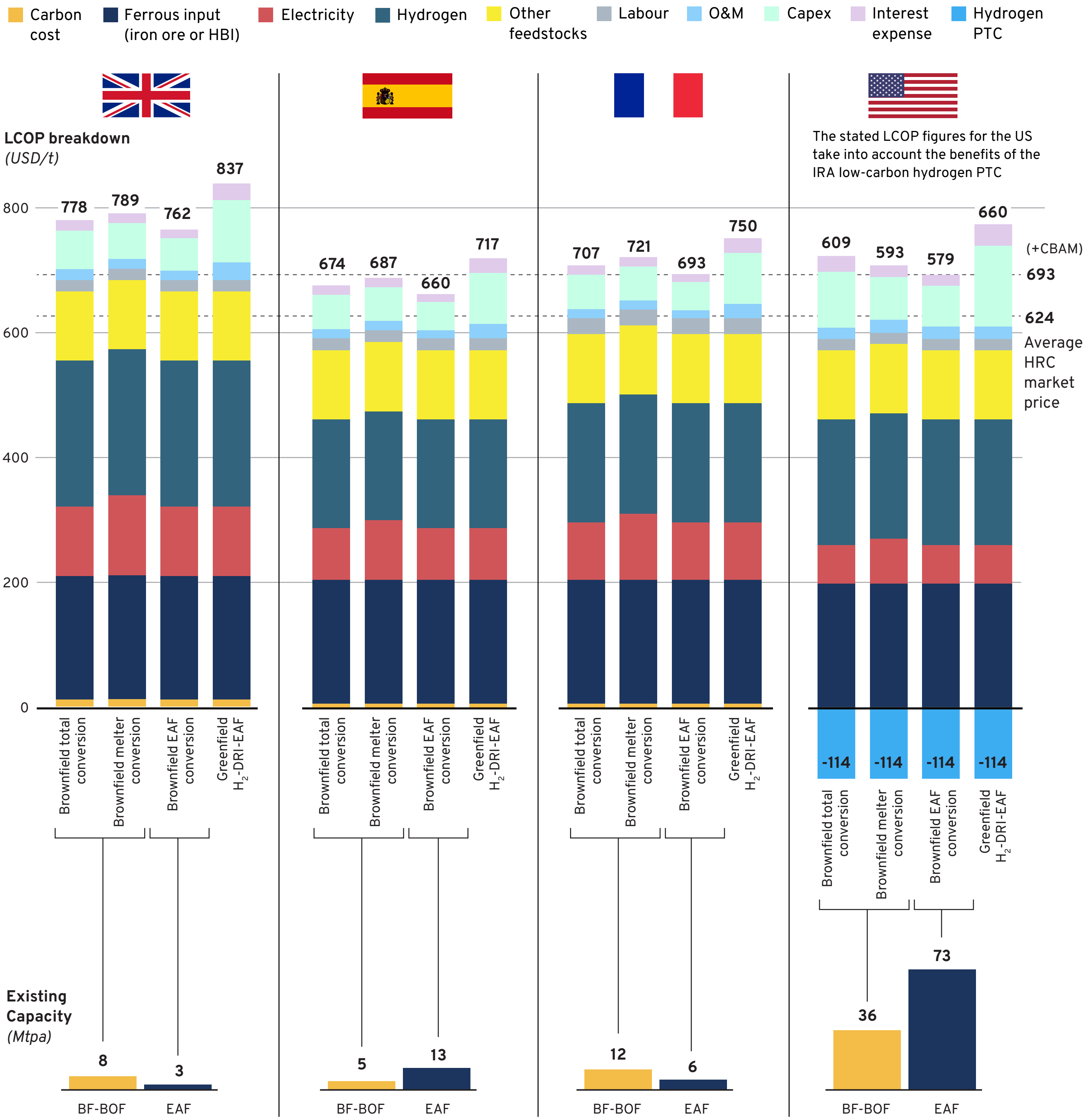
Energy costs are the key driver of the international competitiveness of breakthrough iron and steel. A cross-country comparison of the LCOP of the different archetypes highlights how electricity and hydrogen combine to account for 34%–46% of the production cost of integrated steelmaking across the four countries (Exhibit 5, next page). Other factors, such as capital expenditure and ferrous input, are also important but relatively less so at the international level. Capital expenditure, for example, only accounts for 5%–17% of LCOP across all archetypes, a fraction of energy costs. Ferrous input costs may be higher but are broadly equal for the archetypes across the four regions, given that highly globalised and commoditised iron ore markets.

Given that the main driver of the hydrogen costs faced by the archetypes is the cost of power for electrolysis to produce green hydrogen, electricity becomes the decisive factor in determining the competitiveness of breakthrough iron and steel. In Europe, Spain leverages its excellent renewable energy resources to achieve electricity prices averaging $50/megawatt-hour (MWh) between 2024–50. These compare with $59/MWh in France and $70/MWh in the UK. This enables Spain to achieve a more competitive LCOP than its European peers on a crude steel (HRC) benchmark basis.

EXHIBIT 5

LCOP of breakthrough iron and steel archetypes in selected forum countries (integrated archetypes)

Plant size:	Utilisation rate:	Scrap intake:	Plant lifetime:	Debt-to-equity:	Equity IRR:	Average interest rate:	FID date:
2 Mtpa	90%	0%	20 years	1.5	8%	6%	2024



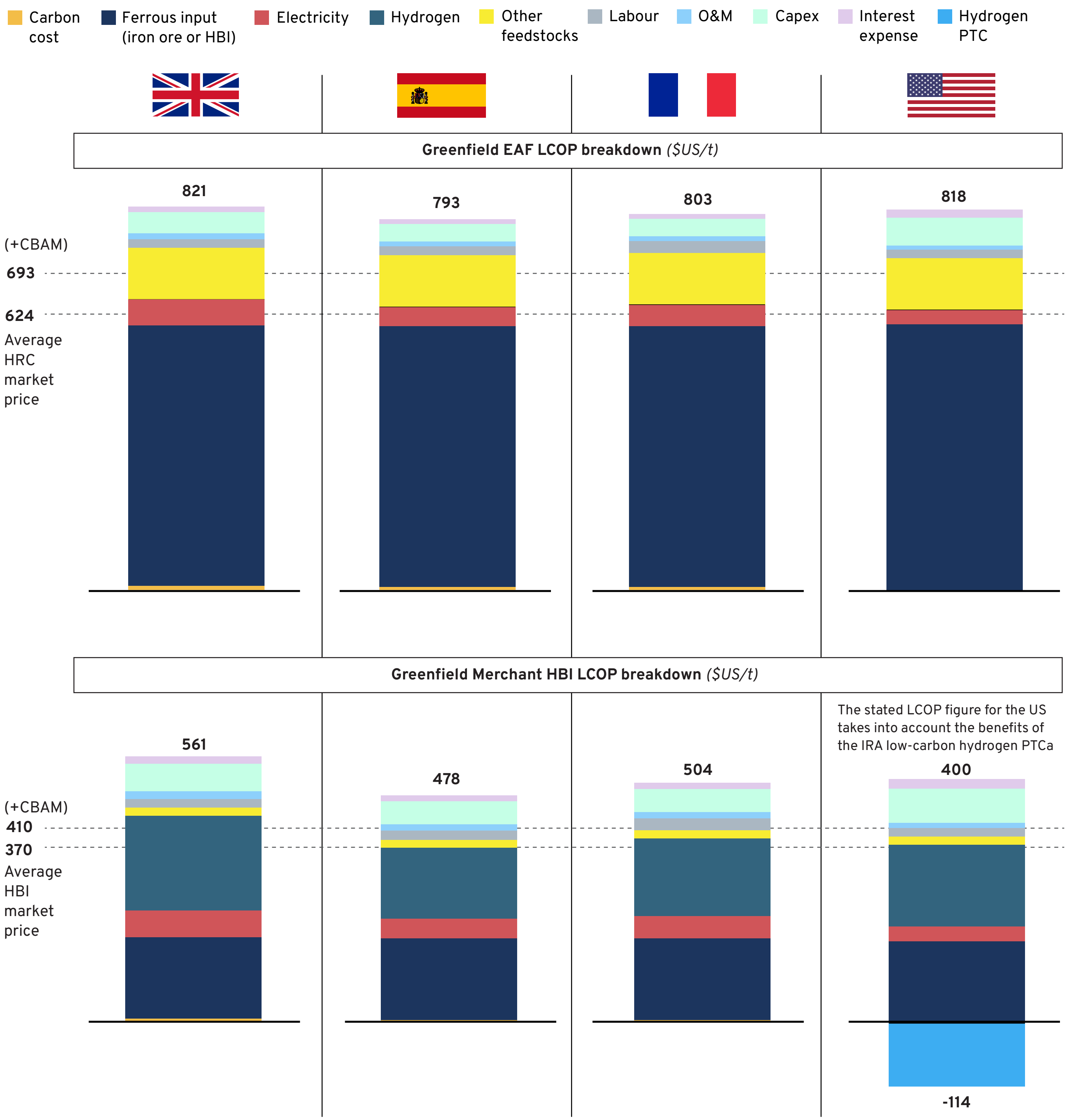
Notes: In all regions, archetypes assume a 15-year debt repayment schedule with a one-year grace period, a three-year construction period, and a one-year ramp-up to full production. The dashed lines represent the average market price of HRC or HBI across the four countries before and after the effect of carbon pricing. In practice, this effect would only be seen in countries where carbon pricing is applied to both domestic production and imports from abroad in the manner intended by the forthcoming EU CBAM. Despite ongoing issues of overcapacity in global steel markets, the financial analysis assumed a utilisation rate of 90% on the basis that the near-zero steel produced by the archetypes would stand out as a differentiated product and would not necessarily be crowded out by oversupply of conventional, emissions-intensive steel.

Source: ETC analysis

EXHIBIT 5

LCOP of breakthrough iron and steel archetypes in selected forum countries (separate iron- and steelmaking archetypes)

Plant size:	Utilisation rate:	Scrap intake:	Plant lifetime:	Debt-to-equity:	Equity IRR:	Average interest rate:	FID date:
2 Mtpa	90%	0%	20 years	1.5	8%	6%	2024



Notes: In all regions, archetypes assume a 15-year debt repayment schedule with a one-year grace period, a three-year construction period, and a one-year ramp-up to full production. The LCOP figures for the US consider the benefits of the IRA low-carbon hydrogen PTC. The dashed lines represent the average market price of HRC or HBI across the four countries before and after the effect of carbon pricing. In practice, this effect would only be seen in countries where carbon pricing is applied to both domestic production and imports from abroad in the manner intended by the forthcoming EU CBAM.

Source: ETC analysis

The US benefits from lowest electricity prices of all (averaging $42/MWh between 2024–50).[xvii] This advantage allows the archetypes in the US be competitive versus their European counterparts, even in the face of relatively higher capital expenditures (amounting to 9%-17% of LCOP). Building on this foundation, the low-carbon hydrogen PTC helps the archetypes in the US to achieve the lowest production cost of all four countries. With green hydrogen prices in the country averaging $3.5/kg across 2024-2050, a $3/kg reduction for 10 years reduces starting LCOP by $114/t, a 15%-16% reduction for the archetypes that integrate iron- and steelmaking that significantly improves their competitiveness.

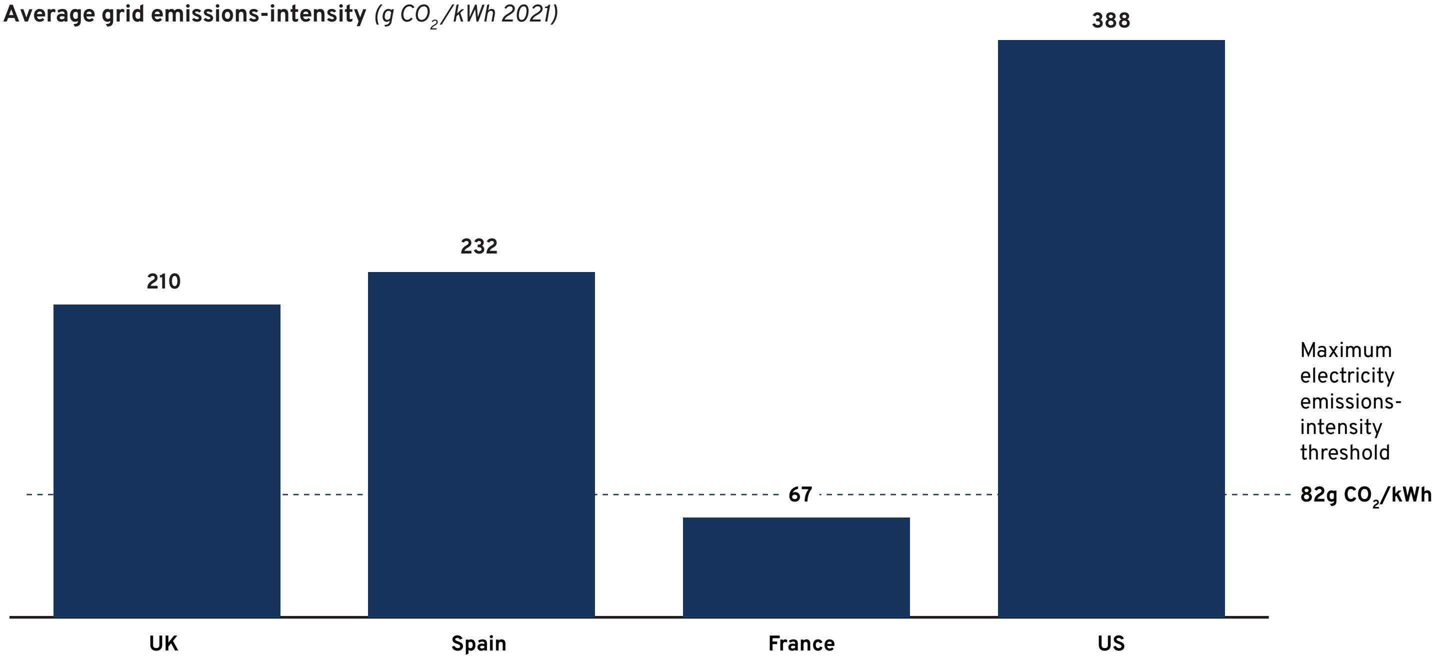
Given the significance of electricity to breakthrough iron and steel production, ensuring its supply is as low-carbon as possible is crucial for avoiding indirect emissions and guaranteeing deeply decarbonised primary steelmaking. The archetypes benefit from better electricity prices in the United States and Spain because they both constitute relatively more mature markets for corporate power purchase agreements (PPAs), offering a more affordable alternative to power supply from the grid. However, in practice, a 'baseload' PPA (capable of fully covering electro-intensive green hydrogen and steel production) supplying 100% renewable power may be difficult to secure at such prices due to the challenges and costs of firming intermittent supply from renewables.

Fortunately, even a power supply with emissions up to 82gCO_2/kWh would nonetheless allow an H_2-DRI-EAF site to produce HRC at an emissions intensity of no more than 0.4tCO_2/t, the upper threshold for low-emissions steel as defined by key actors such as the International Energy Agency, ResponsibleSteel, and the First Movers Coalition. France possesses a unique advantage in this respect. Due to the significance of nuclear power to the country's electricity generation mix, the archetypes could, in principle, produce deeply decarbonised iron and steel in France with power supplied from the grid alone (Exhibit 6).[xviii] For

EXHIBIT 6

Emissions intensity of the electricity grid in selected forum countries

Average grid emissions-intensity *(g CO_2/kWh 2021)*



Notes: The dashed line represents the maximum emissions intensity permitted for the electricity to be considered 'breakthrough' archetypes for their production to remain within an emissions threshold of 0.4tCO_2/t HRC.

Source: ETC analysis based on data from the UK Department for Business, Energy & Industrial Strategy, the UK Department for Environment, Food & Rural Affairs, the European Environment Agency, and the US Energy Information Administration.

xvii The power price projection for the USis based on electricity price assumptions for a breakthrough project located in the Midwest region. For more information on power price assumptions, please see the financial tool and Technical Appendix to this report.

archetypes in the UK, Spain, and the United States, a sufficiently low-carbon power supply would be equivalent to a PPA under which a significant proportion of the electricity comes from renewables (61% for the UK, 65% for Spain, and 79% for the United States), with the rest being covered by the grid.

Electricity prices highlight a broader point about locational contexts and their potential implications for the competitiveness of breakthrough technologies and steel decarbonisation. The high costs associated with steelmaking have historically caused steel mills to be located close to their supplies of key inputs, particularly coal.[xix] If a scale-up of breakthrough iron and steel capacity follows the same pattern, new locations, such as those with good renewable energy resources, availability of land to develop those resources, and electricity infrastructure to harness them, may offer a competitive advantage for low-emissions steelmaking and a correspondingly more attractive investment case.

3.2 Policy

Current and planned policy support mechanisms mean it is already possible to close the financial gap for breakthrough brownfield projects in the EU and United States. Existing and planned carbon pricing regulation in the EU is enough to achieve positive NPV for all brownfield archetypes in Spain and France and secure a payback period of fewer than 10 years for the brownfield EAF archetype specifically. In the United States, the hydrogen PTC has a similar effect but secures an attractive payback period for all brownfield archetypes (Exhibit 7, next page).

In the case of the United States, the hydrogen PTC, made available under the IRA, reduces the hydrogen price faced by the archetypes by $3/kg for 10 years, significantly reducing their operational expenditure and improving their financial performance.

In the EU, the key measure at work in Spain and France is the introduction of the CBAM to the EU ETS. An effective CBAM ensures the price of carbon under the EU ETS is applied to all iron and steel sold within the EU, both imports from outside the bloc and EU production. Effective carbon pricing raises the market price of iron and steel by increasing the cost of conventional, emissions-intensive production. This benefits the breakthrough archetypes with better margins by allowing them to sell their output at higher market prices without facing the carbon costs of their emissions-intensive counterparts.

The CBAM is applied in line with current EU plans and will affect imported iron and steel prices from 2026. Similarly, the treatment of free allocation of carbon allowances for steelmakers under the EU ETS is also broadly in line with current EU plans, with free allocation gradually being phased out by the end of 2034. The impact of effective carbon pricing on iron and steel market prices in the EU is significant enough that even a modest rise in the price of EU allowances, from $83/t CO_2 in 2024 to $100/t CO_2 by 2030 and to $122/t CO_2 by 2050, is enough to result in a positive NPV for all brownfield breakthrough archetypes in Spain and France and achieve a payback period of fewer than 10 years for a brownfield EAF conversion in both countries.[xx]

xviii In practice, breakthrough iron and steel projects in France (and elsewhere in the EU) would necessitate new low-carbon electricity generation capacity due to the European Commission's **new delegated regulation on union methodology for RFNBOs**, issued February 2023, which will require hydrogen to be produced with new low-carbon power generation (as opposed to existing assets) to qualify as 'renewable hydrogen'.

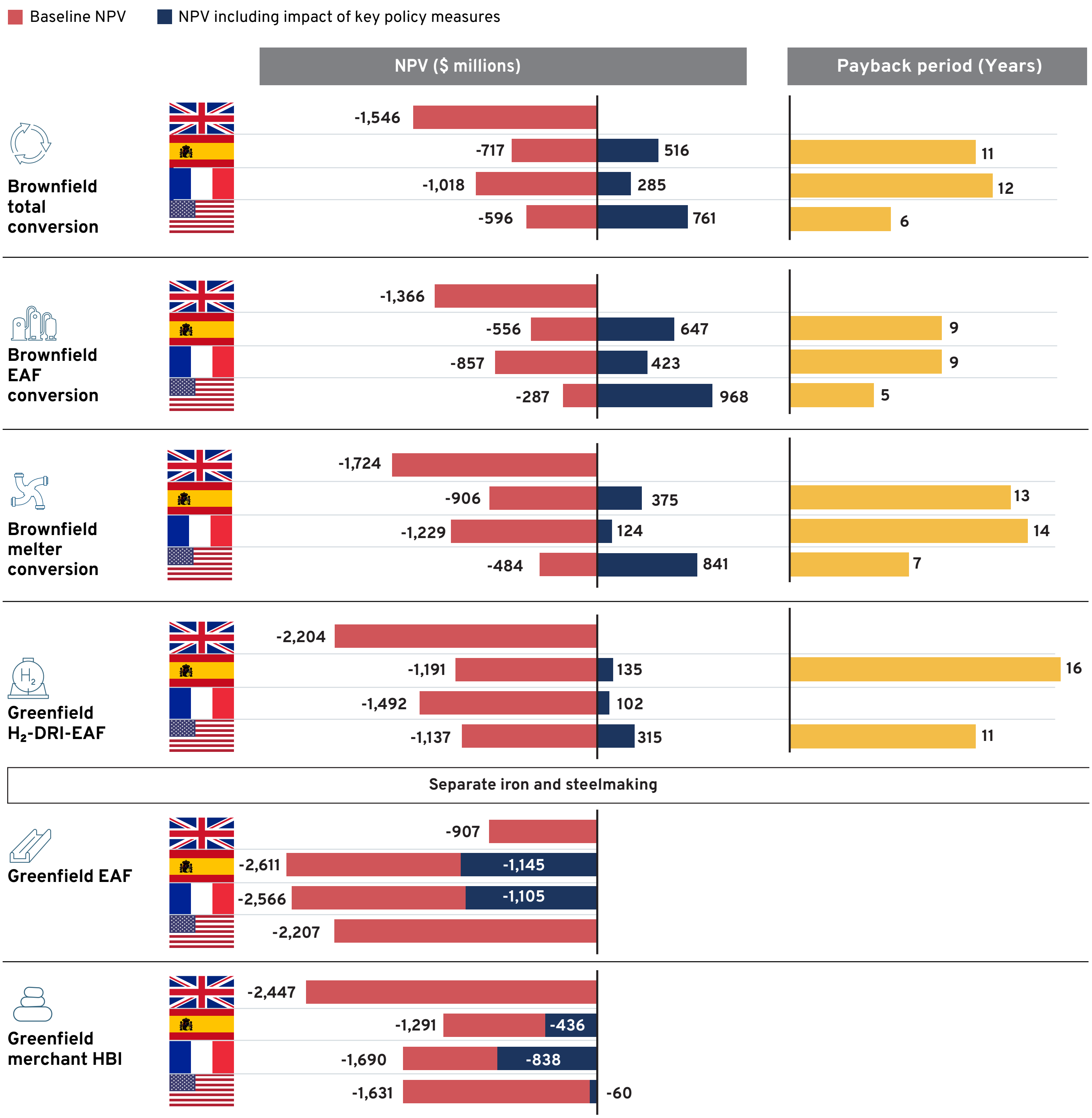
xix ***World Energy Outlook 2022***, International Energy Agency, p. 212.

xx The carbon price trajectory applied in Exhibit 5 can be considered conservative relative to current European Union Allowance (EUA) prices. However, it was applied in this way due to inherent uncertainties around the future prices, particularly given that they are currently impacted by recent developments such as the ongoing war in Ukraine.

EXHIBIT 7

Financial performance of breakthrough iron and steel archetypes under prevailing market and policy conditions

Plant size:	Utilisation rate:	Scrap intake:	Plant lifetime:	Debt-to-equity:	Equity IRR:	Average interest rate:	FID date:
2 Mtpa of HRC	90%	0%	20 years	1.5	8%	6%	2024



Notes: Archetype NPV is influenced by the expected investment rate of return (IRR) applied to equity investment, corporate tax rates, and the method used to calculate the depreciation of assets. Although equity IRR is kept constant at 8% in all countries, a different tax rate and depreciation method is applied in each as follows: UK: 30% tax on earnings and Inland Revenue Service (IRS) General Depreciation System (GDS) 200% + straight-line depreciation method; Spain: 25% tax on earnings, and straight-line depreciation in 17 years; France: 25% tax on earnings and straight-line depreciation in 7 years; and US: 30% tax on earnings and IRS GDS 200% + straight-line depreciation. All other assumptions remain the same as in Exhibit 4 unless otherwise stated.

Source: ETC analysis

The EU CBAM and IRA in the United States have sparked significant international debate across several sectors on the implications of decarbonisation measures on international competition and trade relations. Importantly, these measures have a similar impact on the NPV of archetypes within their respective jurisdictions. The hydrogen PTC delivers a $1.3 billion to 1.6 billion improvement in NPV across the integrated steelmaking archetypes in the United States, while the carbon price trajectory mentioned above combined with the CBAM achieves a $1.2 billion to 1.4 billion improvement in NPV for those same archetypes across Spain and France. However, given the highly globalised nature of iron and steel markets, the international impact of these policy developments must be addressed in the context of scaling up breakthrough iron and steel.

The effect of the EU ETS and CBAM on archetype performance in France and Spain assumes all of the output of a given project in those countries would be sold into markets that face the same carbon price. Without this assumption, the impact of the EU ETS on iron and steel market prices cannot be guaranteed. It is for this reason that the archetypes in the UK do not see a parallel improvement in NPV, despite the presence of a similar carbon pricing regime in the form of the UK ETS. The UK government is coordinating with the EU and plans to open a consultation on the development of a UK CBAM. However, the current absence of such a policy means that decisions around archetypes in the UK today are based on market pricing influenced by emissions-intensive imports that do not face the same carbon price as domestic production.

Current plans for the CBAM should enable the EU ETS to create this effect, at least within the EU iron and steel market, but they have no provisions that would improve the competitiveness of breakthrough iron and steel exports from Spain or France outside of the EU. The implication is that the output of breakthrough projects in Spain or France would initially need to be directed towards domestic or EU markets. This would be a reasonable assumption, given that the goal of the regional forums and their analysis is to assess what would be needed to unlock a first wave of breakthrough projects rather than transform the entire steel industries of both countries. With total steel consumption in the EU reaching almost 150 Mt in 2021,[xxi] the internal market should be sufficient to absorb the output of the first few breakthrough projects.

In contrast, the IRA low-carbon hydrogen PTC could improve the domestic and international competitiveness of breakthrough iron and steel made in the United States. By lowering the key input cost, the PTC reduces the LCOP of breakthrough iron and steel, making it more competitive on an international basis rather than solely within a domestic market. Given the concerns other parts of the IRA (such as the requirement that electric vehicles be assembled in the United States for them to be eligible for support via the Clean Vehicle Credit) have engendered among trade partners of the United States, particularly the EU, the potential impact of the PTC on archetype competitiveness underscores the importance of addressing the international trade implications of supporting breakthrough iron and steel investment.

xxi *European Steel in Figures 2022*, Eurofer, 2021, p. 25.

3.3 Levers to strengthen the investment case

Practical interventions can put a viable investment case within reach in all four countries. While some countries may benefit from more favourable starting conditions, such as better electricity prices or policy support, strategic action involving different parts of the steel value chain can improve the financial performance of breakthrough iron and steel in the near-term. This action could create a viable investment case in all four countries and close the financial gap for archetypes that face one under prevailing conditions, particularly greenfield ones, encouraging investment in the critical two-to-three years ahead.

In the previous section, the hydrogen PTC and CBAM showcased the impact of operational expenditure subsidies and effective carbon pricing on the financial performance of breakthrough archetypes. While similar levers could be applied in countries that do not yet use them, other measures, such as capital expenditure subsidies and forward offtake agreements (at a price premium), offer additional practical solutions for closing the financial gap. Taking the greenfield H_2-DRI-EAF archetype as an illustrative example, the levers can be applied within reasonable limits to achieve a positive NPV and payback period of fewer than 10 years in both countries (Exhibit 8, next page).

Capital expenditure subsidies amounting to 30% of the cost of a new DRI unit (equivalent to $210 million to $300 million per project) improve financial outcomes by covering part of the up-front cost of expensive ironmaking equipment. Lowering up-front costs in this way also reduces the amount of debt financing a future project would need to raise, further improving financial outcomes by reducing the amount of interest that would need to be paid on that debt.

As a support mechanism, up-front support on capital expenditures could be an attractive option for governments, given government preferences for one-off support mechanisms compared with ongoing measures requiring longer (and potentially costlier) commitments. Moreover, there are already real-world examples and precedents of governments committing large amounts of funding to breakthrough steel projects in this way. Examples include the €1 billion of German state aid approved by the European Commission for the Salzgitter SALCOS project,[xxii] and the €460 million of funding from the Spanish Strategic Project for Economic Recovery and Transformation (PERTE) on industrial decarbonisation channelled towards ArcelorMittal's project in Gijón.[xxiii]

The hydrogen PTC combined with a DRI capital expenditure subsidy is sufficient to achieve a payback period of 10 years of the greenfield H_2-DRI-EAF archetype in the United States. In the European countries, forward offtake agreements at a premium offer a final step to closing the financial gap for the archetype. These agreements work by first guaranteeing a price for part or all of the output of a breakthrough iron or steel mill. Then, the share of output subject to the agreement can benefit from a price premium above market prices for the relevant product.

Forward offtake agreements are already beginning to emerge in practice as steel buyers see the value of securing the first scarce volumes of low-emissions primary steel to decarbonise their materials supply chains. H2 Green Steel, for example, secured advance agreements for 1.5 Mtpa of offtake starting from 2025 despite not yet having an operational plant.[xxiv] A growing number of major steel buyers setting upstream Scope 3 emissions reductions target, combined with the likely initial scarcity of the lower-emissions steel they will need, suggests the output of a first wave of breakthrough steel plants in Europe could command a premium over market prices for equivalent, emissions-intensive products.

To reflect these dynamics, a premium of +$110/t is applied in France (18% above market prices), +$120/t is applied in Spain (20% above market prices), and +$210/t is applied in the UK (33% above market prices) to close the financial gap in each country. Crucially, these premium figures represent a peak that only applies to the initial output of a breakthrough project and gradually declines over its operational lifetime. This distribution reflects how breakthrough steel would be more likely to command a premium when supplies are initially scarce but that the premium would likely fall over time as breakthrough steelmaking becomes more widespread. Buyers could structure offtake agreements accordingly, paying a higher premium at first to lock in scarce supplies but then seeing the premium decline over time.

If the total premium secured by the archetype in France, Spain, or the UK in this way were averaged over the total lifetime production of the project, it would amount to +$54/t in France, +$59/t in Spain, and +$103/t in the UK. In practice, the level of premium offtake required to close the financial gap for breakthrough iron and steel could depend substantially on the archetype or project circumstances. For example, in contrast to the greenfield H_2-DRI-EAF considered in Exhibit 6, the necessary peak or average premium values would be lower for brownfield archetypes that leverage existing site equipment and have comparatively lower up-front investment to pay back.

xxii "**State aid: Commission approves €1 billion German measure to support Salzgitter decarbonise its steel production by using hydrogen**," European Commission, October 2022.

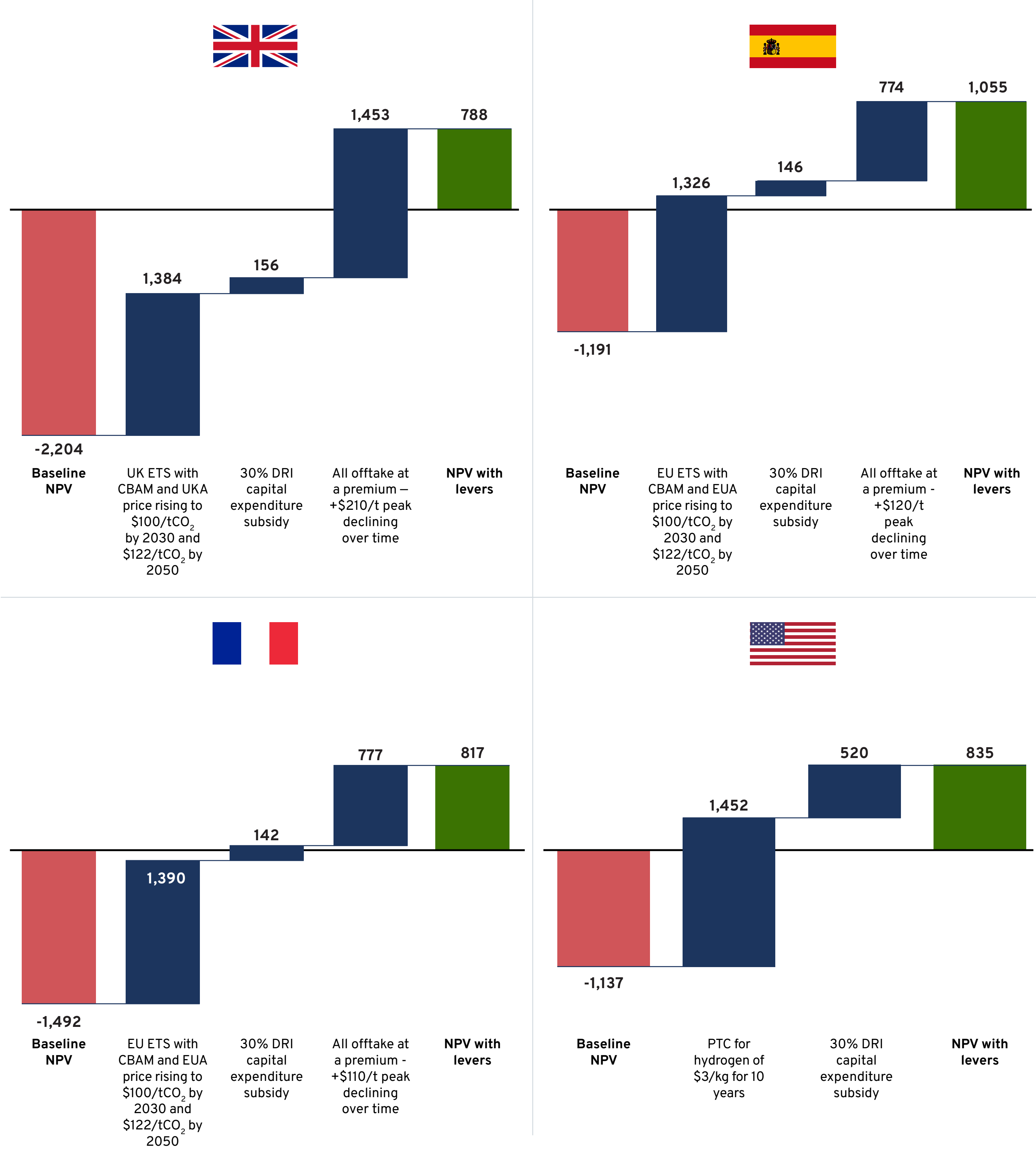
xxiii "**State aid: Commission approves €460 million Spanish measure to support ArcelorMittal to decarbonise its steel production**," European Commission, February 2023.

xxiv "**H2 Green Steel has pre-sold over 1.5 million tonnes of green steel to customers**," H2 Green Steel, May 2022.

EXHIBIT 8

NPV impact of measures to strengthen the investment case for a greenfield H_2-DRI-EAF project in selected forum regions

Plant size:	Utilisation rate:	Scrap intake:	Plant lifetime:	Debt-to-equity:	Equity IRR:	Average interest rate:	FID date:
2 Mtpa of HRC	90%	0%	20 years	1.5	8%	6%	2024



Notes: All other assumptions remain the same as in Exhibit 5 unless otherwise stated.

Source: ETC analysis

PART 4

A WAY FORWARD — INTERNATIONAL

INTERNATIONAL PERSPECTIVES AND RECOMMENDATIONS

As the global project pipeline (Exhibit 1) and regional analyses (Exhibit 5) demonstrate, a viable investment case for breakthrough iron and steel is within reach in numerous locations around the world. At the same time, a market for low-emissions iron and steel is starting to emerge as buyers of these products face growing demand and regulatory pressures to decarbonise their supply chains, particularly in Europe and North America.

A low-emissions supply of lower-grade 'long' steel products (typically used for construction) could be established using existing materials and technology, namely, scrap processed via EAF mills using low-carbon electricity. However, new solutions will require a low-emissions supply of 'flat' products (steels that can be used in higher-grade applications such as in the automotive and engineering sectors), including the iron required to make them. Breakthrough H_2-DRI technology appears best placed to offer one such solution for the near future.

Developments in multiple countries show that breakthrough iron and steel opportunities are already being seized. With projects breaking ground in Sweden (H2 Green Steel), Germany (Salzgitter), and Canada (ArcelorMittal) following FIDs to proceed,[xxv] the race to secure valuable forward offtake agreements and bring the first volumes of production to market is very much underway.

Two of the countries considered in this report have similarly entered the race, namely, Spain (with projects involving ArcelorMittal, H2 Green Steel, and Hydnum Steel) and France (ArcelorMittal, GravitHy, and Liberty Steel). However, FIDs have yet to be confirmed for the projects in those countries, and a first wave of projects in the UK and the United States remains forthcoming.

Industry, government, buyers, and finance in all four countries (as well as others) should take action to enter this race in the coming 12 months. In doing so, they can capture the environmental benefits of breakthrough technologies, accelerate the development of important adjacent sectors (such as renewable electricity and clean hydrogen), and benefit from the learnings of being first movers in the emergent market

xxv Corporate press releases.

for near-zero-emissions primary steel. At the same time, the scale, strategic importance, and international nature of steel and its supply chains will mean important debates on industrial and multilateral policy will commence.

In all regions, a positive investment case will require strong coordinated intervention from industry, policy, and the wider value chain. It will be imperative that the potentially distortionary effects on highly commoditised and margin-based iron and steel markets are not used as an excuse to slow the necessary deployment of breakthrough steelmaking technologies. Instead, high-ambition multilateral efforts will be needed to navigate complex new competitiveness issues that low-emissions steelmaking will entail. Such efforts will be in the interest of policymakers as deep subsidisation of the steel sector is unlikely to be fiscally sustainable in the long run. The Steel Breakthrough, agreed at COP26 under the Breakthrough Agenda, is an example of such an effort and has sought to coordinate initiatives on steel decarbonisation at the global level. The Breakthrough offers a possible foundation for further multilateral engagement and could be leveraged to deepen the necessary cooperation.

Fortunately, international competitive issues need not be treated as an entirely zero-sum game for the first wave of projects, particularly by national and regional governments. The potential market opportunity for low-emissions flat steel products is significant. An estimated 170 Mtpa of production is needed globally by 2030 for the global steel industry to be on a credible 1.5°C-aligned pathway to net zero by 2050.[xxvi] Moreover, breakthrough steel investments also point to opportunities for cross-border cooperation to create enabling conditions for investment at the international level. Cooperating in this way could foster healthy competition and learning effects, allowing individual countries and regions to future-proof their steel industries and safeguard high-value jobs. Key enabling conditions requiring international collaboration include:

Coordinated aggregation of public and private sector demand: The market for low-emissions flat steel (and the iron required to make it) is emerging. However, demand remains fragmented across various buyers, who can be geographically disparate and possess different product needs. Efforts to aggregate demand for near-zero-emissions steel across borders would send clear market signals of demand

xxvi ***Making Net-Zero Steel Possible***, Mission Possible Partnership, September 2022, p. 49. The estimated 170 Mt corresponds to 190 Mtpa of production capacity (based on typical capacity utilisation factors) and amounts to 9% of total crude steel output today, based on 2021 production figures from ***World Steel in Figures 2022***, worldsteel, April 2022.

for breakthrough iron and steel products and encourage expansion of the project pipeline. Moreover, these groups of buyers would be well-placed to enter negotiations with project proponents on individual forward offtake agreements, which would help underpin project investment and secure financing. Buyer initiatives and alliances, such as the United Nations Industrial Development Organization (UNIDO) Industrial Deep Decarbonisation Initiative (IDDI), First Movers Coalition (FMC), and SteelZero, whose members have pledged to begin purchasing low-emissions steel by 2030, are well placed to support this coordination.[xxvii]

Forge alignment on product standards, definitions, and certification: Given the importance of demand-side interventions to strengthen the investment case for potential projects, prospective buyers of breakthrough iron and steel will need clear standards, definitions, and certification schemes for low-emissions products to give them confidence in their purchasing decisions, particularly if they are required to commit to long-term offtake agreements involving green premiums that projects can collateralise. Efforts to establish these measures are already underway, both from the private (e.g., the ResponsibleSteel Standard) and public sectors (e.g., UNIDO IDDI). Enhanced coordination to ensure alignment on standards, ambitious definitions, and certification schemes would help maximise the utility of these measures. While absolute alignment is likely impractical, harmonisation of standards and definitions, particularly across national and regional governments, could form the basis of international 'carbon clubs' for iron and steel, such as the Global Arrangement on Sustainable Steel and Aluminum proposed by the United States to the EU.[xxviii]

Coordinated separation of iron and steelmaking: Given the shifts in production economics that breakthrough steelmaking technologies will bring, new cost-optimal locations for producing near-zero-emissions steel will likely emerge. For policy and decision-makers, these new locational contexts will require careful consideration of the trade-offs of the potential separation of iron and steelmaking processes (both nationally and internationally). Options to source low-emissions iron from more cost-optimal locations will entail complex trade-offs involving access to raw materials, security of supply, logistics, labour, and new partnerships. Coordination within and across international borders will be essential.

Breakthrough iron and steel projects are being taken forward worldwide, and a viable investment case appears achievable in multiple locations. Whole-value-chain action at the national and regional level could establish investment cases in the UK, Spain, France, the US, and beyond. With the multiyear lead times involved in planning and building steel mills, it will be important that a first wave of projects is followed by deeper and successive waves of deployments to 2030 and beyond.

xxvii The **FMC Steel Commitment** requires signatories to ensure that at least 10% (by volume) of all steel purchased per year will be near-zero emissions (as per FMC definition) by 2030. **SteelZero** requires members to make a public commitment to buying and using 100% net-zero steel by 2050 and an interim commitment to buy and use 50% of their steel requirement by 2030.

xxviii "**US Proposes Green Steel Club That Would Levy Tariffs On Outliers**," *New York Times*, December 2022.

Energy Transitions Commission

The Energy Transitions Commission is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century.