Alliance for Industry Decarbonization

Solutions to decarbonise heat in the steel industry

ISBN: 978-92-9260-596-4

CITATION: AFID (2023), *Solutions to decarbonise heat in the steel industry,* Alliance for Industry Decarbonization, Abu Dhabi.

About AFID

The mission of the Alliance for Industry Decarbonization is to foster action for decarbonisation of industrial value chains, promote understanding of renewables-based solutions and their adoption by industry with a view to contributing to country-specific net-zero goals. The AFID is open for members and ecosystem knowledge partners to any legal entity engaged in decarbonising industry based on renewable energy solutions. This can+ include but is not limited to public or private sector industrial firms, industry associations, the financial community and intergovernmental organisations.

The International Renewable Energy Agency (IRENA) co-ordinates and facilitates the activities of the AFID.

IRENA
International Renewable Energy Agency

About this report

This report was developed jointly by members of the AFID Working Group (WG) "Heat process optimization and integration". It builds on exchanges and discussions among the WG members that took place during a series of meetings to realise joint initiatives. This report is informed by the experience of AFID members and ecosystem knowledge partners from different regions across the world.

Acknowledgements

The AFID would like to express its gratitude to all the authors who participated in the meetings and discussions that informed this report. The Alliance also thanks the United Arab Emirates for its voluntary contribution to support this publication.

The report was produced by IRENA, with publications support provided by Francis Field and Stephanie Clarke. The text was edited by Lisa Mastny, with design provided by Strategic Agenda.

Contributors

Asmaa Fahad Alameri (Siemens Energy)
Maitha Salim Alqaydi (Siemens Energy)
Ali Alzaabi (Siemens Energy)
Michael Czarnecki (Kent)
Jaafar El Masri (Siemens Energy)
Hassan Ismail (Elsewedy)
Luis Janeiro (IRENA)
Lisa Kamin (Siemens Energy)
Karan Kochhar (IRENA)
Amit Kumar (Tata Steel)
Navlok Kumar (Siemens Energy)
Saurabh Kundu (Tata Steel)
Odellia Matangi-Mangwengwende (ATC Development)
Evgeniya Mitchell (Kent)
Abdelrahman Najjar (Siemens Energy)
Juan Pablo Jimenez Navarro (IRENA)
Begonia Gutierrez (IRENA)
Zafar Samadov (IRENA)
Ayden Smith (BX Ventures)
Philip Stephenson (Electrified Thermal)
Jaison Thomas (Tata Steel)

For further information or to provide feedback: **AFID@irena.org**
This report is available for download: **www.allianceforindustrydecarbonization.org**

Contents

Figures

Tables

Abbreviations

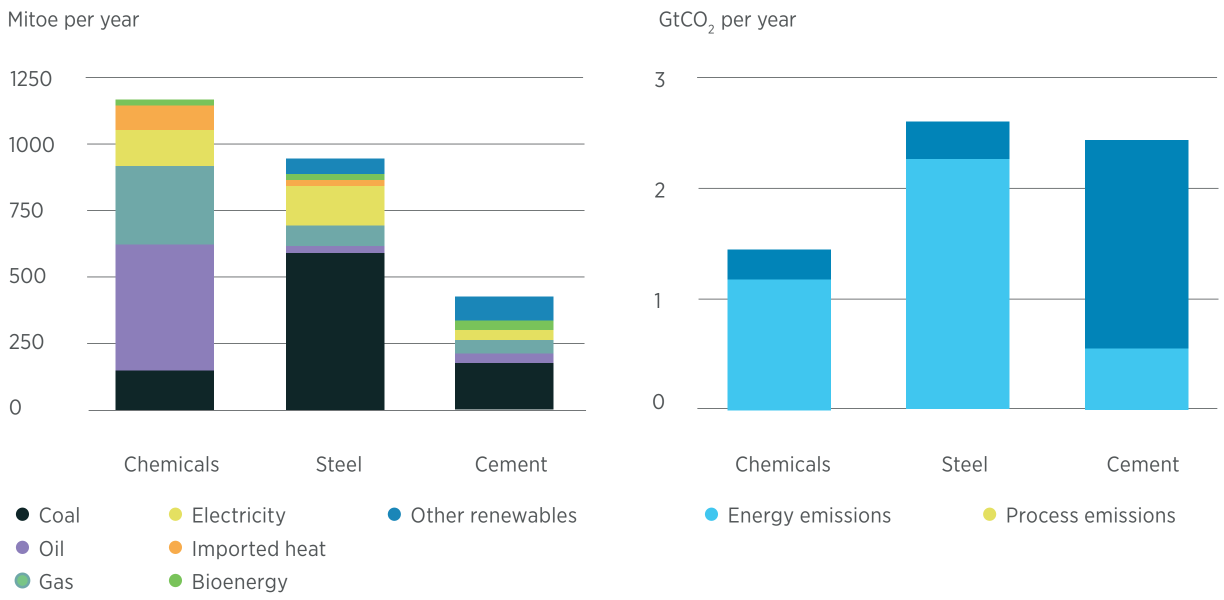
BF	blast furnace
BOF	basic oxygen furnace
CAPEX	capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
DRI	direct reduced iron
EAF	electric arc furnace
ISBL	inside battery limits
OEM	original equipment manufacturer
OPEX	operational expenditure
ORC	organic Rankine cycle
OSBL	outside battery limits
PCI	pulverised coal injection
R&D	research and development
sCO_2	supercritical carbon dioxide cycle
SRC	steam Rankine cycle
SWOT	strengths, weaknesses, opportunities, threats
TRL	technology readiness level
WSC	water-steam cycle

01 Introduction

The iron and steel industry has long been a cornerstone of global industrialisation, playing a vital role in infrastructure development, manufacturing and economic growth. However, the environmental impacts of this industry cannot be overlooked. The energy-intensive processes involved in steel production contribute greatly to greenhouse gas emissions, thereby exacerbating climate change.

The production of steel requires immense amounts of energy, currently derived primarily from fossil fuels and resulting in substantial emissions of carbon dioxide (CO_2). The iron and steel sector accounts for a large share of global industrial emissions and for an estimated 8% of total energy-related emissions (10% if indirect emissions are included) (IEA, 2023). According to the International Energy Agency (IEA, 2020, 2023), the steel industry contributes 2.8 gigatonnes annually of direct CO_2 emissions, with 88% of this resulting from energy emissions and 12% from process emissions (see Figure 1).

FIGURE 1 (Top) Final energy demand of selected heavy industry sectors by fuel and (bottom) direct CO_2 emissions



Source: (IEA, 2020).
Notes: $GtCO_2$ = gigatonnes of CO_2; Mtoe = million tonnes of oil equivalent.

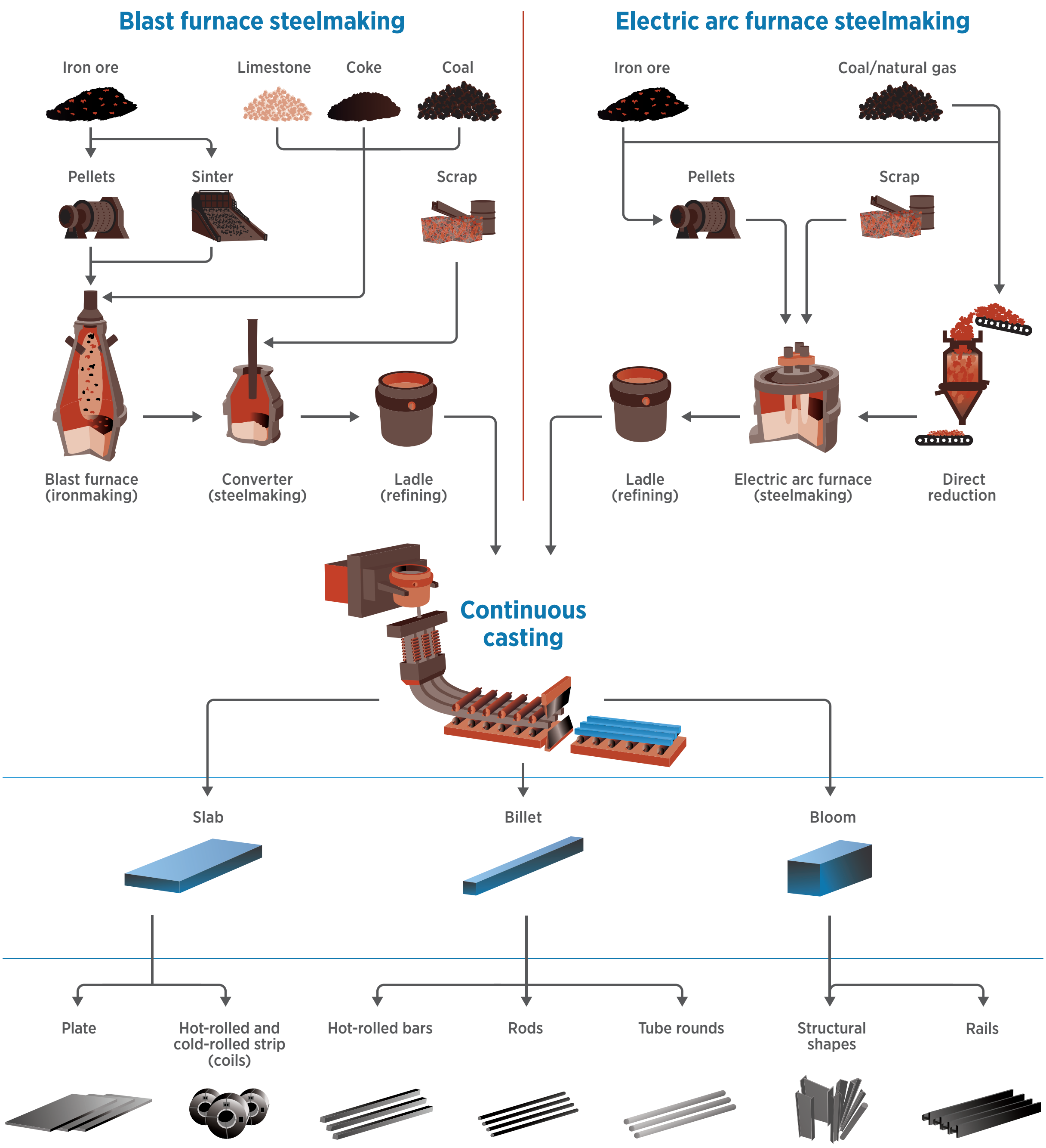
To understand the overall process flows from steel production and the related CO_2 emissions, it is essential to consider the different stages involved. The primary production route in use today contributes to 70% of steel production globally and involves the extraction of iron ore, coke production and ironmaking in the furnace, followed by steelmaking (IRENA, 2023). This primary route can be conducted via two different processes:

1. Blast furnace – basic oxygen furnace (BF-BOF); and
2. Direct reduced iron – electric arc furnace (DRI-EAF).

The BF-BOF route is used for around 90% of primary steel production (IRENA, 2023). First, iron ores are reduced to iron, also called hot metal or pig iron, in a blast furnace. The iron is then converted to steel in the basic oxygen furnace. After casting and rolling, the steel is delivered as coil, plate, sections or bars. This traditional process is highly energy intensive and emits substantial amounts of CO_2 throughout each stage. Additionally, the use of coal as a reducing agent in the blast furnace further contributes to greenhouse gas emissions.

Ironmaking based on the DRI-EAF process accounts for the remaining 10% of primary steel production (IEA 2020). Sponge iron is produced through the direct reduced iron process and then converted to steel in an electric arc furnace, which has lower CO_2 emissions compared to the BF-BOF route. Additives, such as alloys, are used to adjust the material to the desired chemical composition. Figure 2 provides an overview of the primary steelmaking process (WSA, n.d.).

FIGURE 2 Overview of the primary steelmaking processes



Source: (WSA, n.d.).

The secondary production route refers to the use of recycled scrap steel in an electric arc furnace (EAF). Here, electricity is used as the main source of energy, in contrast to primary production where coal and natural gas are commonly the energy sources. Around 30% of steel is produced via the EAF route (IEA, 2020). Steel scrap recycling is at the core of a shift towards greater circularity in the steel sector (IRENA, 2023).

Downstream process stages in secondary production, such as casting, reheating, and rolling, are the same as those found in the BF-BOF route. However, their adoption faces challenges due to limitations in scrap availability, since steel products have long life spans.

The main process steps that generate CO_2 in iron and steelmaking are the production of coke and the production of hot metal in the blast furnace. Ancillary facilities such as power plants also produce large volumes of CO_2. Table 1 identifies typical CO_2 production volumes per tonne of output for each stage of the steelmaking process (Pardo *et al*. 2012).

TABLE 1 Estimated specific CO_2 emissions per tonne of product in the current pathways for iron and steel production in Europe

Process step	Direct CO_2 emissions (tCO_2/t)
Coke plant	0.794
Sinter plant	0.2
Pellet plant	0.057
Blast furnace	1.219
Basic oxygen steelmaking plant	0.181
Electric arc furnace	0.24
Bloom, slab and billet mill	0.088
Basic oxygen steelmaking plant	0.082
Plate mill	0.098
Section mill	0.084
Pickling line	0.004
Cold mill	0.008
Annealing	0.049
Hot dip metal coating	0.059
Organic coating	0.003
Power Plant	1.989

Source: Pardo, Moya and Vatopoulos (2012).

Notes: tCO_2/t = tonne of CO_2 emission per tonne of output.

To decarbonise steel manufacturing processes, several potential solutions have emerged:

1. **Fuel shift** strategies, which entail a transition from coal and coke to low- or no-carbon alternatives (such as biochar, e-methane, natural gas and hydrogen) as reducing agents in the blast furnace.

2. **Electrification** of steelmaking processes, which aims to replace fossil fuel-based energy sources with renewable electricity, eliminating direct emissions associated with traditional methods.

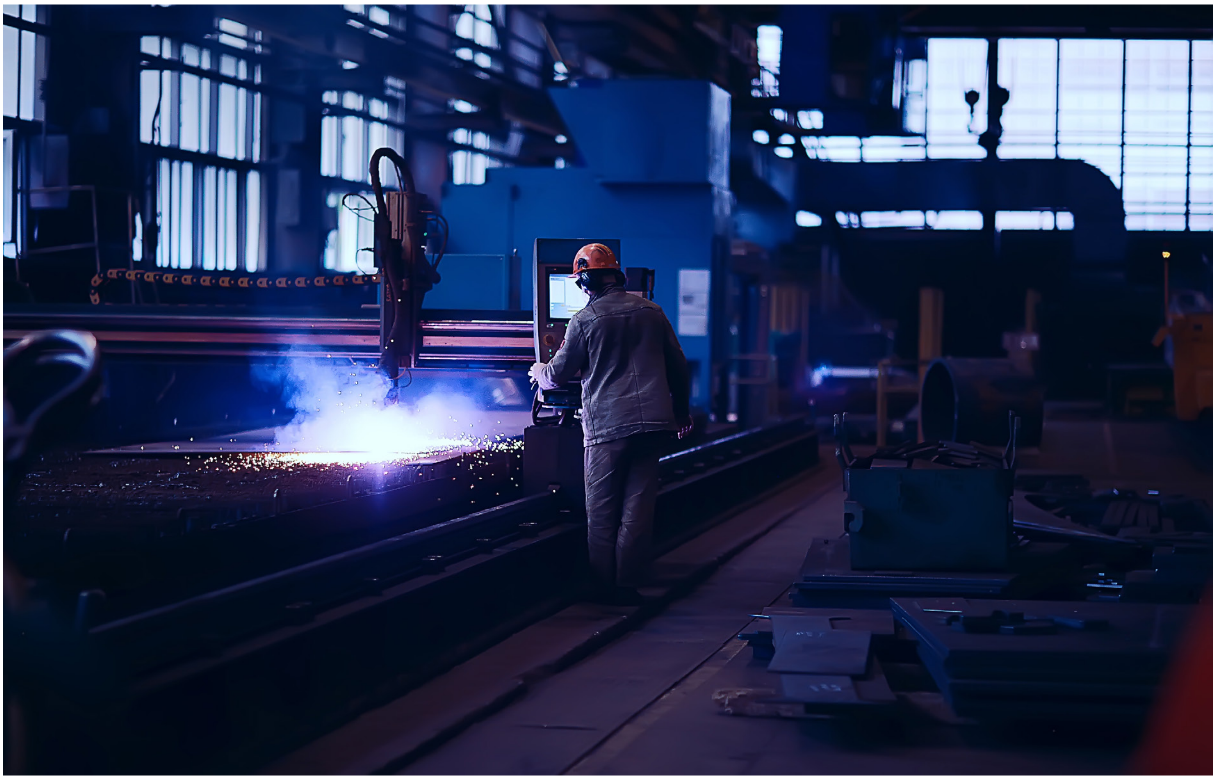
3. **Waste heat recovery**, which involves capturing and utilising the excess heat generated during steel production, thereby improving energy efficiency and reducing the overall carbon footprint.

4. **Carbon capture, utilisation and storage (CCUS)** technologies, which can capture CO_2 emissions from steel plants and either store them underground or convert them into useful products.

These solutions hold promise in mitigating the environmental impacts of steel manufacturing while ensuring the industry's continued growth and sustainability. Figure 3 shows the different technologies that can be implemented to decarbonise the process heat requirement at each stage of the steelmaking process.

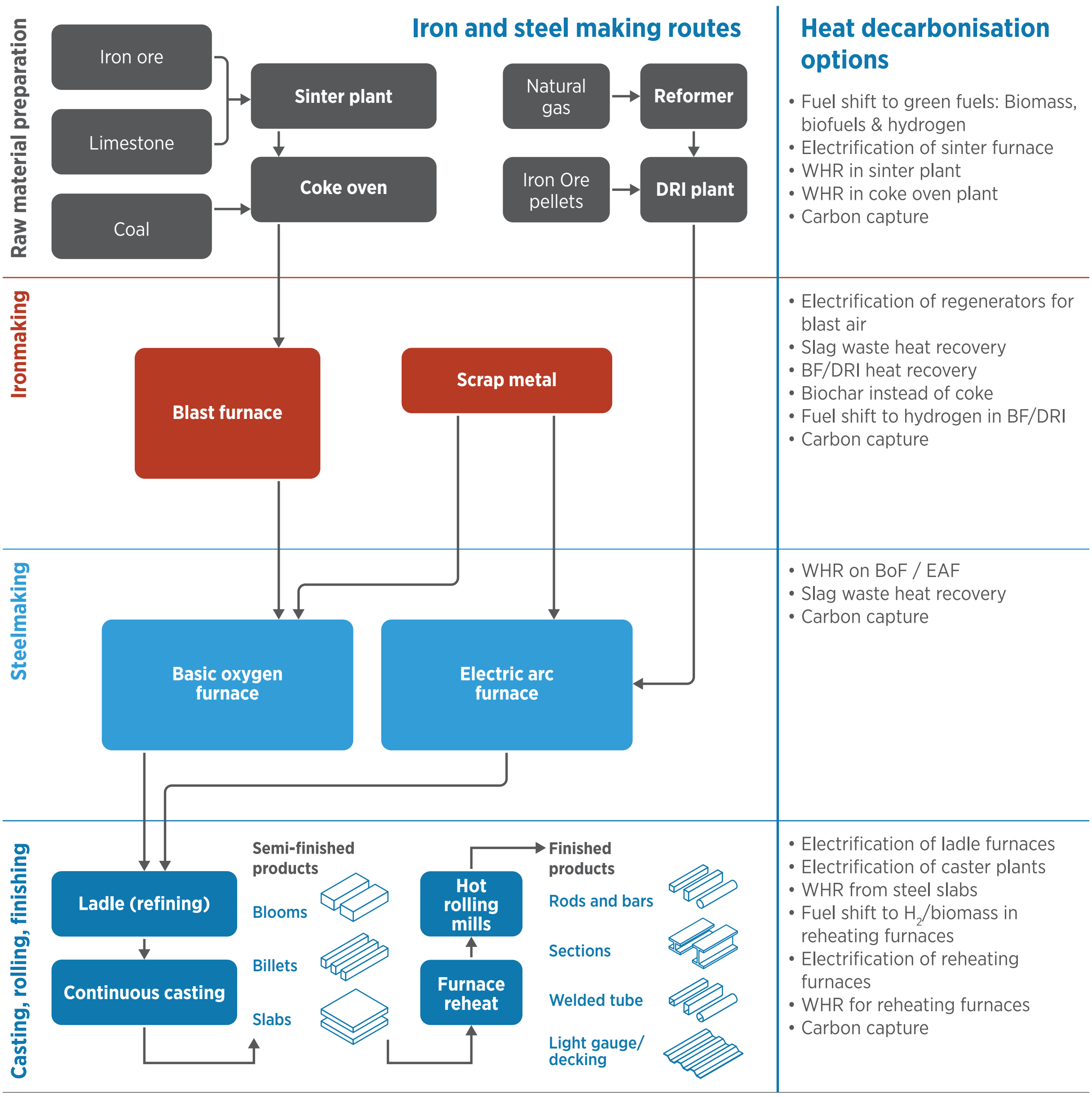
In this report, three key technology groups are explored for decarbonising the industrial process heat requirement in ironmaking and steelmaking:

- **fuel shift to low- or no-carbon fuel**
  - partial shift: Hydrogen injection instead of pulverised coal injection (PCI) in a blast furnace
  - full shift: Hydrogen-based DRI instead of natural gas-based DRI
- **electrification of process heat**
- **waste heat recovery solutions**



Carbon capture utilisation and storage (CCUS) has been studied extensively in several technical reports and research papers. For instance, the technical paper *Reaching Zero With Renewables: Capturing Carbon* (IRENA, 2021) explores the status and potential of carbon capture and storage (CCS), carbon capture and utilisation (CCU) and carbon dioxide removal (CDR) technologies and their roles alongside renewables in the deep decarbonisation of energy systems. It complements and builds upon the broader discussions on the energy transition in other recent IRENA reports, including the *World Energy Transitions Outlook* (IRENA, 2023) and *Reaching Zero with Renewables* (IRENA, 2020).

FIGURE 3 Heat decarbonisation options in the steelmaking process



Notes: WHR = waste heat recovery; BF = blast furnace; DRI = direct reduced iron; BoF = basic oxygen furnace; EAF = electric arc furnace.

02 Fuel shift

Conventional ironmaking and steelmaking uses coal or natural gas as fuel in several processes. In the BF-BOF route, coal is used as both the fuel and reducing agent (reduced to coke in coke oven plants) in blast furnace plants. In the DRI-EAF route, natural gas is used as the fuel and reducing agent (reformed as reducing gas in reformers) in direct reduced iron plants.

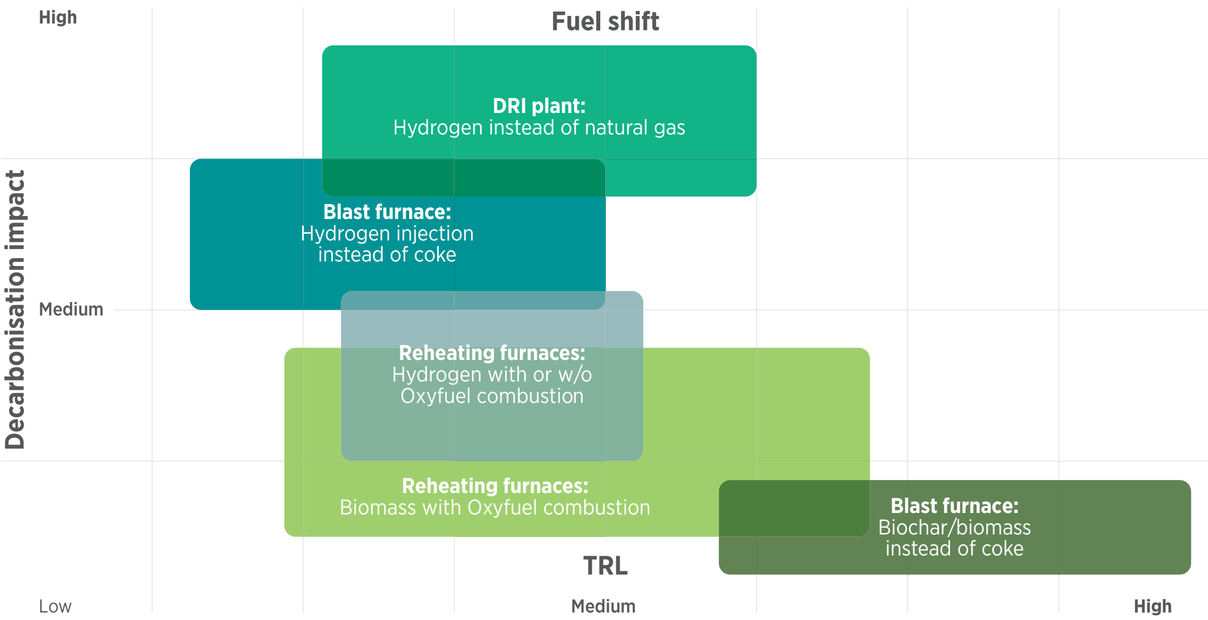
Biomass or biochar has the potential to partially or fully replace the coke in a blast furnace, with little or no modification. Countries with large biomass availability, such as Brazil, are already using biomass in small-scale blast furnaces. However, the availability and affordability of biomass often present significant challenges for wide-scale implementation.

Plastics could theoretically be used in blast furnaces as an alternative to coal, resulting in an estimated 30% reduction in CO_2 emissions from the iron and steel industry (Devasahayam *et al.* 2019). However, plastic waste separation will be critical to avoid the introduction of chemicals that have an adverse effect on the steel quality, such as chlorine from polyvinyl chloride (PVC).

Hydrogen is another fuel shift option that has shown promising results in pilot projects. It offers the potential to fully decarbonise the ironmaking process in a blast furnace or direct reduced iron plant if so-called green (renewable) hydrogen is considered. Hydrogen can be used as the reducing agent in both processes, instead of coke or reducing gas. This approach is being studied under several research and development (R&D) programmes in Europe, and these projects are expected to be commercialised by 2026 (IRENA, 2023). Table 2 provides a comprehensive list of announced hydrogen-DRI projects.

Figure 4 illustrates the decarbonisation impacts in different iron and steelmaking processes using alternate fuel options, mapped against the maturity of the technology.

FIGURE 4 Fuel shift options for decarbonising iron and steelmaking processes



Based on: (Harlin and Sandell, 2013; Hu *et al.* 2019; IRENA, 2023; Mauret *et al.* 2023; Mousa *et al.* 2016; von Schéele, 2021; Zhuo *et al.* 2021).

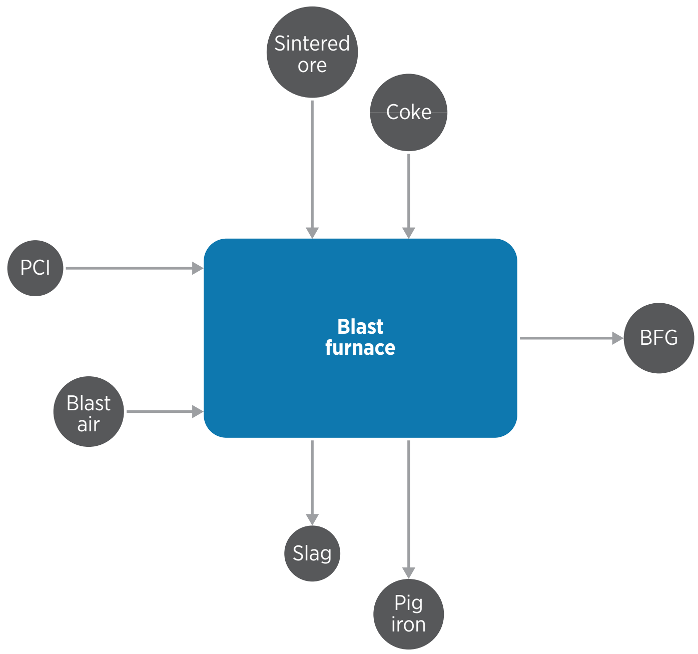
Note: TRL = technology readiness level.

Collaboration is needed among technology companies, original equipment manufacturers (OEMs) and steel manufacturers to make the existing processes compatible with the use of alternate fuels, such as hydrogen in blast furnace or direct reduced iron plants.

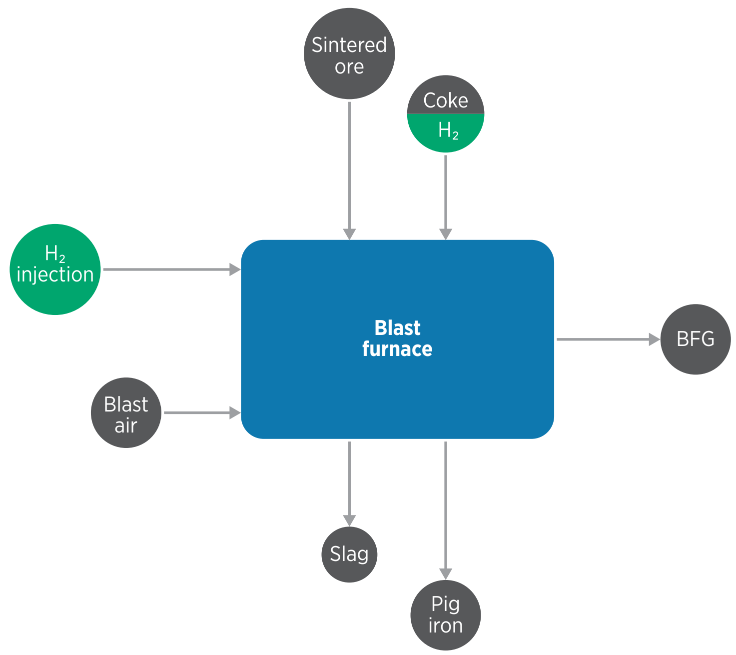
The following sub-sections provide two examples of how a fuel shift to hydrogen could help reduce the CO_2 emissions partially in blast furnace operations and fully in hydrogen-DRI operations.

2.1 Partial decarbonisation: Hydrogen injection to replace pulverised coal injection for blast furnaces

Typical current operation



Potential low-carbon operation: Hydrogen injection in a blast furnace



Notes: BFG = blast furnace gas; PCI = pulverised coal injection.

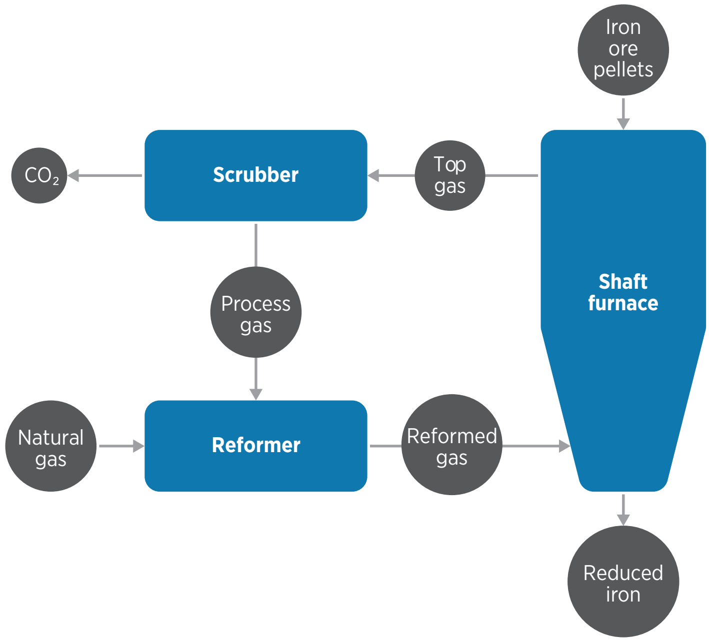
How it works	Pulverised coal injection (PCI) is replaced with hydrogen injection in the blast furnace with little or no major modification in the blast furnace operation. The hydrogen can be generated locally using an electrolyser and green electricity. Replacing PCI with hydrogen can reduced the CO_2 emission by up to 20% in the blast furnace operation (Thyssenkrupp, n.d.). Further reduction in CO_2 emissions is possible by partially or fully replacing coke with hydrogen as the reducing agent. However, the effect of this shift on the blast furnace process, iron quality, *etc.* needs to be studied and optimised.
Economics	The economics will largely depend on the cost of the (green) hydrogen, the scale of the fuel shift and the CO_2 tariff. These factors make it difficult to generalise the capital expenditure/operational expenditure (CAPEX/OPEX) incremental production cost (if any) and hence needs to be evaluated for identified use cases.
Decarbonisation potential	By replacing PCI with hydrogen in the blast furnace operation, CO_2 emissions can be reduced by up to 20% (Thyssenkrupp, n.d.). The decarbonisation potential of blast furnace hydrogen injection is significant, with estimates ranging from 9.4 to 9.7 tonnes of CO_2 reduced per tonne of hydrogen injected (Tang *et al.* 2021).
SWOT analysis	**Strengths** • Reduces carbon emissions by up to 20%. • Improves iron ore reducibility. • Can be implemented in existing blast furnaces with modification of the injection system. **Weaknesses** • Current high cost of (green) hydrogen. • Unfavourable radial temperature pattern of the raceway. • May cause unsustainable furnace operation. • Injection techniques need to be further developed. • May affect the operational constraints of the blast furnace. • Requires significant investment in infrastructure if hydrogen cannot be easily and economically sourced. **Opportunities** • Investment is much less compared to replacing a blast furnace with direct reduced iron. • Potential to manufacture low-carbon steel in the BF-BOF route when only PCI is replaced with (green) hydrogen. • Potential to manufacture green steel in the BF-BOF route when both PCI and coke are replaced with (green) hydrogen. **Threats** • Highly sensitive to the costs of (green) electricity and hydrogen. • Uncertainty regarding the long-term viability of the technology.

Policy and society	**Headwinds** • Uneven carbon pricing. • Lack of CO_2 intensity targets and renewable energy targets. • Wide variation in maturity of hydrogen policy debate between regions. • Current policies do not provide line of sight to sufficient renewable power capacity and integrating renewable power in the power mix. • Uneven renewable power certification regimes. **Tailwinds** • Strong government policies, regulations and incentives encouraging the adoption of new technologies for producing low-carbon/green steel. • Financial support, tax incentives, grants and subsidies will help offset initial implementation costs and motivate steel producers to invest in sustainable technologies. • Higher societal and political acceptance of green steel, and policies such as the European Union's (EU's) Carbon Border Adjustment Mechanism (CBAM), will further motivate companies to decarbonise their processes.
Ease to implement in brownfield (Inside and outside battery limits – ISBL/ OSBL*)	**BF inside battery limits (ISBL):** Modification of injection system and auxiliaries for hydrogen injection. Top gas recycling system may be required to improve the utilisation factor of hydrogen in the blast furnace. BF internal may require some modifications/upgrade. **Disruption: Medium** **BF outside battery limits (OSBL):** Space for the required capacity electrolyser unit can be substantial in the case of local hydrogen generation. When space is limited, the unit can be located at some distance. Significant power infrastructure will be required. Hydrogen storage and transport may be required as a lever to manage the intermittency of green electricity. **Disruption: High**
Technology readiness level / example projects	Electrolyser at scale: TRL of 8 (expected commercialisation before 2030) Example projects: **Thyssenkrupp** tested hydrogen in a working blast furnace in 2019 as a replacement for PCI grade. **Tata Steel** completed a trial injection of hydrogen in 2023 using 40% of the injection systems in one of its blast furnaces in Jamshedpur, India.

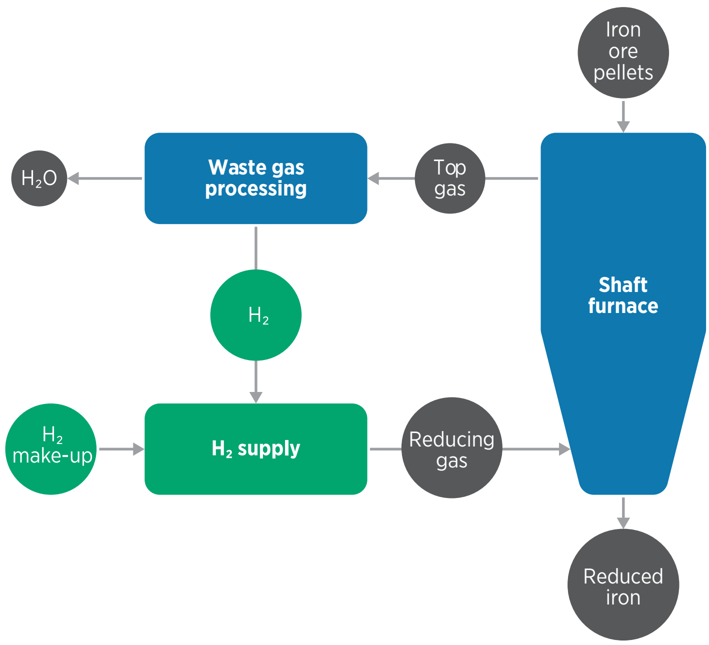
*ISBL refers to the area within the physical boundary of the plant where the primary process equipment is located. OSBL refers to the area outside the physical boundary of the plant where the secondary process equipment and facilities are located.

2.2 Full decarbonisation: Hydrogen-based direct reduced iron

Typical current operation



Potential low-carbon operation: Hydrogen-based direct reduced iron



Notes: H_2 = Hydrogen; H_2O = water.

How it works

Hydrogen-DRI is a steel production process that uses hydrogen gas to produce reduced iron, replacing traditional carbon sources such as coke in the blast furnace method. Additionally, it eliminates the need for natural gas reforming processes to produce hydrogen as a feed for the natural gas-DRI. Hydrogen can be produced through methods such as electrolysis.

In the direct reduction reactor, preheated iron ore and hydrogen gas react, generating reduced iron and water vapour. The resulting direct reduced iron can be processed into steel using electric arc furnaces. Hydrogen-DRI greatly reduces greenhouse gas emissions, making it a promising technology for sustainable, low-carbon steelmaking.

Economics

The economics will largely depend on the cost of (green) hydrogen, the scale of the fuel shift and the CO_2 tariff. These factors make it difficult to generalise the CAPEX/OPEX incremental production cost (if any) and hence needs to be evaluated for identified use cases. To implement hydrogen-DRI technology, modifications to the existing plant infrastructure are necessary, resulting in an increase in CAPEX. Consequently, it would be more efficient to incorporate this technology in the design of new steel plants.

Decarbonisation potential

Blast furnace steel production – which accounts for two-thirds of global crude steel output, or a massive 1.95 billion tonnes in 2021 – typically produces 2.0 tonnes of CO_2 per tonne of crude steel. Hydrogen-DRI brings this to below 0.5 tonnes of CO_2 per tonne of crude steel (Kinch, 2022).

Renewables-powered fully green hydrogen-DRI production can add CO_2 emissions reductions of 80-95% compared with the traditional BF-BOF route (IRENA, 2023). Using hydrogen-DRI instead of a blast furnace in steel production offers high decarbonisation potential and a path to carbon-neutral steel. However, its realisation depends on factors such as the hydrogen source, cost, technology advancements and infrastructure for large-scale hydrogen use.

SWOT analysis

Strengths

- Hydrogen-DRI steel production method minimises the release of harmful gases such as CO_2, making it a sustainable option for steel production.
- DRI (and its premium form, hot briquetted iron) ensures quality control, with consistent low residual content.
- The DRI process offers flexibility, with easy start and stop.
- DRI technology enables green production of premium steel.

Weaknesses

- Energy-intensive hydrogen-DRI requires high electricity consumption.
- High cost of green hydrogen production even with the current incentives or taxes.
- Technical challenges exist in iron and steelmaking steps.
- Infrastructure for green hydrogen DRI conversion needs substantial renewable energy capacity.

Opportunities

- Growing demand for green steel: By 2033, green steel demand could surpass an estimated 230 million tonnes as costs decrease and policy incentives align (Future Markets Inc., 2023).
- Potential cost competitiveness: The green hydrogen-DRI-EAF production route may be cost-competitive with traditional methods in favourable locations in the next decade, and for most locations towards 2050.
- H_2 Green Steel has signed 1.5 million tonnes of pre-orders from several steel end users, including BMW, Marcegaglia and Electrolux (Hallstan, 2022).
- Policy incentives: Increases in the price of carbon emissions and policy incentives could make hydrogen-based steel production more competitive.

Threats

- Hydrogen-DRI needs emission-free hydrogen and electricity from renewables.
- The green hydrogen transition may initially raise steel prices, causing material substitution.
- Despite hydrogen-DRI-EAF pilot success, further development is needed to resolve issues.
- Competition from lower-cost conventional steel production methods (IRENA, 2023).

Policy and society

Headwinds

- Uneven carbon pricing.
- Lack of CO_2 intensity targets and renewable energy targets.
- Wide variation in maturity of hydrogen policy debate between regions.
- Current policies do not provide line of sight to sufficient renewable power capacity and integrating renewable power in the power mix.
- Uneven renewable power certification regimes.
  In the future, as the hydrogen-DRI process scales up to use green hydrogen, there will be increased demand for high-grade iron ore that is suitable for hydrogen-DRI

Tailwinds

- Strong government policies, regulations and incentives encouraging the adoption of new technologies for producing low-carbon/green steel.
- Financial support, tax incentives, grants and subsidies will help offset initial implementation costs and motivate steel producers to invest in sustainable technologies.
- Higher societal and political acceptance of green steel, and policies such as the EU's CBAM, will further motivate companies to decarbonise their processes.

Ease to implement in brownfield (Inside and outside battery limits – ISBL/ OSBL*)	**BF ISBL:** Modification of injection system and auxiliaries for hydrogen injection. Top gas recycling system may be required to improve the utilisation factor of hydrogen in DRI. DRI internal and its auxiliaries may require some modifications/upgrade. **Disruption: Medium** **BF OSBL:** Requires significant modifications, including establishing renewable energy sources, setting up energy storage systems, developing hydrogen-related infrastructure and securing policy support. Space for the required capacity electrolyser unit can be substantial in the case of local hydrogen generation. When space is limited, the unit can be located at some distance. Significant power infrastructure will be required. Hydrogen storage and transport may be required as a lever to manage the intermittency of green electricity. **Disruption: High**
Technology readiness level / example projects	Several pilots with have been constructed and/or are operational. Several commercial-scale projects have been announced and are at different stages, as listed in Table 2.

A report from the International Renewable Energy Agency (IRENA) provides a list of several hydrogen-based ironmaking and steelmaking projects, including plants using green hydrogen and plans to transition to green hydrogen from natural gas (IRENA, 2023), as listed in Table 2.

The use of fuel alternatives represents a significant step forward in pursuing sustainable steel production. While the use of biomass and other fuels can lower the CO_2 emission intensity of ironmaking and steelmaking, green hydrogen shows the potential to fully decarbonise the steelmaking process.

In addition to fuel alternatives, addressing challenges such as replacing old processes and enhancing existing infrastructure remains a barrier to decarbonising steelmaking. By testing and implementing pilot projects, these barriers can be overcome. Another key aspect of decarbonising steel production is the electrification of heat processes. This approach could involve, as an example, electrifying blast furnace stoves using renewable energy, or other downstream processes such as reheating, *etc.*

TABLE 2 List of hydrogen-based iron and steelmaking projects

Company	Stage	Scale	(Expected) year of operation	Country	Location	Iron production capacity (million tonnes per year)	Steel production capacity (million tonnes per year)
ArcelorMittal	Feasibility	Pilot	-	ZAF	Vanderbijlpark	-	-
ArcelorMittal	Feasibility	Commercial	2025	ESP	Gijon	2.3	2.7
ArcelorMittal	Advanced	Commercial	2027	FRA	Dunkirk	2.5	2.7
ArcelorMittal	Announced	-	2026	DEU	Bremen	-	3.5
ArcelorMittal	Announced	-	2026	DEU	Eisenhüttenstadt	-	0.5
ArcelorMittal	Announced	Commercial	2030	DEU	Hamburg	-	1..0
ArcelorMittal	Feasibility	Commercial	2028	CAN	Hamilton	2.5	2.4

Baowu Group	Construction	-	-	CHN	Zhanjiang	-	1.0
Blastr	Announced	Commercial	2026	FIN	Inkoo	-	2.5
Blastr	Announced	Commercial	2028	NOR	Gildeskål	-	-
Calix	Operational	Pilot	-	AUS	-	0.03	-
DRI d'Italia	Announced	Commercial	2026	ITA	Taranto	2.0	-
Fortescue Metals	Announced	Commercial	2023	AUS	Pilbara	-	-
GravitHy	Announced	-	-	FRA	Fos-sur-Mer	2.0	-
H2 Green Steel	Construction	Commercial	2024	SWE	Svartbyn	-	5.0
H2 Green Steel	Announced	Commercial	2025	ESP	Iberia	-	2.0
HBIS Group	Announced	-	-	CHN	Xuanhua	-	1.2
Jindal Steel & Power Ltd	Announced	Commercial	2026	OMN	Muscat	-	5.0
Liberty Steel	Feasibility	Commercial	-	FRA	Dunkirk	2.0	2.0
Liberty Steel	Announced	-	-	ROU	Galati	-	4.0
LKAB	Announced	Commercial	2030	SWE	Kiruna, Malmberget, Svappavaara	5.0 by 2030, 24.4 by 2050	-
POSCO	Announced	Commercial	-	KOR	Pohang	-	1.0
POSCO	Announced	Pilot	-	AUS	-	-	-
Rizhao Steel	Announced	-	-	CHN	Rizhao	-	0.5
Salzgitter	Advanced	Commercial	2033	DEU	Salzgitter	-	1.9
Salzgitter	Feasibility	Pilot	-	DEU	Wilhelmshaven	2.0	-
Salzgitter	Construction	Pilot	2022	DEU	Salzgitter	1.0	-
SSAB	Operational	Pilot	2021	SWE	Luleå	-	-
SSAB	Construction	Pilot	2026	SWE	Gällivare	1.3, expand to 2.7 by 2030	-
Stahl-Holding-Saar	Announced	Pilot	2021	CAN	-	-	-
Stahl-Holding-Saar	Advanced	Commercial	2027	DEU	Saarland	-	3.5
Tenaris	Feasibility	Commercial	-	ITA	Dalmine	-	-
Thyssenkrupp	-	Pilot	-	NLD	Rotterdam	-	-
ThyssenKrupp	Feasibility	Commercial	2026	DEU	Duisburg	2.5	-
Voestalpine	Operational	Pilot	2021	AUT	Donawitz	0.25	-
Vale GCC steel hubs	Announced	-	-	SAU, ARE, OMN	Multiple locations	-	-

Notes: ARE = The United Arab Emirates; AUS = Australia; AUT = The Republic of Austria; CAN = Canada; CHN = The People's Republic of China; DEU = The Federal Republic of Germany; ESP = The Kingdom of Spain; FIN = Finland; FRA = The French Republic; ITA = The Republic of Italy; KOR = The Republic of Korea; NLD = The Kingdom of the Netherlands; NOR = Norway; OMN = The Sultanate of Oman; ROU = Romania; SAU = The Kingdom of Saudi Arabia; SWE = The Kingdom of Sweden; ZAF = The Republic of South Africa. Mtpa = million tonnes per annum. The table includes plants using green hydrogen as well as those with plans to transition to green hydrogen from natural gas.

Source: (IRENA, 2023).

03 Electrification of process heat

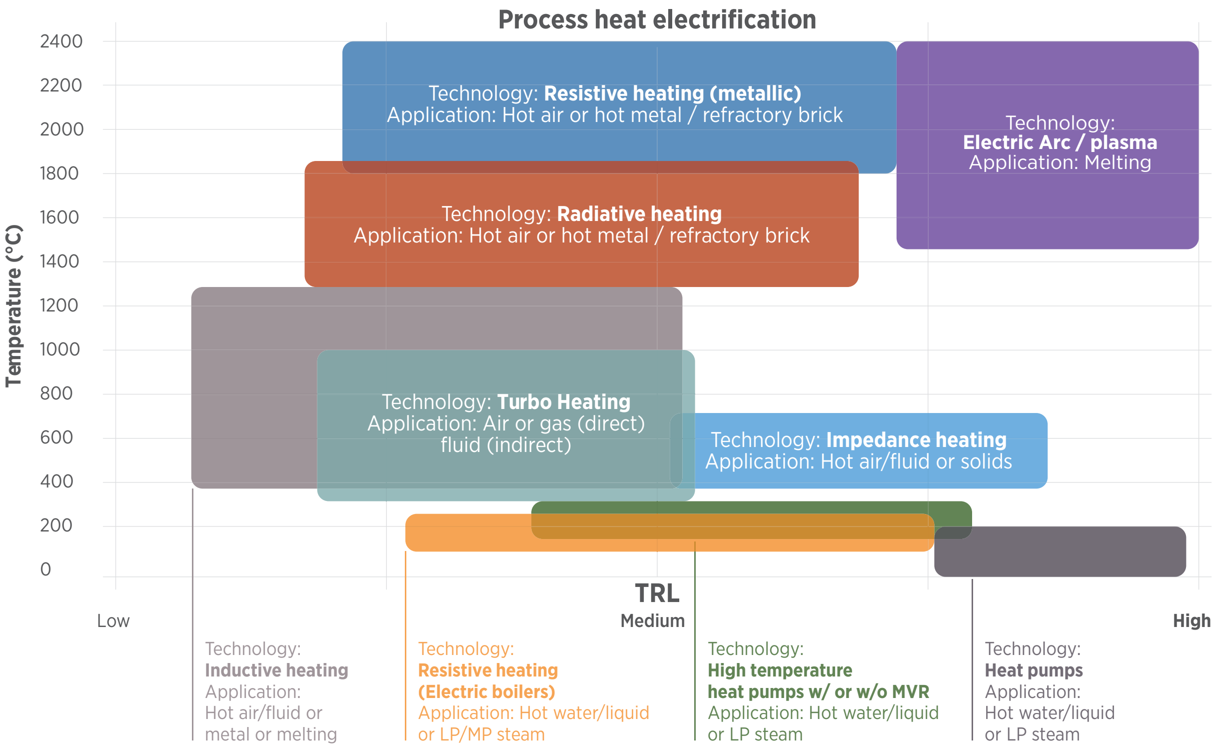
Converting electricity into heat offers the opportunity to make use of (and promote further) the large-scale production of renewable energy to substitute fossil fuel-generated process heat. Heat can be electrified directly by converting electricity into heat, or indirectly by using electricity to produce green fuels such as hydrogen. The direct option is by far more efficient (more than 98% efficient, compared to more than 60% in the indirect option) and cost-effective, and hence also preferable. Heat storage solutions may be added to balance the fluctuations of electricity supply and heat demand. This section focuses on the direct option.

Electrification appears to be a very promising strategy for industrial heat applications, as it enables high process temperatures to be achieved in a tailor-made and efficient way and allows for the use of other energy sources such as waste heat, geothermal or ambient heat (via heat pumps) with little or no CO_2 emissions (Baylin *et al.* 2023; IEA, 2018).

One promising electrification technology is the heating. It uses electric heating to accelerate gases to supersonic speeds and then convert the kinetic energy to heat. This boosts the process heat directly (heating up any gas mixture without a separate heat exchanger) to high temperatures and therefore achieves a high level of conversion efficiency (95% or higher), eliminating fuel burning and related emissions.

Hard-to-abate industries such as iron and steel can benefit greatly from the electrification of process heat. Several technologies exist to electrify process heat, as shown in Figure 5.

FIGURE 5 Electrification technologies for process heat application



Based on: (Baylin *et al.* 2023; Carpenter, 2012; Electrical Deck, n.d.; Hasanbeigi, 2021; IEA, 2018; IISD, 2022; Zefelippo and Ranghino, 2023).

Notes: LP = low pressure; MP = high pressure; MVR = mechanical vapor recompression; TRL = technology readiness level.

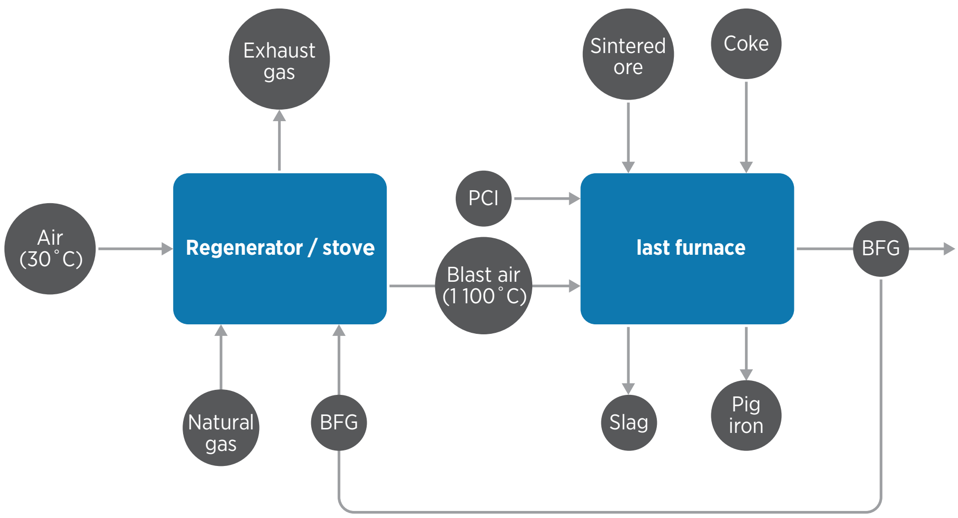
However, most of the commercially available technologies today – such as resistive, radiative, impedance, *etc.* – have the following challenges:

- Size and space constraints, and thus limited scalability.
- Low voltage, and thus limited scalability.
- Low power density, and thus limited scalability.
- Critical electrical components exposed to high temperatures and/or corrosive process fluid, leading to low reliability.
- Inadequate response to process requirements.

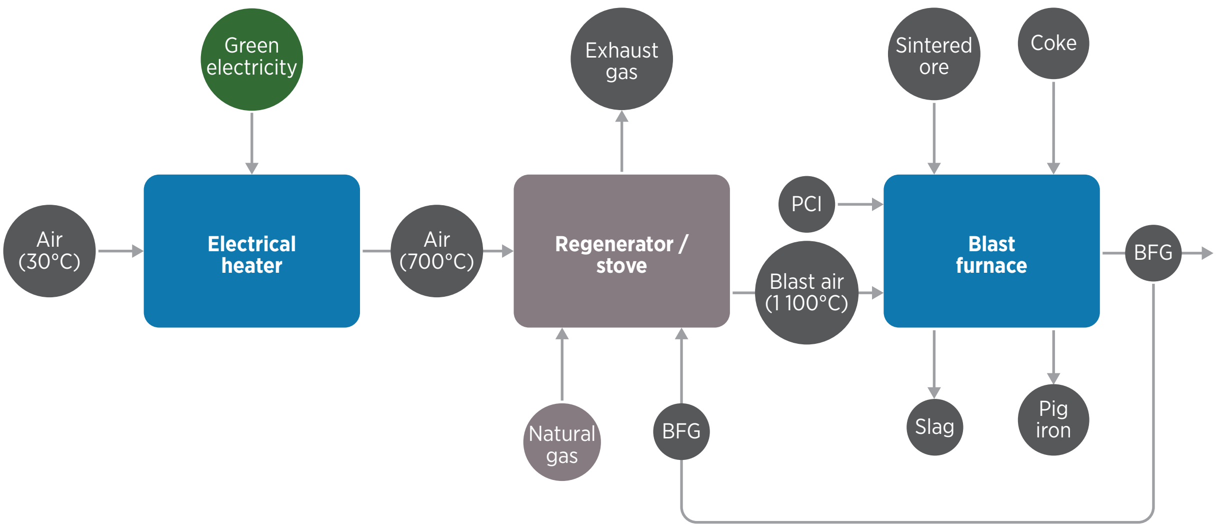
Ironmaking and steelmaking processes can benefit from the electrification of process heat, thereby reducing partially or fully the fossil fuel-related CO_2 emissions. However, strong collaboration is needed among technology companies, OEMs and steel manufacturers in developing potential electrification technologies that would meet all process requirements in both the BF-BOF and DRI-EAF manufacturing routes.

Below is an example of how electrification can help reduce the CO_2 emissions associated with blast furnace operation:

Typical current operation



Potential low-carbon operation: Electrification in a blast furnace



Notes: BFG = blast furnace gas; PCI = pulverised coal injection.

How it works	Partially or fully heating the blast air going to a blast furnace using a heater powered by (green) electricity will reduce or avoid natural gas consumption and greatly reduce CO_2 emissions.
Economics	The economics will largely depend on cost of renewable energy, the scale of electrification, the technology considered and the project complexity. These factors make it difficult to generalise the CAPEX/OPEX incremental production cost (if any) and hence needs to be evaluated for identified use cases.
Decarbonisation potential	CO_2 emissions from the plant can be reduced by up to 18% when the regenerator stoves are electrified, depending on various factors such as the specific technology used, the source of electricity and the overall efficiency of the process (Carpenter, 2012).
SWOT analysis	**Strengths** • Direct heating of gases to elevated temperatures (more than 1 000 °C). • Improved efficiency of the blast furnace due to reduced waste heat. • Reduced fuel consumption and lower emissions. • Increased safety compared to fossil fuel heaters. • Lower footprint compared to fossil fuel heaters. **Weaknesses** • The levelised cost of heat for electric heaters may be higher than for traditional fossil fuel heaters due to a higher electricity cost compared to the fuel cost. • The availability and reliability of renewable energy sources may be a challenge in some areas. **Opportunities** • The use of electrified blast air can help reduce emissions and meet environmental regulations. • The development of more efficient and cost-effective electric heaters can improve the process. • The use of renewable energy sources can reduce costs and improve sustainability. **Threats** • The cost of electricity may fluctuate and affect the economics of electrified blast air. • The availability at scale and reliability of renewable energy sources may be affected by weather conditions. • Energy storage will be a key lever in electrification, as many processes require discontinuous heat. • The use of electrified blast air may face resistance from traditionalists in the industry who prefer fossil fuel heaters.

Policy and society	**Headwinds** • Uneven carbon pricing. • Lack of CO_2 intensity targets and renewable energy targets. • Wide variation in maturity of electrification policy debate among regions. • Current policies do not provide a line of sight to sufficient renewable power capacity. • Uneven renewable power certification regimes. **Tailwinds** • Strong government policies, regulations and incentives encouraging the adoption of new technologies for producing low-carbon/green steel. • Financial support, tax incentives, grants and subsidies will help offset initial implementation costs and motivate steel producers to invest in sustainable technologies. • Higher societal and political acceptance of green steel, and policies such as the EU's CBAM, will further motivate companies to decarbonise their processes.
Ease to implement in brownfield (Inside and outside battery limits – ISBL/ OSBL*)	**Regenerators/stove ISBL:** Modification of duct between compressor and regenerator/stove including installation of dampers for bypass arrangement in case the electrical heater is offline. **Disruption: Low** **Regenerators/stove OSBL:** Significant power infrastructure required. The electrical power network may require some modification to provide high voltage to electrical heaters. Clear space will be required for the installation of such heaters. When the plot plan is limited, the unit can be located at some distance; however, interconnecting duct work will increase, thereby increasing the investment. **Disruption: Medium**
Technology readiness level / example projects	Small electrical heaters are already commercially available. However, they cannot serve the purpose in their existing capacity. Several megawatt-range electrical heater technologies are in development and are presently in technology readiness level 4-6 (expected commercialisation in 2030).

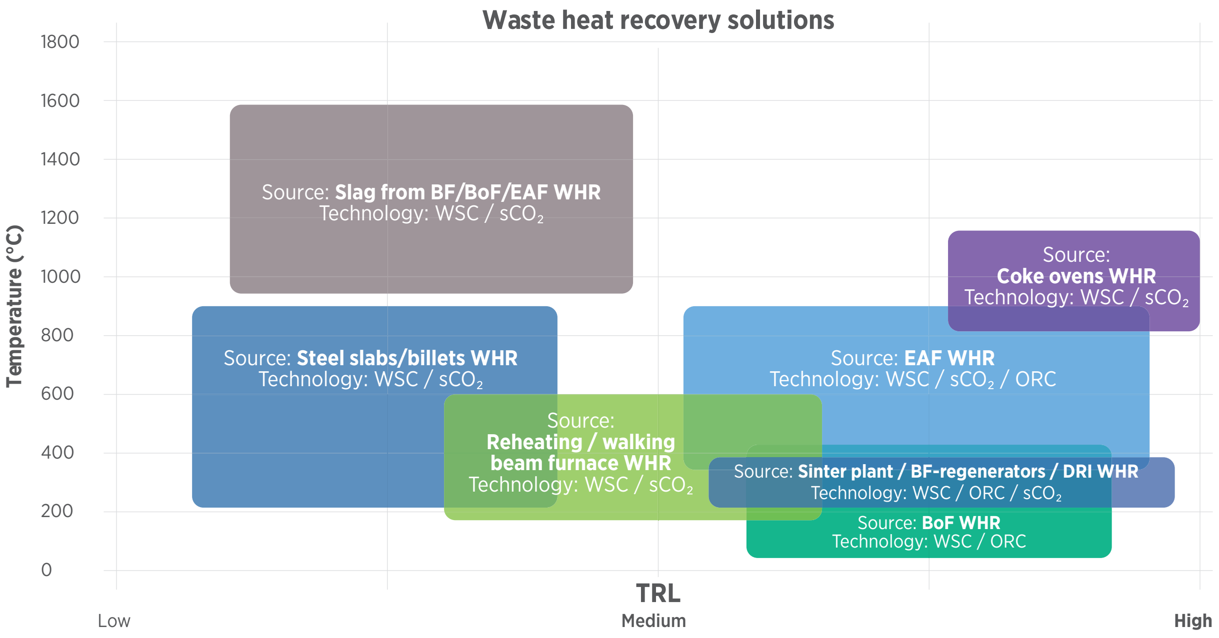
The electrification of steel production plants can lead to substantial energy savings and reduced CO_2 emissions. However, even with the electrification of process heat, the need for energy efficiency will remain unchanged. The steel industry has considerable potential for waste heat recovery: currently, around one-third of the total energy supplied to the process in electric arc furnaces is wasted. By capturing and recycling waste heat, these systems can contribute to reducing energy costs, lowering CO_2 emissions, and increasing the competitiveness and sustainability of steel production.

04 Waste heat recovery solutions

Ironmaking and steelmaking plants have several processes that generate waste heat at different temperatures. The waste heat is now widely used for the preheating of the fuel/feed using different kinds of heat exchangers, such as economisers, regenerators, recuperators, air preheaters, *etc.* With the use of technologies such as heat pumps, the temperature of the low-grade waste heat can also be increased to higher levels and used for providing process heat in the form of hot water or low-pressure steam. The excess heat that cannot be utilised back in the process, can be converted to electricity by different waste heat recovery technologies.

Several studies indicate that up to 30-35% of a plant's electricity requirement can be met using waste heat recovery systems. In Figure 6, these sources are mapped based on the temperature of the waste heat generated and on the maturity level of the waste heat recovery solutions.

FIGURE 6 Waste heat recovery solutions in different processes of iron and steelmaking



Based on: (Fleischanderl and Trunner, 2015; Primetals Technologies, n.d.; Thekdi *et al.* 2015)

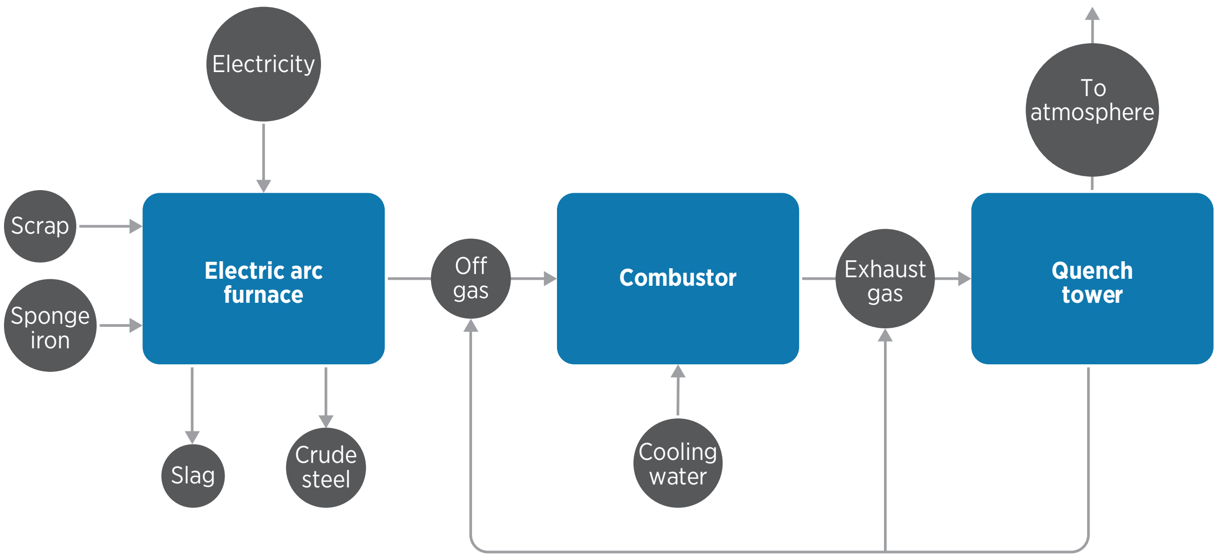
Notes: WSC = water-steam cycle (or steam Rankine cycle); ORC = organic Rankine cycle; sCO_2 = supercritical carbon dioxide cycle; TRL = technology readiness level.

While Figure 6 maps different waste heat sources and their temperatures against the maturity of waste heat recovery solutions, the utilisation technologies (water-steam cycle, organic Rankine cycle and supercritical carbon dioxide cycle) are at different technology readiness levels. The water-steam cycle and organic Rankine cycle are commercially available technologies, whereas supercritical carbon dioxide cycle technology is still at an early stage, being developed and evaluated in several R&D-funded programmes in the United States and Europe.

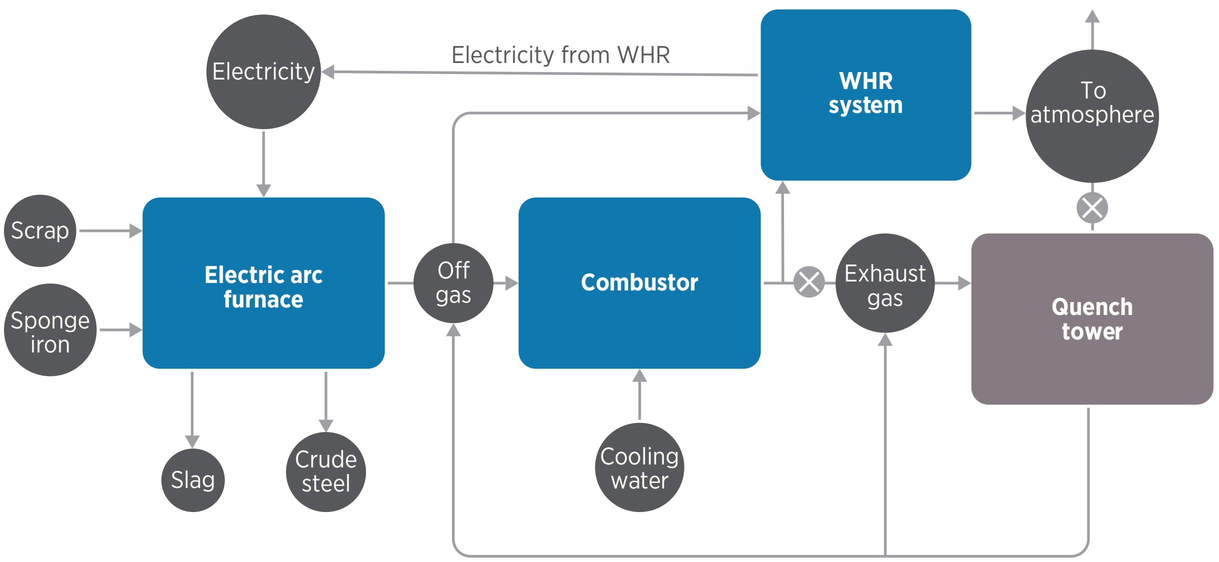
Efforts are required in the development of efficient, economic and reliable heat recovery technologies that can be implemented in a water-steam cycle, organic Rankine cycle or supercritical carbon dioxide cycle technology-based solution.

Below is an example of how a waste heat recovery solution can help reduce the CO_2 emissions associated with the electric arc furnace process:

Typical current operation



Potential low-carbon operation: Waste heat recovery in an electric arc furnace



Notes: WHR = waste heat recovery.

How it works	The waste heat recovery system captures the waste heat in the off-gas from the electric arc furnace, which otherwise is lost in cooling towers via circulating waters and water sprayed in the quench tower. This heat is then converted to electricity via the water-steam cycle-based solution, which can be used to meet the partial electricity demand of the electric arc furnace and thus reduce the net energy required in the process and its associated CO_2 footprint.
Economics	The economics will largely depend on the capacity of the waste heat recovery plant, the technology considered, the process parameters and the site conditions. These factors make it difficult to generalise the CAPEX/OPEX incremental production cost (if any) and hence needs to be evaluated for identified use cases.
Decarbonisation potential	The asset decarbonisation reduction (scope 1-2) is subject to various factors such as the specific technology used, the source of electricity, and the overall efficiency of the process and the process itself.
SWOT analysis	**Strengths** • Proven technology with only incremental innovation required. • Can handle the operational characteristics of an electric arc furnace, such as varying waste heat temperature and quantity. • Customisable to site-specific conditions. • Significant reduction in water consumption in process. • Reduced net energy consumption and thus lower emissions. **Weaknesses** • Layout and site constraints may limit the extent of heat recoverable. • High capital and operational costs **Opportunities** • Can be used as a hybrid solution offering process heat (such as for CCUS or district heating, *etc.*) and power generation, which will further improve the heat utilisation factor and emission reduction. • A much-needed technology for energy efficiency improvement. **Threats** • Business case is exposed to power prices and sources: savings are highly dependent on the electricity price and on the CO_2 intensity of the electricity consumed.
Policy and society	**Headwinds** • Uneven carbon pricing. • Lack of energy efficiency targets. • Focus on CO_2-intensive processes such as blast furnace/direct reduced iron.

	• Priority to carbon capture, and the use of hydrogen in the manufacturing process, have diverted the attention from energy efficiency and optimisation. **Tailwinds** • Strong government policies, regulations and incentives encouraging the adoption of new technologies for producing low-carbon/green steel. • Financial support, tax incentives, grants and subsidies will help offset initial implementation costs and motivate steel producers to invest in sustainable technologies. • Higher societal and political acceptance of green steel, and policies such as the EU's CBAM, will further motivate companies to decarbonise their processes.
Ease to implement in brownfield (Inside and outside battery limits – ISBL/ OSBL*)	**EAF ISBL:** The waste heat recovery unit is installed as close to the electric arc furnace as is allowed by the site. The water-jacketed duct is retrofitted/designed for coupling with the waste heat recovery unit; tapping is provided by diverting the off-gases after the combustion chamber to the waste heat recovery unit. Adequate bypass provision is provided by operating the electric arc furnace when the waste heat recovery system is offline. **Disruption: High** **EAF OSBL:** The space for the required waste heat recovery system components (turbine building and condenser system) can be significant (around 40 x 150 metres). When space is limited, investment can be slightly higher. **Disruption: Low**
Technology readiness level / example projects	Technology readiness level (TRL) is quite high (7-9). Example project: Primetals Technologies implemented a waste heat recovery unit for an electric arc furnace, with the aim of capturing and utilising the waste heat generated during the steelmaking process to improve energy efficiency and reduce greenhouse gas emissions (Primetals Technologies, n.d.).

05 Conclusion and recommendations

This comprehensive report explores various strategies for decarbonising steel manufacturing processes, aiming to reduce the industry's carbon footprint. The following section summarises the key findings and provides actionable recommendations for successful implementation.

Key findings:

1. Fuel shift strategies:

- Transitioning from coal and coke to low- or no-carbon alternatives (such as biochar, e-methane, and hydrogen) can significantly reduce emissions.
- These alternatives serve as reducing agents in the blast furnace or fuel for the process minimising CO_2 output.

2. Electrification of steelmaking:

- Replacing fossil fuel-based energy sources with renewable electricity is a promising approach.
- This shift eliminates direct emissions and allows for the utilisation of other energy sources (*e.g,* waste heat, geothermal energy).

3. Waste heat recovery:

- Capturing and utilising excess heat generated during steel production improves energy efficiency.
- It contributes to reducing the overall carbon footprint of the steel manufacturing process.

4. Carbon capture, utilisation and storage (CCUS):

- CCUS technologies capture CO_2 emissions from steel production.
- The captured CO_2 can either be stored underground or used in other industrial processes

Recommendations for implementation

1. Collaboration and policy support

- Governments, industry stakeholders, and research institutions should collaborate to create supportive policies and incentives for adopting decarbonisation strategies.
- Financial support, tax incentives, and research grants can accelerate the transition.

2. Investment in research and development

- Allocate resources to research and develop innovative technologies.
- Focus on improving the efficiency and scalability of CCUS technologies.

3. Pilot projects and demonstrations

- Implement pilot projects to test and validate decarbonisation strategies.
- Learn from real-world experiences and adapt accordingly.

4. Capacity building and training

- Train steel industry professionals in the use of new technologies.
- Foster a skilled workforce capable of implementing and maintaining these changes.

5. Lifecycle assessment and circular economy

- Consider the entire lifecycle of steel products, from raw materials to end-of-life recycling.
- Promote circular economy practices to

6. Public awareness and consumer demand

- Educate consumers about the importance of sustainable steel production.
- Encourage demand for low-carbon and/or green steel products.

Achieving a low-carbon or green steel industry is both a challenge and an opportunity. By implementing these strategies, we contribute to global climate goals and pave the way for a more sustainable future. Let us act collectively to transform the steel industry and build a greener world.

References

Baylin, A., *et al.* (2023), "Frontier electric technologies in industry", *International Energy Agency, Paris.* **www.iea.org/commentaries/frontier-electric-technologies-in-industry**

Bonilla-Campos, I., *et al.* (2019), "Energy efficiency assessment: Process modelling and waste heat recovery analysis", *Energy Conversion and Management, vol. 196, pp. 1180–92,* **https://doi.org/10.1016/j.enconman.2019.06.074**

Carpenter, A. (2012), CO_2 abatement in the iron and steel industry, *International Energy Agency Clean Coal Centre, Paris* **https://usea.org/publication/co2-abatement-iron-and-steel-industry-ccc193**

Devasahayam, S., *et al.* (2019), "Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry", *Materials Science for Energy Technologies, vol. 2/3, pp. 634–46,* **https://doi.org/10.1016/j.mset.2019.08.002**

Electrical Deck (n.d.), "Types of Electric Heating - Resistance, Induction, Dielectric Heating", *Electrical Deck,* **www.electricaldeck.com/2022/05/types-of-electric-heating.html**

Fleischanderl, A., and Trunner, P. (2015), "Waste Heat Recovery for EAF-Innovative Concepts and Industrial Implementation", *Iron and Steel Technology,* vol. 15/1 **www.electricaldeck.com/2022/05/types-of-electric-heating.html**

Future Markets Inc. (2023), *The Global Market for Green Steel 2023-2033,* **www.futuremarketsinc.com/the-global-market-for-green-steel-2023-2033/**

Hallstan, K. (2022), "H2 Green Steel has pre-sold over 1.5 million tonnes of green steel to customers", **www.h2greensteel.com/latestnews/h2-green-steel-has-pre-sold-over-15-million-tonnes-of-green-steel-to-customers**

Harlin, K., and Sandell, M. (2013), *Alternative Fuel for reheating furnace with aiming at CO_2 mitigation,* **www.semanticscholar.org/paper/Alternative-Fuel-for-reheating-furnace-with-aiming-Harlin-Sandell/01aaa4ccb3ac6ec209fb3519151c6bc45e59d979#citing-papers**

Hasanbeigi, A. (2021), "Industrial Heating Profile and Electrification", *Global Efficiency Intelligence,* **www.globalefficiencyintel.com/new-blog/2021/3/22/industrial-heating-profile-and-electrification**

Hu, Y., *et al.* (2019), "Feasibility Study of Biomass Gasification Integrated with Reheating Furnaces in Steelmaking Process", *DEStech Transactions on Environment, Energy and Earth Sciences, ICEEE,* **https://doi.org/10.12783/dteees/iceee2019/31824**

IEA (2018), *World Energy Outlook 2018,* International Energy Agency, Paris, **www.iea.org/weo2018**

IEA (2020), *Iron and steel technology roadmap,* International Energy Agency, Paris, **www.iea.org/reports/iron-and-steel-technology-roadmap**

IEA (2023), *Emissions Measurement and Data Collection for a Net Zero Steel Industry,* International Energy Agency, Paris, **www.iea.org/reports/emissions-measurement-and-data-collection-for-a-net-zero-steel-industry**

IISD (2022), *Industrial electrification,* International Institute for Sustainable Development, **www.iisd.org/publications/brief/industrial-electrification**

IRENA (2020), *Reaching zero with renewables, International Renewable Energy Agency, A*bu Dhabi, **www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Sep/IRENA_Reaching_zero_2020.pdf**

IRENA (2023a), *Towards a circular steel industry,* International Renewable Energy Agency, Abu Dhabi, **www.irena.org/Publications/2023/Jul/Towards-a-Circular-Steel-Industry,**

IRENA (2023b), *World Energy Transitions Outlook 2023:* 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi, **www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023**

Kinch, D. (2022), *"Direct-reduced iron becomessteel decarbonization winner"*, S&P Global, **https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/0**

Lyons, M., et al. (2021), *Reaching zero with renewables: Capturing carbon, 4/2021,* International Renewable Energy Agency, Abu Dhabi, **www.irena.org/Technical-Papers/Capturing-Carbon**

MATIL (n.d.), "56 Emerging Technologies for Energy-efficiency and GHG Emissions Reduction in the Iron and Steel Industry", *MATIL,* **www.matil.org/en/news/steel-sector/56-emerging-%20technologies-for-energyefficiency-and-ghg-emissions-reduction-in-the-iron-and-%20steel-industry-841.html (accessed 17 November 2023).**

Mauret, F., *et al.* (2023), "Impact of Hydrogenous Gas Injection on the Blast Furnace Process: A Numerical Investigation", *Metallurgical and Materials Transactions B,* vol. 54/4, pp. 2137–58, **https://doi.org/10.1007/s11663-023-02822-4**

Mousa, E., *et al.* (2016), "Biomass applications in iron and steel industry: An overview of challenges and opportunities", *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 1247–66, **https://doi.org/10.1016/j.rser.2016.07.061**

Pardo, N., *et al.* (2012), *Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry,* Institute for Energy and Transport Joint Research Centre, *DOI: 10.2790/64264*

Primetals Technologies (n.d.), "Energy Efficiency Solutions by Primetals Technologies", **www.primetals.com/portfolio/eco-solutions/energy-efficiency/ (accessed 17 November 2023).**

von Schéele, J. (2021), "Decarbonisation and Use of Hydrogen in Reheat Furnaces", Conference: 3. Aachener Ofenbau- und Thermprocess-Kolloquium, Aachen, Germany.

Tang, Z., *et al.* (2021), "The Influence of Hydrogen Injection on the Reduction Process in the Lower Part of the Blast Furnace: A Thermodynamic Study", in A.A. Baba *et al.* (eds.), *Energy Technology 2021* (pp. 149–60), Springer International Publishing, Cham, **https://doi.org/10.1007/978-3-030-65257-9_14**

Thekdi, A., *et al.* (2015), *Preliminary Results from Electric Arc Furnace Off-Gas Enthalpy Modeling,* US Department of Energy Office of Scientific and Technical Information, **www.osti.gov/servlets/purl/1221728**

Thyssenkrupp (n.d.), "Thyssenkrupp tests hydrogen as coal replacement in its blast furnaces", *Hazardx,* **www.hazardexonthenet.net/article/175717/Thyssenkrupp-tests-hydrogen-as-coal-replacement-in-its-blast-furnaces.aspx# (accessed 17 November 2023).**

WSA (n.d.), "Steelmaking", World Steel Association, **https://worldsteel.org/about-steel/about-steel/steelmaking/**

Zefelippo, S., and Ranghino, F. (2023), "Electrifying Industrial Heat: A Trillion Euro Opportunity Hiding in Plain Sight", *Ambienta,* **https://ambientasgr.com/wp-content/uploads/2023/02/2023_I-Ambienta-Lens_Electrifying-Industrial-Heat.pdf**

Zhuo, Y., *et al.* (2021), "CFD study of hydrogen injection through tuyeres into ironmaking blast furnaces", *Fuel,* vol. 302, pp. 120804, **https://doi.org/10.1016/j.fuel.2021.120804**

Alliance for Industry Decarbonization