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TOWARDS A CIRCULAR STEEL INDUSTRY

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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FOREWORD

The iron and steel sector is responsible for roughly 7% of overall carbon dioxide emissions, making it one of the most notable contributors to climate change. However, the industry also plays a crucial role in the global economy, providing essential materials for infrastructure, transportation and many other sectors. The production and consumption of steel are likely to rise with the growth of emerging economies.

Circularity approaches can help promote the efficient use of steel and its production inputs. Although these approaches are essential, they will not be sufficient to mitigate the environmental impacts arising from the steel sector in the long term. This report proposes the use of renewable energy in steel production - as an integral component of circular approaches - to transform the steel industry as we strive to achieve a sustainable and net-zero future. Adopting the circular principles presented in this report can help close the loop in the material value chain of steel and reduce greenhouse gas emissions from the sector.

The global nature of steel necessitates coordinated action to overcome common challenges and seize opportunities. G20 members account for about four-fifths of the world's production and consumption of steel, and collaboration among members can accelerate the adoption of circularity. By working together, G20 members can lead the way in implementing circularity by fostering the exchange of best practices, removing trade barriers, and establishing common standards for sustainable steel production.

This report, prepared by the International Renewable Energy Agency (IRENA) in collaboration with the Ministry of Environment, Forest and Climate Change of India (MOEF&CC) as a contribution to India's G20 Presidency, explores the vital topic of circularity in the steel sector and its implications for the future of steel production and consumption. The report draws upon IRENA's expertise and previous analysis on the sector, including *Reaching Zero with Renewables, Breakthrough Agenda 2022* and IRENA's Innovation Week, as well as inputs from several organisations and experts. The recommendations in this report provide the principles for enhancing circularity by leveraging domestic opportunities and international collaboration.

IRENA continues to be fully committed to supporting the G20 and our Member States in developing action plans that promote circularity approaches and the integration of renewables in the steel industry.

Francesco La Camera
Director-General
International Renewable Energy Agency (IRENA)

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ABBREVIATIONS

ALLIANCE	Affordable Lightweight Automobiles Alliance
BF	blast furnace
BOF	basic oxygen furnace
CCUS	carbon capture, utilisation and storage
CE	circular economy
CO_2	carbon dioxide
DRI	direct reduced iron
EAF	electric arc furnace
ECSWG	Environment and Climate Sustainability Working Group
EJ	exajoule
G20	Group of Twenty
GW	gigawatt
H_2	hydrogen
H_2-DRI	hydrogen-based direct reduced iron
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	kilogramme
LCA	life cycle assessment
LiFE	Lifestyle for Environment
Mt	million tonnes
PV	photovoltaics
SIDERWIN	Development of new methodologie**S** for **I**n**D**ustrial CO_2-fre**E** steel p**R**oduction by electro**WIN**ning
tCO_2	tonne of carbon dioxide
ULCOS	Ultra-low CO_2 Steelmaking
WSA	World Steel Association

Country Codes

G20 members

3-LETTER COUNTRY CODE	FULL NAME
ARG	The Argentine Republic
AUS	Australia
BRA	The Federative Republic of Brazil
CAN	Canada
CHN	The People's Republic of China
EU	The European Union
FRA	The French Republic
DEU	The Federal Republic of Germany
IND	The Republic of India
IDN	The Republic of Indonesia
ITA	The Republic of Italy
JPN	Japan
KOR	The Republic of Korea
MEX	The United Mexican States
RUS	The Russian Federation
SAU	The Kingdom of Saudi Arabia
ZAF	The Republic of South Africa
TUR	The Republic of Türkiye
GBR	The United Kingdom of Great Britain and Northern Ireland
USA	The United States of America

Other countries

3-LETTER COUNTRY CODE	FULL NAME
ARE	The United Arab Emirates
AUT	The Republic of Austria
ESP	The Kingdom of Spain
KOR	The Republic of Korea
NLD	The Kingdom of the Netherlands
OMN	The Sultanate of Oman
ROU	Romania
SWE	The Kingdom of Sweden

EXECUTIVE SUMMARY

Steel is a vital material for the progress of human societies. It is used for a wide range of applications, including infrastructure, buildings, transport vehicles and home appliances, among many others. Steel can be recycled without loss of quality, which also makes it a crucial enabler for a transition towards a more circular economy.

On the other hand, the steel sector is one of the most significant contributors to climate change. It is responsible for about 7% of global energy-related carbon dioxide emissions, since the majority of steel production relies on fossil fuels as energy sources and as reductants to process iron ore. A transition towards a fully sustainable and climate-neutral steel sector will require decisive action to continue advancing all levers of circularity. Key steps include improving material efficiency, increasing the share of recycled steel (as more scrap becomes available over time) and making steel production processes more efficient.

While all the above measures can make an important contribution, they will not be enough on their own to make the sector environmentally sustainable in the long run. Addressing the global climate change challenge will require a shift towards sustainable energy sources for producing steel. Central to achieving this objective will be the scale-up of renewable energy use in the sector.

Policy action at the national level is fundamental to achieving the circularity of the steel sector, but international dialogue and co-operation in the Group of Twenty (G20) can play a key role in advancing circularity strategies for the sector's transformation globally.

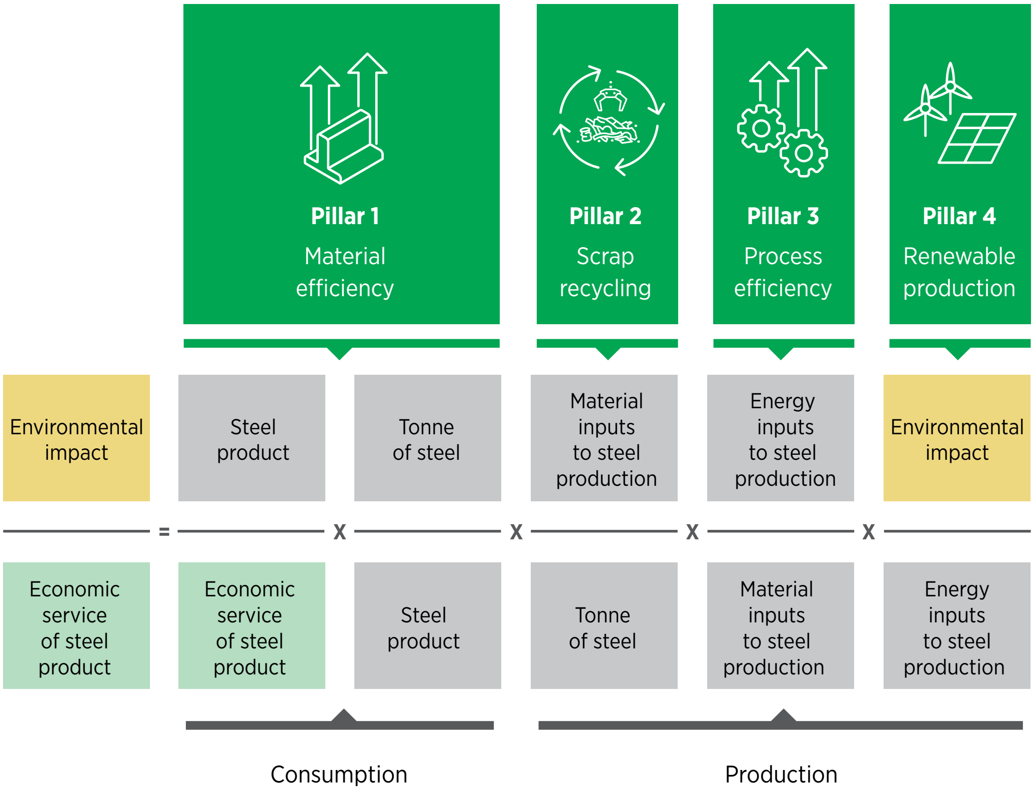
In terms of material efficiency, blueprints exist for the smarter, more optimal use of steel in key consuming sectors, such as construction and automobile production. National regulatory frameworks can act as drivers for the more efficient use of steel.

> **Recommended collaboration area: Co-operation in the G20, to identify and scale best practices in the major steel-consuming sectors, through mutual learning and exchange of regulatory experience, can contribute to the more efficient use of steel globally.**

Steel scrap recycling is at the core of a shift towards greater circularity in the steel sector. But the availability of scrap is a limiting factor, since steel products have long lifespans. About 30% of steel produced today comes from recycling scrap.

The role of steel recycling will continue to grow over time as more scrap becomes available in emerging economies, resulting in larger shares of recycled steel, in turn progressively reducing the need for primary production. By 2050, about half of the world's steel production could come from recycled scrap. National governments can make a difference

Figure S.1 Key factors in the environmental impact of steel products and four pillars of a circularity strategy



by adopting and enforcing regulations that ensure environmentally sound and thorough steel scrap collection and sorting processes. Adopting such good practices in the recovery of end-of-life steel products is also crucial to minimise scrap's contamination by other materials, for example, copper, thereby enabling the use of scrap as input for higher-quality steel specifications.

> **Recommended collaboration area: Dialogue and co-operation in the G20 can contribute towards removing the barriers to international scrap trade, allowing scrap to be transported and used where it creates the most economic and environmental value.**

A more circular and sustainable steel sector can also be achieved through making steel production processes more efficient, with widespread adoption of the best available technologies across the G20.

> **Recommended collaboration area: G20 members can facilitate the exchange of best practices among national policy makers and regulators. These discussions may focus on preventing market distortions that disincentivise investments in energy efficiency projects. Implementing best practices can make the industry more competitive and provide sufficient incentives to invest in improving efficiency in domestic steel industries.**

A shift from fossil-fuel-based steel to renewables-based steel will be crucial in a transition to a more sustainable iron and steel sector. Renewables already supply a substantial fraction of the power used for secondary steel production in electric arc furnaces today. However, primary steel production, which accounts for about 70% of the global steel output, still relies almost exclusively on fossil fuels.

One key alternative to fossil fuels for steel production is the use of renewable hydrogen for iron ore reduction, which enables the production of near-zero-carbon primary steel. But the higher costs of production with renewable hydrogen compared with conventional steel production processes pose a barrier to its widespread adoption. However, deployment at scale could substantially reduce costs, also benefiting from further reductions in the costs of renewable hydrogen over time.

Regions with low-cost, abundant and high-quality renewable energy and iron ore resources are in the best position to make hydrogen-based iron ore reduction competitive. This creates an opportunity for international co-operation. Iron ore exporters with abundant and inexpensive renewables could capture more value by exporting processed iron. Importing countries could reduce the overall costs of decarbonising their domestic industries while retaining steel production within their borders.

A transition towards renewables-based steel will require decisive policy support in the early stages of technology adoption. Policy action at the national level can help create the conditions for investment by defining roadmaps for the sector's transformation, and the adoption of supporting measures. However, since steel is an internationally traded commodity, multilateral co-ordination will be vital.

> **Recommended collaboration area: G20 members can accelerate a transition towards renewables-based steel by co-operating in several areas, including dialogue towards internationally agreed definitions, standards and certifications for low-carbon steel; initial demand creation through multilateral public procurement commitments; knowledge exchange on technology research and development; professional skills needed for the transition; and technical and financial assistance to developing countries, among others.**

1. INTRODUCTION

India's presidency of the Group of Twenty (G20) has selected *Vasudhaiva Kutumbakam* ("One Earth, one family, one future") as its theme, reflecting a commitment to fostering collective responsibility for a sustainable future for our planet.

In line with this, the Environment and Climate Sustainability Working Group, under India's G20 presidency, has identified five priority areas. Among them, the third priority area specifically emphasises resource efficiency and the promotion of a circular economy. The report sets forth principles to achieve the objectives set within this theme, encouraging a holistic approach to promoting the circularity of the iron and steel sector.

Towards a circular steel industry

Steel is a vital commodity for human activities. Almost 2 billion tonnes of steel are consumed annually in buildings, transport, consumer goods and machines. Steel's remarkable strength, durability and recyclability make it easy to work with and ensure its widespread use. It is also remarkably versatile since it can be modified by alloying it with different elements, such as manganese and nickel, to ensure the desired properties for a broad set of applications. Steel can also be recycled without loss of property, which makes it a crucial enabler for a transition towards a more circular economy.

The iron and steel sector is among the most prominent industries globally, with a market value of USD 1.51 trillion in 2021 (GVR, 2022). It serves as the lifeline for several communities and regions, providing direct employment to over 6 million people globally and indirectly generating jobs in related sectors of the economy (IEA, 2020). The iron and steel industry is crucial to a functioning human society since critical infrastructure depends on the availability of steel.

However, the methods used today to produce steel have environmental impacts. It is therefore essential that the iron and steel sector is transformed in a manner that allows it to continue to deliver valuable services to society while having minimal environmental impacts.

This report examines how the iron and steel sector can become more circular. It systematically looks at each key driver of circularity for the sector, showcases best practice examples and discusses both technological and non-technological options at all stages of the steel production and consumption chain for G20 countries to increase circularity and minimise environmental impact.

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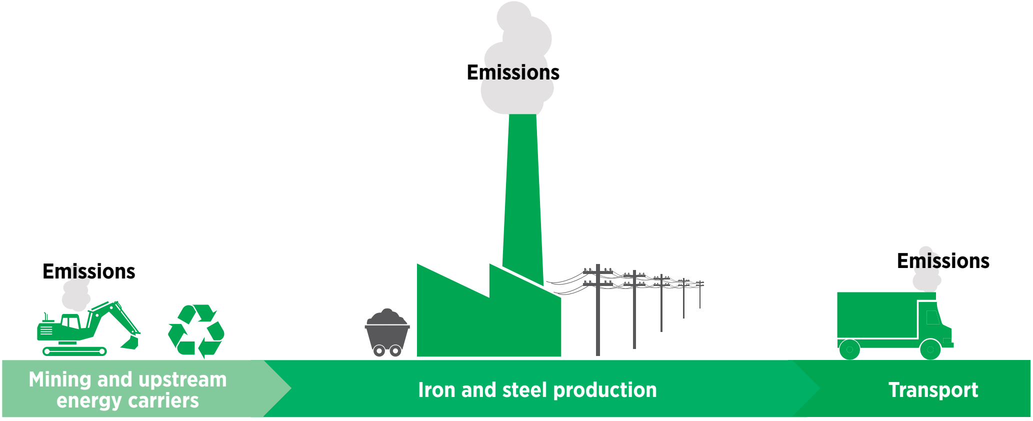
1.1 ENVIRONMENTAL RELEVANCE OF THE STEEL SECTOR

The iron and steel sector was responsible for 2.6 gigatonnes (Gt) of direct carbon dioxide (CO_2) emissions in 2019, representing about 7% of the total energy sector emissions (including process emissions) (IEA, 2020). Steel production is energy intensive since the majority of the production occurs at high temperatures. The sector consumed over 35 exajoules (EJ) of energy in 2021 (IEA, 2020). Additionally, most iron ore is converted into metallic iron using fossil fuels, such as coal and natural gas, as reducing agents, releasing CO_2 in the process (reduction is a necessary step, involving oxygen removal from iron ore to create iron). Upstream activities consuming coal and natural gas also produce substantial methane emissions (Kholod *et al.*, 2020).

Besides direct CO_2 emissions, current methods of iron and steel production – in the absence of appropriate pollution control systems – can also have detrimental impacts on human health. Dust and volatile matter can escape from raw material preparation (Figure 1), causing air pollution (IEA, 2020). Air pollution can also be an issue where such production facilities are located near urban centres.

Figure 1 Sources of emissions in iron and steel production



Based on: (Carbon Smart Materials Palette (n.d.)).

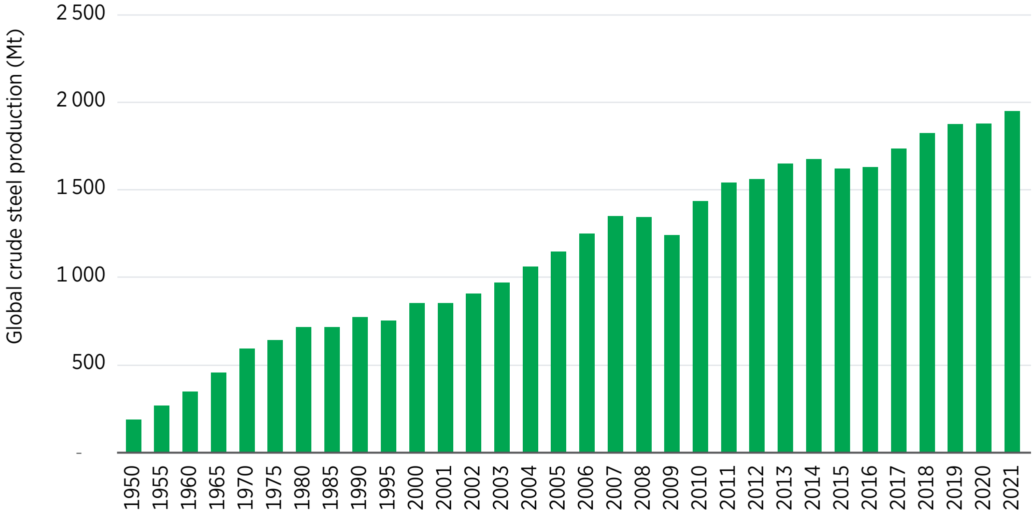
1.2 STEEL SECTOR TODAY

Almost everything that surrounds us contains steel – from large objects such as the houses and buildings we live and work in, to the transport vehicles and infrastructure that we utilise, to the appliances and consumer products that we use daily. A growing economy increases the demand for these products and, consequently, the demand for steel. In essence, the demand for steel closely follows the development of an economy, particularly at the early stages of industrialisation. Also, steel's use in electric vehicles, wind turbines and solar photovoltaic (PV) structures makes it a key input material in the energy transition.

Steel production has risen steadily over time. From just 190 million tonnes in 1950, it grew to almost 2 billion tonnes in 2021 (Figure 2), due to demographic growth and economic development (WSA, 2022). The increase in global steel production over the past few decades was driven by growth in emerging economies, particularly China. While crude steel production capacity doubled in the previous two decades, almost three-quarters of the capacity growth occurred in China (IEA, 2020).

The demand for steel is closely tied with economic activity in various sectors. As shown in Figure 3, 52% of steel in 2019 was used in buildings and infrastructure and 17% in transport. Machinery consumed one-fifth of the steel, while consumer goods represented approximately one-tenth of the total steel demand. The steel used in construction is stored in products and structures for extended periods, and thus constitutes the bulk of the steel in use (Pauliuk, Wang and Müller, 2013). In 2021, both steel demand and production experienced volatility triggered by supply chain issues and lockdowns in response to the COVID-19 pandemic. However, steel demand rebounded quickly as the steel-consuming construction and automotive sectors recovered faster than other sectors (WSA, 2020).

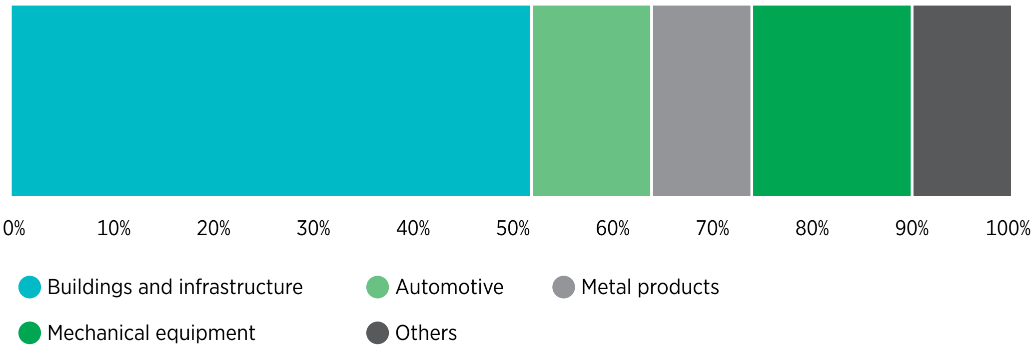
Figure 2 Annual global crude steel production



Source: (WSA, 2022).
Note: Mt = million tonnes.

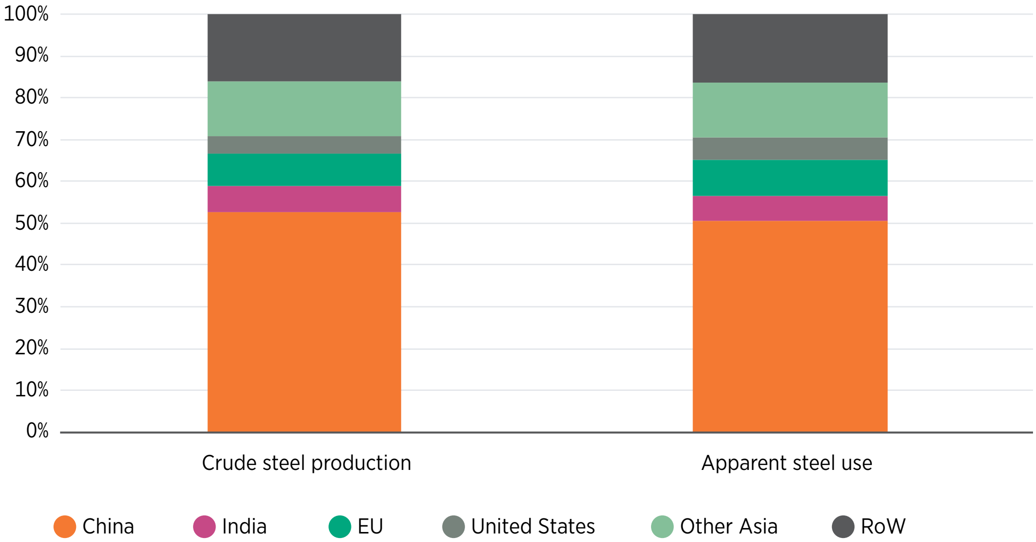
The iron and steel industry is global in nature. Ninety-one countries produce crude steel in substantial quantities, consumed across the world. Meanwhile, a few jurisdictions dominate global steel production. China produces more than half of the global crude steel output, followed by the European Union, India and the United States. These regions produce roughly 70% of the steel globally. Similarly, a large share of steel consumption is concentrated in these regions, which consume 70% of the total steel produced globally (Figure 4) (IEA, 2020).

Figure 3 Breakdown of steel demand by sector



Source: (WSA, 2018a).

Figure 4 Steel supply and apparent steel use[a] by region, 2021



Source: (WSA, 2022).
Note: EU = European Union; RoW = rest of the world; [a] "Apparent steel use" is defined as the sum of the steel produced domestically and net direct imports.

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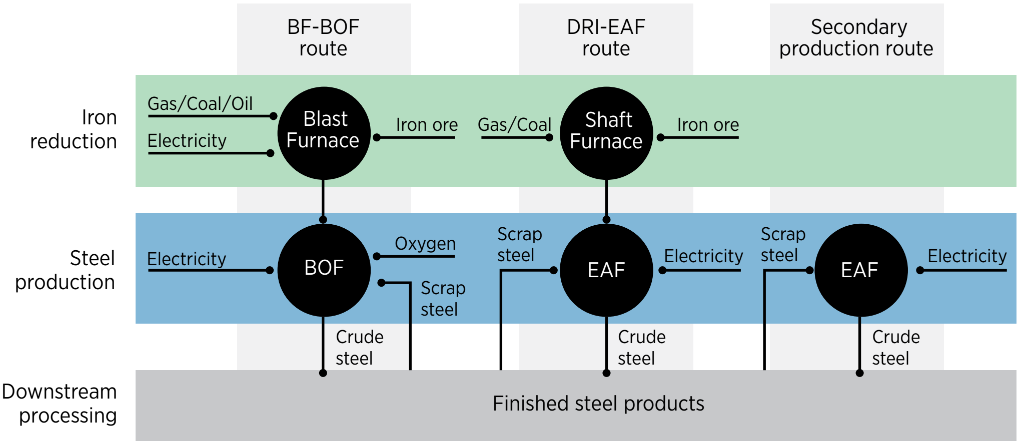
1.3 STEEL PRODUCTION ROUTES

Steel can be produced from iron ore and recycled steel scrap. Primary steel production refers to the operations in which iron ore is used as the main metallic input, whereas secondary production processes are based on scrap. Scrap is also used in primary production along with iron ore as cooling material and metallic input.

In primary production, the iron ore is reduced to iron. Today, this is primarily done in two ways – in a blast furnace (BF) or in a direct reduced iron (DRI) shaft or kiln furnace. The iron output from the BF is processed in a basic oxygen furnace (BOF), whereas the output from the DRI furnace is typically processed in an electric arc furnace (EAF), for the next stage, which is also called steelmaking (Figure 5) (IRENA, 2020). Today, the BF-BOF is the route for roughly 70% of global steel production, and constitutes 90% of primary production (IEA, 2020). On the other hand, secondary production uses recycled steel scrap. Secondary production uses electricity as the main energy input instead of coal and natural gas, which are used in primary production. Sponge iron, the output from the DRI furnace, can be fed to the BOF. Approximately 30% of global steel production uses scrap as metallic input to the process (IEA, 2020).

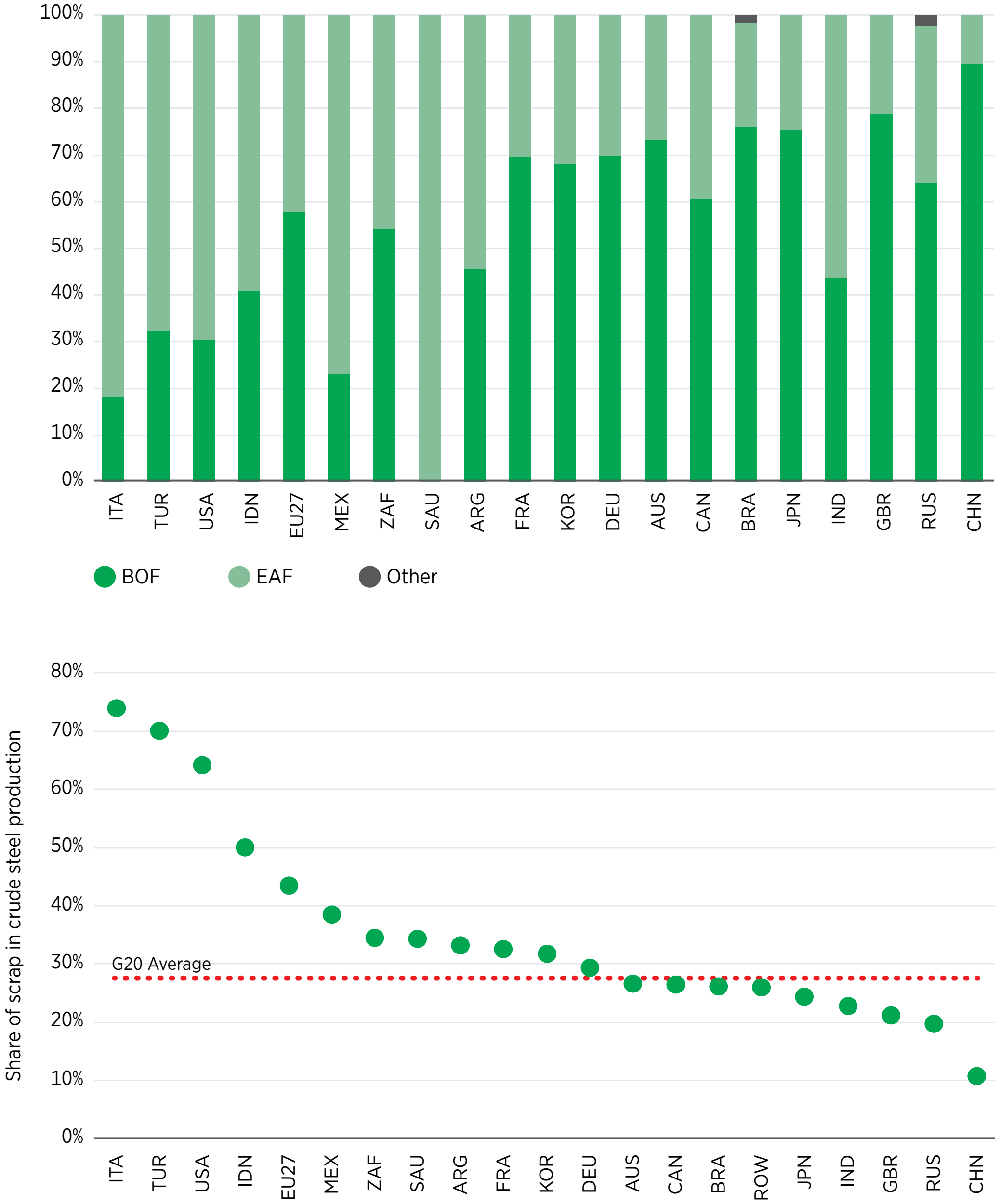
Today, G20 countries produce approximately 85% of the total crude steel output globally. The main production routes vary among countries depending on access to raw material, energy, technological development and economic development. Availability of scrap – driven by historic steel consumption – is one of the primary factors determining the development of the production process used (Figure 6). Scrap availability varies significantly between mature and developing countries, with the latter typically more reliant on primary production methods to meet steel demand.

Figure 5 Traditional pathways for steel production



Based on: (Lopez, Farfan and Breyer, 2022).
Note: BF = blast furnace; BOF = basic oxygen furnace; DRI = direct reduced iron; EAF = electric arc furnace.

Figure 6 Breakdown of different production methods and share of scrap in crude steel production across G20 countries, 2019



Source: (Bataille, Stiebert and Li, 2021; WSA, 2020).

Note: BOF = basic oxygen furnace; EAF = electric arc furnace; G20 = Group of Twenty; ARG= The Argentine Republic, AUS= Australia, BRA= The Federative Republic of Brazil, CAN= Canada, CHN= The People's Republic of China, EU= The European Union, FRA= The French Republic, DEU= The Federal Republic of Germany, IND= The Republic of India, IDN= The Republic of Indonesia, ITA= The Republic of Italy, JPN= Japan, KOR=The Republic of Korea, MEX= The United Mexican States, RUS= The Russian Federation, SAU= The Kingdom of Saudi Arabia, ZAF= The Republic of South Africa, TUR= The Republic of Türkiye, GBR= The United Kingdom of Great Britain and Northern Ireland, USA= The United States of America

2. IMPROVING THE CIRCULARITY OF THE STEEL SECTOR

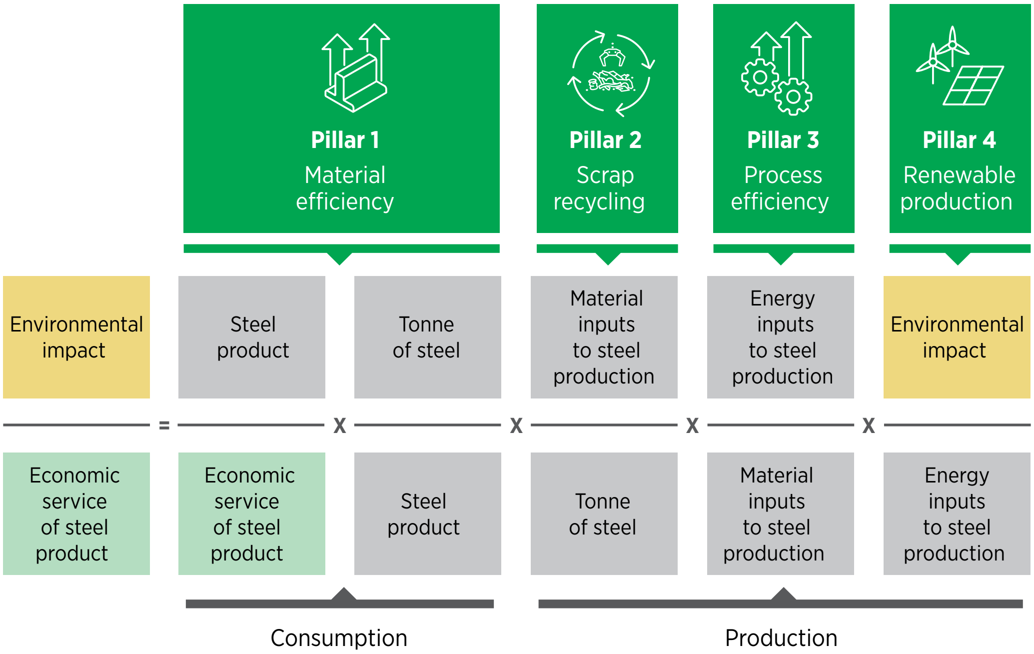
2.1 CIRCULAR ECONOMY MODELS IN THE IRON AND STEEL SECTOR

The circular economy (CE) is a concept that refers to the conversion of linear product value chains into circular life cycles. Commonly used definitions of CE tend to focus on reducing, reusing and recycling products or raw materials to avoid wastage. For the iron and steel sector, material efficiency and scrap recycling are essential pillars of circularity. While these are important aspects, a broader definition should also incorporate the sustainability of the energy sources and reductants used in the production process, since these are key drivers of the sector's environmental impact.

The global steel sector is already circular to an extent. About 30% of the steel produced today comes from scrap recycling. It is also possible to rely on renewable power sources to produce recycled steel. However, most steel produced today still relies on fossil fuels as energy sources and reducing agents for iron ore processing.

Figure 7 shows a breakdown of the key factors driving the environmental impact of steel products, and four related pillars for increased circularity. The steel sector will become more circular by deploying material efficiency measures, increasing the share of recycled steel as more scrap becomes available over time, deploying (process) efficient technologies and transitioning to production methods that use renewable energy sources and alternative "green" reducing agents. A transition towards a fully circular steel sector in the future should consider all these levers to deliver a meaningful impact.

Figure 7 Key factors of the environmental impact of steel products, and four pillars for a circularity strategy



Given below are brief explanations of how the four pillars contribute to the circularity of the steel sector:

- **Material efficiency in steel use:** Material efficiency measures can contribute to advancing the circularity of the iron and steel sector by optimising the use of steel products. These measures include producing lighter steel products and structures, refurbishing and reusing steel products, and redesigning products with alternative materials when justified based on life cycle analysis.

- **Steel scrap recycling:** Recycling steel improves circularity by allowing steel from end-of-life products to be repurposed for other applications. Steel recycling reduces the need for primary steel production.

- **Process efficiency:** Improving energy efficiency enhances circularity by minimising the need for resources in steel production. Process efficiency reduces the environmental impact of the production processes proportionally.

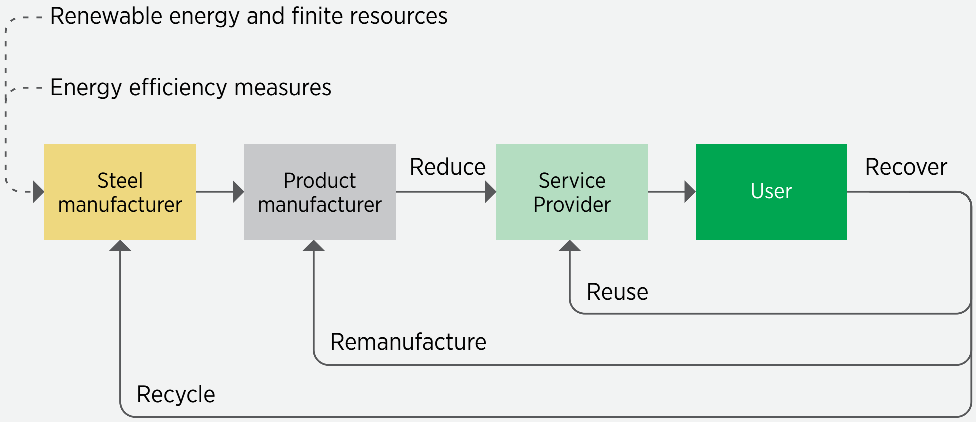
- **Renewables-based steel production:** A transition towards renewables-based steel production entails a structural shift away from fossil fuels as sources of energy and reducing agents. One of the most promising options is the use of renewable energy and green hydrogen to reduce iron ore. A shift to using renewables can improve the environmental performance from more environmentally friendly iron and steel and reduce the dependence on finite fossil fuels, in turn advancing circularity.

The circularity of the iron and steel industry will entail a suite of technological solutions, policy interventions, innovative financial and business models to eliminate waste and emissions, and circulating products and source materials.

Box 1 Framework for a circular steel sector

Circular economy principles aim to capture maximum value from a product through continuous loops in its value chain. The principles aim to ensure a constant flow of material between manufacturing and the final-use stage, minimising the need for primary material at each step. Essentially, circular economy principles aim to transform how the production system works to benefit business, society and the environment. The principles include reusing, redesigning, reducing, remanufacturing, recovering and recycling (Jayal *et al.*, 2010). In applying these principles, it is important to take into account the overall life cycle impact of steel products versus alternative materials.

Figure 8 Six Rs of a circular economy in the steel sector



Reduce: Using alternative materials can enable a product to provide the same services with less materials or greater efficiency.

Redesign: Products may be designed to use less steel. Measures such as lightweighting using high-strength steel can drastically reduce the steel required in a product.

Remanufacture: Repair and refurbishments allow a product to be sold for original use in primary and secondary markets.

Reuse: A product in its original form can be used to perform the same function more than once. Business models may grant such products access to secondary markets.

Recover: Recovery involves collecting and sorting material that cannot be reused or remanufactured since its serviceable life has ended or the function it served is no longer needed.

Recycle: Through the process of recycling, metal may be transformed from an end-of-life product into a newly usable commodity. Recycling steel saves significant energy and carbon emissions relative to producing new steel. Steel can be recycled multiple times without loss of quality or functionality; it can even be recycled to improve its quality to suit a new service or end use.

Box 2 Lifestyle for Environment principles for the circularity of the steel industry

The Lifestyle for Environment (LiFE) movement was launched by the Indian prime minister at the 2021 United Nations Climate Change Conference in Glasgow in November 2021. It focuses on the mindful and deliberate utilisation of resources, which are at the core of the steel sector's circularity. The key pillars of the LiFE movement – focus on individual behaviours, co-create globally and leverage local cultures – align well with the four pillars of the steel industry's circularity:

- **Focus on individual behaviours:** Promoting circular economy principles can help motivate individuals to make more sustainable choices when purchasing steel products. For example, they may prefer buying products made from recycled steel or products that are designed to be easily repaired or recycled.

- **Co-create globally:** Collaborative efforts between governments and the steel industry globally can facilitate the sharing of knowledge and best practices to boost material efficiency, increase steel recycling and promote low-carbon steel production. This can include partnerships between steel manufacturers, governments and environmental organisations to develop new technologies and standards that promote circularity.

- **Leverage local cultures:** Local cultures can be leveraged to promote circularity by building awareness and engaging communities in circular economy initiatives. Traditional practices, such as repair and reuse of items, can be applied to steel products, and local artisans can develop new designs for steel products that can be recycled or repaired more easily.

Box 3 Benefits of iron and steel sector circularity in combating climate change

The iron and steel sector is responsible for about 7% of global energy-related carbon dioxide emissions, making it one of the most significant contributors to climate change (IRENA, 2020). The sector's climate impacts will continue to grow alongside emerging economies unless action is taken.

The sector is one of the hardest to decarbonise. Today, it relies predominantly on fossil fuels as energy sources and for raw material processing. A transition towards a climate-neutral steel sector will require a fundamental shift in energy sources, reducing agents and steel production processes. This includes a transition towards a renewables-powered supply for secondary steel, but also, more importantly, towards renewables-based technologies for primary steel, which accounts for about 70% of today's steel production.

Besides these fundamental shifts, other circularity approaches can substantially contribute to addressing the global climate change challenge. These include more efficient use of steel through material efficiency, minimising the need for primary steel production by recycling increasing quantities of scrap as they become available and making steel production processes as efficient as possible. A holistic approach towards the sector's transformation, considering all levers of circularity, can accelerate progress towards carbon neutrality in the steel industry. Further research can help quantify the cumulative decarbonisation potential of these levers in the iron and steel sector. This is a possible area to be advanced by future G20 presidencies.

2.2 OPTIONS TO IMPROVE THE CIRCULARITY OF THE SECTOR

Circularity strategy 1: Reduce steel demand through increased material efficiency

Implementing material efficiency measures can help advance circularity in the iron and steel sector by optimising the use of steel products. These measures help mitigate steel demand, reducing the pace of the required technological shift to sustainable steel production processes.

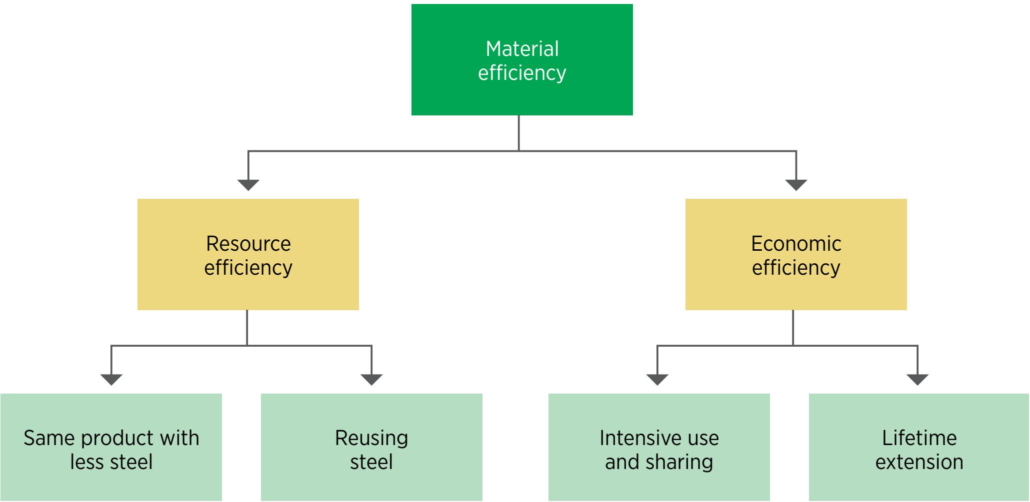
Apart from reduction in direct material demand, material efficiency strategies can also bring various systemic environmental and economic benefits beyond the steel sector. For example, the use of high-strength steel in vehicles makes them lighter, and reduces their fuel consumption and emissions, while helping them maintain service efficiency. This is particularly true of electric vehicles, which have smaller carbon footprints.

We consider two types of efficiency measures, both of which use technical interventions, consumer preferences, business models and policy instruments to reduce end-use steel consumption (Figure 9) (Allwood *et al.*, 2013):

1. "Resource efficiency" measures involve providing the same service with less steel. These measures are implemented at the "design", "manufacture" and "use" stages of steel value chains and at their end of life.

2. "Economic efficiency" measures can either extend the serviceable life of a steel product or help it deliver more services with the same quantity of material inputs. These interventions are implemented at the "design" and "use" stages of steel value chains.

Figure 9 Resource and economic efficiency in steel



"Resource efficiency" measures (Table 1) can be implemented using two strategies:

1. "Same product with less steel" involves reducing the quantity of steel needed to produce a unit of end use. An example of this is the use of "lightweighting" techniques that optimise designs together with high-strength steel or steel substitutes to minimise vehicles' weight.

2. "Reusing steel" allows repurposing steel from end-of-life steel products for other applications with minimum processing. This strategy uses negligible energy compared with both primary and secondary steel production and can play a role in a strategy to improve resource efficiency.

Table 1 Resource efficiency principles in different end uses

END USE	SAME SERVICE WITH LESS STEEL	REUSE
Construction	Higher-strength rebar and design optimisation to reduce demand	Modular structures to enable relocation
Transport	Reducing steel use in vehicles through lightweight design and materials (high-strength steel, aluminium and carbon fibre, among others)[1]	Secondary markets to allow for reuse of products with steel content
Machinery and consumer goods	Computer-aided manufacturing can produce units with less wastage	

Based on: (Wang *et al.*, 2021).

"Economic efficiency" measures (Table 2) can be implemented using the following strategies:

1. **Lifetime extension:** Better design for repairability can help extend a product's lifetime. Repairing lightly damaged parts of products, especially consumer products and vehicles[2], can significantly extend their useful life.

2. **More intensive use:** This involves changes in behaviours and preferences to increase the useful service of individual steel products. For vehicles, several options can be considered, such as car sharing (shift from personal to shared cars) and ride-sharing (among people with the same or similar destinations). A switch to public transport modes from private transport also increases the utilisation rate of steel products. For buildings, a shift to co-working spaces or working from home, among others, improves the utilisation of the built surface, which is a key driver of steel demand.

---

[1] *When considering the substitution of steel with alternatives, the full life cycle impact of both materials should be evaluated.*

[2] *Extending a vehicle's lifetime may reduce emissions due to material use, but it can lead to higher emissions per kilometre due to performance differences in fuel efficiency between old and new internal combustion engines, and between hybrid and electric vehicles.*

Table 2 Economic efficiency principles in different end uses

END USE	INTENSIVE USE AND SHARING	LIFETIME EXTENSION
Construction	Higher utilisation rates of built space	Renovation and refurbishment of existing buildings
Transport	Ride-sharing and switching to public transport	Better design for repairability, refurbishment and reuse
Machinery and consumer goods	Equipment sharing	

Based on: (Wang *et al.*, 2021).

Understanding the potential

Material efficiency strategies can have a substantial impact on the demand for steel. The International Energy Agency's Iron and Steel Technology Roadmap estimates that a combination of material efficiency measures could decrease the global projected steel demand by about a fifth by 2050 (IEA, 2020).

The most significant drivers of this demand reduction are improved design and construction, and extended lifetimes of buildings. "Lightweighting" and intensive use of vehicles are the primary drivers of the demand reduction for the transport sector. Apart from specific sectors, significant demand reductions can be added by promoting the reuse of products across applications without remelting.

Challenges to implementing material efficiency strategies

Material efficiency measures hold significant potential to deliver environmental and non-environmental benefits, but they can be challenging to execute. Table 3 outlines several material efficiency strategies along with drivers and barriers.

The adoption of material efficiency measures often requires technical changes that cannot be implemented immediately. For example, it can take the automotive sector several years to redesign vehicle frames or adopt higher-strength alloys, while ensuring safety and performance standards, adapting production processes and realigning upstream supply chains.

Regulatory frameworks can also be a barrier to the adoption of certain practices. For instance, design standards in the construction sector may limit the use of alternative materials. These standards could include building codes that prescribe materials rather than performance specifications (UNEP and IRP, 2020). Implementing material efficiency measures might require investments in new technologies and processes, which could be especially challenging for companies with limited financial resources. These could include, for instance, additive manufacturing technologies, which reduce the material input needed to manufacture a product. Apart from challenges with access to financial resources, such companies could also face challenges in upskilling or finding skilled labour to design and use advanced technologies. This can be potentially limiting in sectors such as component manufacturing for automobiles, which may require significant technical expertise.

There can also be a lack of awareness of the need to measure relevant data (*e.g.* on material losses and yield rates) to justify the implementation of material efficiency measures. Lack of data, and in several situations, lack of data sharing among regulators, also leads to formulation of ineffective policies.

Cultural factors and practices, beliefs and behavioural routines can also sometimes act as barriers to material efficiency and the energy transition in general (Sovacool and Griffiths, 2020). For instance, local customs in some regions may influence individuals to prioritise buying newly built homes over renting or refurbishing existing homes (UNEP and IRP, 2020). In certain regions, owning a car is considered prestigious despite the availability of car sharing services.

Table 3 Material efficiency strategies, drivers and barriers

SECTOR	STRATEGY	DRIVERS	BARRIERS
Building	More intensive use	High urbanisation rates	Prescriptive design conventions
	Using less material by design	High construction costs and metal prices	
	Lifetime extension		Complexity of renovation projects
	Reuse		Missing supply chain actors, dismantling costs
Transport	More intensive use	Greater flexibility in mobility	
	Using less material by design	Increasing fuel standard requirements	High substitute material costs
	Lifetime extension	Standardisation and automation of repair process	New models for cars
	Reuse	High metal prices	Poor scrap steel quality, complex supply chains

Based on: (UNEP and IRP, 2020).

Case studies for material efficiency

- **Lightweighting in cars** – ALLIANCE *(Affordable Lightweight Automobiles Alliance)*

  Six European carmakers, along with several suppliers and partners, formed a coalition known as ALLIANCE in 2016 to address the challenges of lightweight design by using advanced high-strength steel and material selection (ALLIANCE, n.d.).

The project's results show that a significant weight reduction of up to 33% is possible with an additional cost of EUR 3 or less per kilogramme saved. The focus on developing technologies to optimise fuel and energy consumption holistically has resulted in the creation of vehicle prototypes that are targeted for market application by 2025. ALLIANCE has further developed several support tools to ensure the market viability of the developed technologies.

- **Lightweighting in construction** – *STIGA Sports Arena Eskilstuna, Sweden*

  STIGA Sports Arena, which opened in 2017, is located near Stockholm. The complex hosts sporting events, concerts and conventions, with its main arena comprising 3 700 seats for sporting events and approximately 5 000 seats for concerts. Designers and other project partners chose lightweight trusses since they are more economical than alternatives such as I-beams. Using high-strength steel with trusses led to lighter and sturdier structures, resulting in lower overall steel use (SCI, 2019).

- **Extending the life of machines and household products** – *CoreCentrics Solutions*

  CoreCentrics Solutions is a US-based enterprise that runs a repair and distribution network for defective household products and machine parts. The company teams with some of the world's largest retailers and consumer goods manufacturers, operating a large repair programme and redistribution networks (Ellen MacArthur Foundation, n.d.[a]). While the repair programme reduces the need for frequent product replacements, the redistribution networks create reliable secondary markets for refurbished components and products. CoreCentric's business allows products to have a longer practical life and higher utility.

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- **Equipment sharing application** – *Rheaply*

  Rheaply enables the sharing of unused assets between and within organisations and institutions, thereby reducing new demand for resource-rich products that are used infrequently (Ellen MacArthur Foundation, n.d.[b]). It lets users keep track of inventory, allowing machines and equipment to be sold, leased or rented.

- **Reusing building structure** – *The Van Unnik building at Utrecht University*

  The Van Unnik building at Utrecht University, the Netherlands, is more than 50 years old. Instead of constructing a new building compliant with current standards, the existing building will be redeveloped keeping the resource-intensive skeleton intact (Utrecht University, 2023). This process will reduce the material load needed to develop a building compliant with building codes.

Box 4 Cross-sectoral circularity: Reuse of slag and other by-products from the iron and steel sector

Using lime fluxes such as limestone and dolomite to remove impurities in industrial processes results in slag as a co-product. One tonne of steel produces roughly 400 kilogrammes (kg) of slag from iron ore, of which 275 kg come from the blast furnace (BF) and the rest comes from a basic oxygen furnace (BOF) (WSA, 2018b). About 110 kg of slag are also generated while recycling steel in an electric arc furnace. Rather than a metallurgical waste, the configurations and properties of slag are designed to optimise iron and steelmaking operations. Due to its properties, slag can be used as a substitute for different materials in several industrial applications.

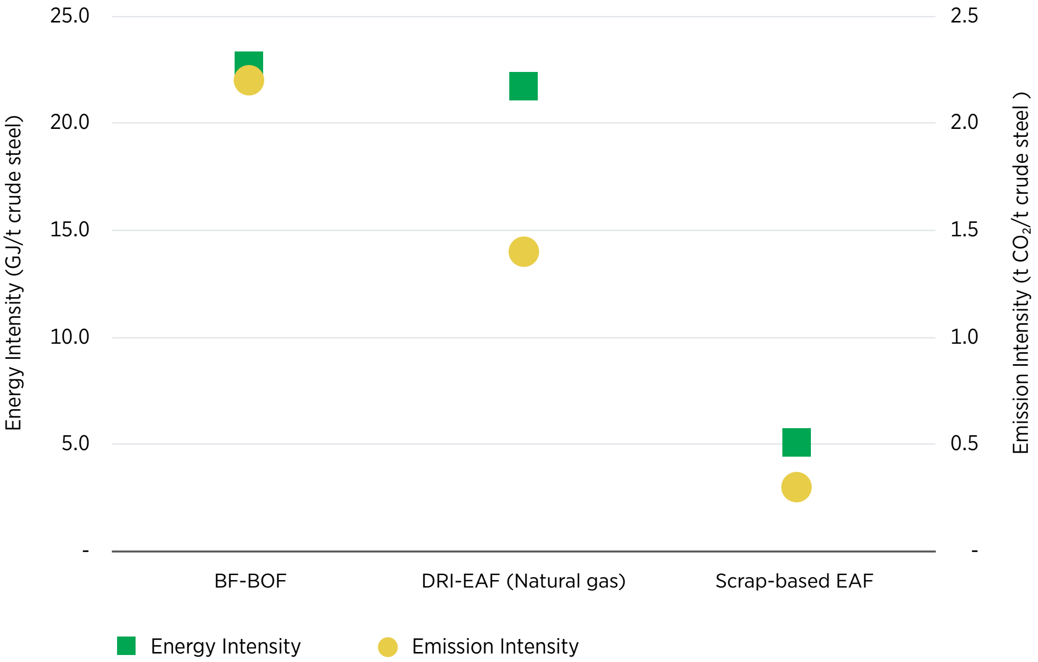
The most prominent use of BF slag is in the construction sector, where it is used as a substitute for clinker, the most emission-intensive ingredient in cement production. Slag can constitute large shares of the clinker's weight along with other substitutes, proportionally reducing emissions from cement production (IEA, 2020). It can also serve as a coarse and fine aggregate for concrete. BF slag can also be used in producing fertilisers. Slag from steelmaking can also be used in the construction of roads and as an aggregate for asphalt concrete (Nippon Slag Association, n.d.).

Iron and steelmaking operations produce significant volumes of gases from the coke oven, BF and BOF. Significant amounts of energy can be recovered from these flue gases when converted into power (Cavaliere, 2019). Also, carbon dioxide from blast furnace gas can be captured for converting feedstocks for different industries.

Circularity strategy 2: Maximise the potential of recycled steel

Steel can be recycled infinitely without loss of quality and remade to have any grade. Recycling steel scrap from end-of-life products is an established practice as it makes economic sense for steel producers to adopt the less-energy-intensive recycling process than producing new steel from iron ore (Wang *et al.*, 2021). Today, about 30% of the world's steel is produced from recycled steel scrap (BIR, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017; WSA, 2020).

Figure 10 Energy and emissions intensity of different iron and steel production routes, 2019



Based on: (IEA, 2020).
Note: BF = blast furnace; BOF = basic oxygen furnace; CO_2 = carbon dioxide; DRI = direct reduced iron; EAF = electric arc furnace; GJ/t = gigajoule per tonne.

Steel recycling is central to a CE strategy as it not only reduces the need for extracting iron ore but also contributes to emissions reductions (Figure 10). Moreover, with renewables' share in electricity grids increasing, recycled steel will have a reduced environmental impact over time without additional actions within the sector.[3]

In countries with a longer and more intense history of industrialisation, a considerable fraction of new steel can usually be produced from steel scrap (Figure 11). This is due to the substantial stock of steel accumulated in their economies over several decades. By contrast, emerging and developing economies must typically rely on primary production processes to a greater extent as they build up the stock of steel (Söderholm and Ekvall, 2020).

The total volume of scrap recycled into new steel increased over time to reach an estimated 622 million tonnes (Mt)/year in 2020 (BIR, 2011, 2012, 2013, 2014, 2015, 2016, 2017). However, the share of scrap inputs in global crude steel production decreased over the last couple of decades due to faster increase in steel demand in emerging economies such as China and India, despite the increase in scrap availability.

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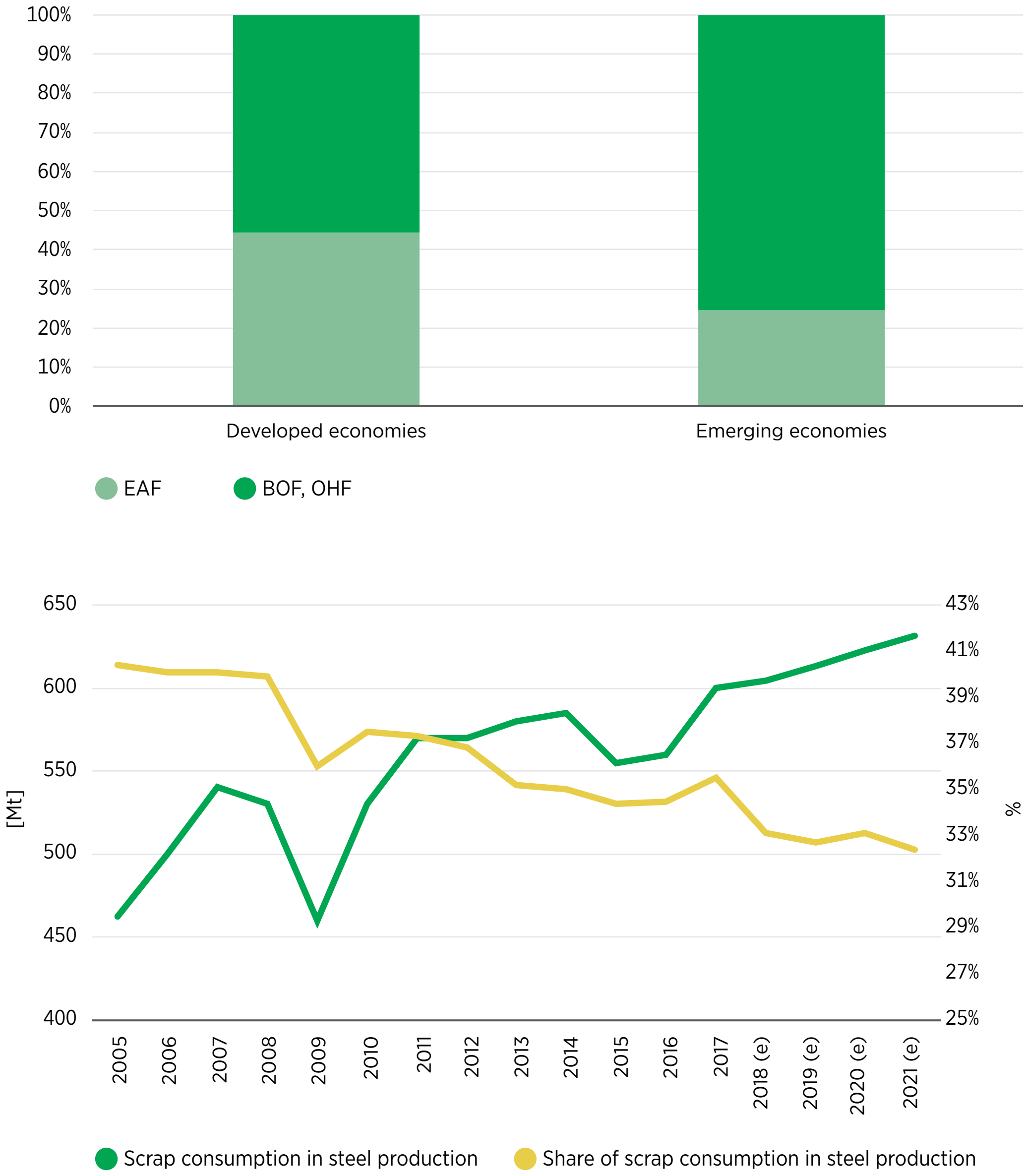
3 The share of renewable energy in global power generation grew from 20.4% in 2011 to 28.3% in 2021 (REN21, 2022).

Figure 11 Share of EAF-based steel in different economies and evolution of scrap use in steel production



Based on: (BIR, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017; WSA, 2020).
Note: BOF = basic oxygen furnace; EAF = electric arc furnace; Mt = million tonne; OHF = open hearth furnace.

Steel recycling rates[4] are already high (~80-85%) for scrap collected from end-of-life products (IEA, 2020). Recycling rates, especially for "old scrap",[5] depend on the use cases of the metal and collection and sorting efficiency. Collecting and sorting processes can require substantial labour, transport and costs, and can constrain the use of scrap for recycling. The specific costs for recycling increase as larger shares of old scrap are collected for recycling. Since the remaining additional scrap may be spread out more geographically, its identification and sorting, especially in smaller quantities, may be more costly.

Despite significant progress in scrap collection and sorting, it is difficult to estimate how much scrap remains unrecovered currently. However, the industry consensus is that there is limited additional potential for scrap collection and recycling today.

The quantity of scrap available – and, therefore, the potential to increase the production of recycled steel – is expected to grow along with historic steel production levels as steel products that were introduced to the market years or even decades ago reach the end of their useful lives. The scrap arising from 2030 onwards will likely replicate the steep production growth from 1990 onwards following the historic increases in demand in China and India.

Global steel scrap availability is estimated to increase from 770-870 Mt/year currently to 1 250-1 550 Mt/year by 2050. The uncertainty in estimates comes from differences in the calculation methodologies and parameters used. These estimates are subject to changing global conditions, domestic policies and technological developments.

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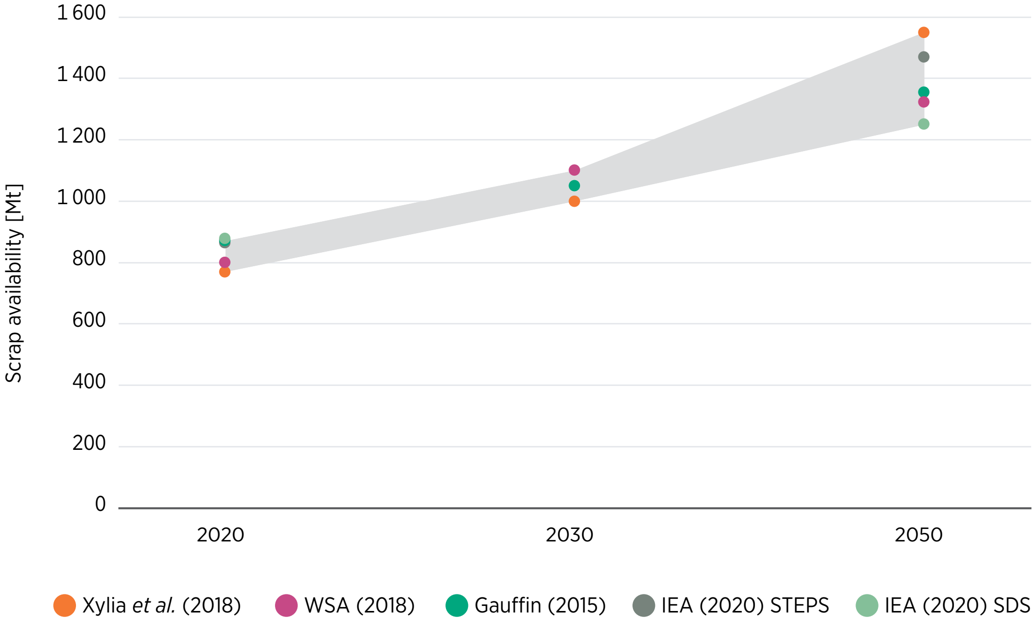
[4] *"Recycling rate" refers to the percentage of steel scrap recycled versus steel scrap collected and available for recycling.*

[5] *"Old scrap" refers to scrap generated from end-of-life products, whereas "new scrap" refers to scrap generated in a steel mill or during the manufacture of steel products. Contrary to old scrap, new scrap is of high quality and its metallurgical composition is typically well known.*

Figure 12 Estimates on scrap available for recycling

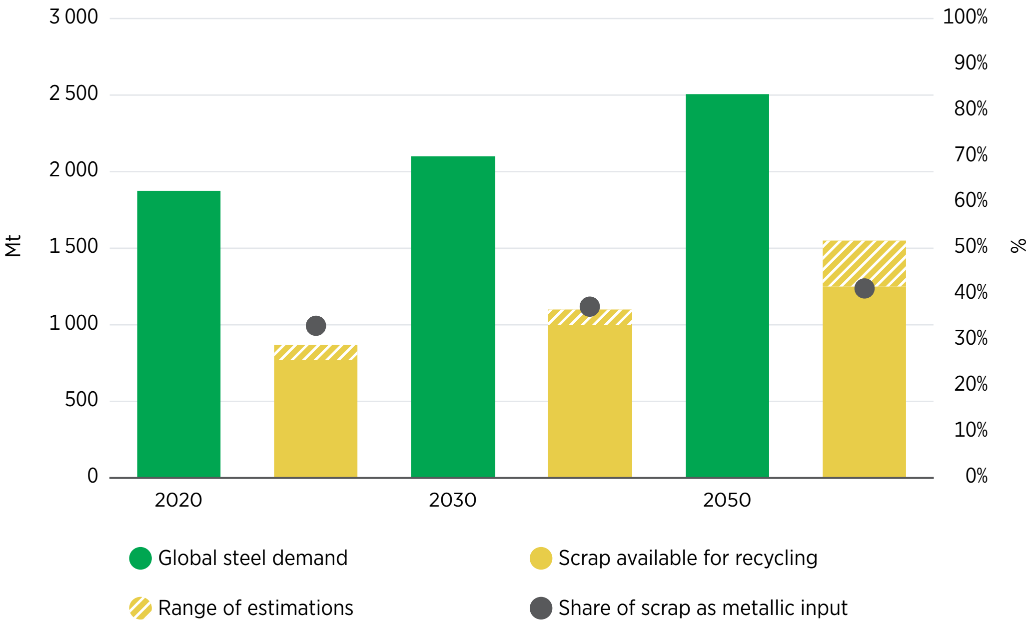


Based on: (Çiftçi, 2018; Gauffin, 2015; IEA, 2020; Xylia *et al.*, 2018).
Note: Mt = million tonnes; SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario.

The demand for steel is expected to continue increasing in the future, with global demand projected to rise from about 2 000 million Mt/year today to 2 500 Mt/year by 2050. However, the implementation of material efficiency measures could potentially help to contain the global demand at about 2 000 Mt/year (IEA, 2020).

Figure 13 shows that the projected increase in scrap availability will result in recycled steel playing a growing role over time, with shares increasing from 30% today to about 40% by 2050 (with a baseline steel demand scenario). In scenarios assuming widespread adoption of material efficiency measures, recycled steel could potentially account for about half of the world's steel production by 2050 (IEA, 2020).

Figure 13 Potential role of scrap recycling in future steel production



Based on: (Çiftçi, 2018; Gauffin, 2015; IEA, 2020; Xylia *et al.*, 2018).
Note: Mt = million tonnes.

Recycling could be limited not just by the availability of scrap in quantitative terms but also by its quality. Contaminants such as copper and tin in steel scrap render scrap less usable for certain applications. These impurities come from the alloying elements from previous use cases or arise due to improper scrap management practices.

A common source of copper contamination is the frequent inadequate separation of wire harnesses and smaller motors from steel scrap in automobiles. These are enmeshed into steel bodies as recyclers typically hammer shred components before sending them through a magnetic separator. This binds the copper elements with the ferrous scrap, resulting in inefficient removal of parts with copper during magnetic separation. Even low concentrations of copper can cause surface cracking in downstream steel processes and degrade the final product (Daehn, Serrenho and Allwood, 2017). Scrap with copper contamination disincentivises its use in sectors such as the automotive sector, which has stringent tolerances (Ruth, 2004).

Scrap contamination can be avoided by improving waste collection and sorting practices and disassembling scrap before it is sent for shredding. These interventions may result in additional costs compared with existing practices and require policy intervention to increase adoption. A robust regulatory framework for scrap collection and processing is also key to minimise environmental risks related to waste management. This is especially important in the construction and automotive sectors, as well as in shipbreaking, where scrap can be recovered in large quantities.

Free scrap trade across different countries and regions is also crucial for maximising its value for a more circular steel sector. Scraps of various qualities are suited for different applications. For instance, steel for construction typically has higher tolerance than what is needed for the automotive sector. Free trade of scrap will allow its use in countries other than where it was sourced. This in turn will enable better matching of scrap supply with the product portfolio specifications of steel producers in different countries.

Circularity strategy 3: Improve process efficiency in steel production

Globally, iron and steel production uses over 35 EJ of energy annually, with coal and natural gas being the predominant sources of this direct energy (IEA, 2020). Energy contributes 20-40% to the total production costs for steel producers, and this is why they generally have a strong economic incentive to reduce the energy consumed in the iron- and steelmaking process (WSA, 2021). The carbon intensity of the iron and steel industry (tonnes of carbon dioxide [tCO_2]/t of crude steel) decreased by roughly two-thirds from 1900 to 2015, but the past few decades saw a substantial slowdown of improvement as the room for further efficiency gains narrowed (Wang *et al.*, 2021).

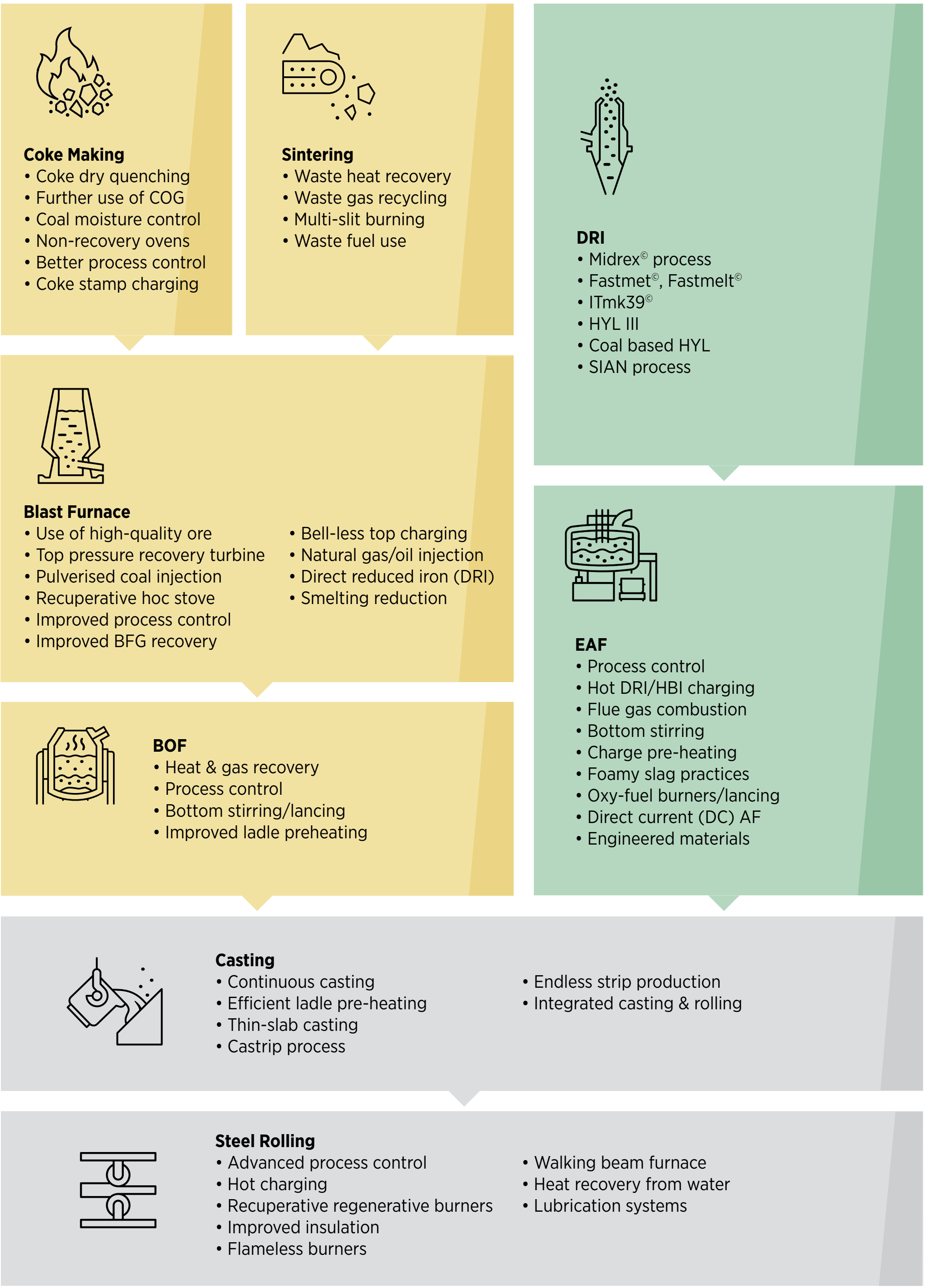
Opportunities for efficiency improvements

The energy and carbon intensity of steel production depends on the production route. The integrated route typically emits between 1.6 and 3.8 tCO_2/t of steel produced, whereas the scrap-based EAF pathway emits 0.2-2.7 tCO_2/t of steel (Koolen and Vidovic, 2022).

The mix of inputs also influences the carbon intensity. In a sample of 238 steel plants, those with near-zero scrap use had emissions intensity between 1.6 and 3.5 tCO_2/t of crude steel, whereas those with an ~96% scrap share emitted between 0.2 and 0.5 tCO_2/t of crude steel (Butterworth and Wan, 2022). The variation in emissions intensity range is partly due to the use of coal or natural gas as a reducing agent and heat source, but it is also influenced by differences in the efficiency of the processes.

Measured (or estimated) carbon intensities vary considerably across regions and production sites, indicating that there remains potential for process efficiency improvements by converging to best practices. Several measures can contribute to making iron and steel production more efficient (Figure 14), including retrofit, process control, waste utilisation, process intensification, heat recovery and new technology measures (IETS and IEA, 2014).

Figure 14 Improving efficiency in iron and steel production processes



Coke Making
- Coke dry quenching
- Further use of COG
- Coal moisture control
- Non-recovery ovens
- Better process control
- Coke stamp charging

Sintering
- Waste heat recovery
- Waste gas recycling
- Multi-slit burning
- Waste fuel use

DRI
- Midrex© process
- Fastmet©, Fastmelt©
- ITmk39©
- HYL III
- Coal based HYL
- SIAN process

Blast Furnace
- Use of high-quality ore
- Top pressure recovery turbine
- Pulverised coal injection
- Recuperative hoc stove
- Improved process control
- Improved BFG recovery
- Bell-less top charging
- Natural gas/oil injection
- Direct reduced iron (DRI)
- Smelting reduction

BOF
- Heat & gas recovery
- Process control
- Bottom stirring/lancing
- Improved ladle preheating

EAF
- Process control
- Hot DRI/HBI charging
- Flue gas combustion
- Bottom stirring
- Charge pre-heating
- Foamy slag practices
- Oxy-fuel burners/lancing
- Direct current (DC) AF
- Engineered materials

Casting
- Continuous casting
- Efficient ladle pre-heating
- Thin-slab casting
- Castrip process
- Endless strip production
- Integrated casting & rolling

Steel Rolling
- Advanced process control
- Hot charging
- Recuperative regenerative burners
- Improved insulation
- Flameless burners
- Walking beam furnace
- Heat recovery from water
- Lubrication systems

Based on: (Hasanbeigi, 2017).
Note: BFG = blast furnace gas; BOF = basic oxygen furnace; COG = coke oven gas; HBI= hot briquetted iron; VFD = variable frequency drive.

Barriers to further efficiency improvements in the iron and steel industry

Energy efficiency measures can lead to significant cost reductions for steel producers, which they can leverage to invest in capacity expansion, maintenance or other efficiency measures. Beyond reducing costs, these measures can lower the carbon footprint of several processes involved in iron- and steelmaking and make them more productive. Nevertheless, steel manufacturers do not always implement efficiency maximisation measures, despite the potential benefits. The barriers encountered depend on the manufacturers' characteristics, the country's economic and legislative landscape, and the operational and technical understanding of the required technologies.

I. Strategy, capacity and organisational barriers

Lack of information and experience with newer, energy-efficient technologies: Producers, particularly smaller companies, may lack the information and technical know-how to operate new technology. They may also be hindered by a lack of capacity to measure, monitor and anticipate the benefits of energy efficiency.

Long investment cycles and equipment depreciation: Energy efficiency improvements can entail a suite of options that may require upgrading to newer equipment. The long life of existing equipment could potentially deter producers to upgrade if the equipment has yet to depreciate fully.

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II. Financial and business case barriers

Access to low-cost capital and viable payback period: Energy efficiency can involve substantial upfront capital investments. However, failure to meet banks' lending criteria leads to producers often finding it difficult to obtain low-cost capital to finance such projects. This issue is especially acute for smaller companies. The longer payback periods can discourage producers from undertaking the higher investments required for energy efficiency improvements (OECD, 2015).

Indirect costs: Several indirect costs associated with executing efficient energy management practices are difficult to account for and quantify. These "indirect costs" can include the cost of collecting and analysing information, and costs due to production disruptions, among others.

III. Economic barriers

Market distortions: Sometimes policies support the cost of the raw materials and inputs required for the iron and steel sector in order to maintain a domestic industrial base. This may in some cases disincentivise adequate energy management practices, hampering investments in productivity improvements and emissions reductions. Similarly, a lack of regulations that incorporate the costs of environmental externalities, *e.g.* carbon emissions, makes the economic case for energy efficiency projects less attractive.

Circularity strategy 4: Renewables-based primary steel production

Material efficiency, scrap recycling and process efficiency are key contributors to a more circular steel sector. However, a truly environmentally sustainable steel sector will require a strategic shift towards renewables for primary steel production, which will be needed for decades to come.

Renewables can be introduced in ironmaking and steelmaking using biomass, hydrogen or direct electrification. Charcoal can be used as a reducing agent instead of coal, but sustainable sourcing for large-scale deployment is a challenge. Also, direct electrification technologies can be used to convert iron ore into steel using renewable power, but the technology is not yet mature enough for large-scale use.

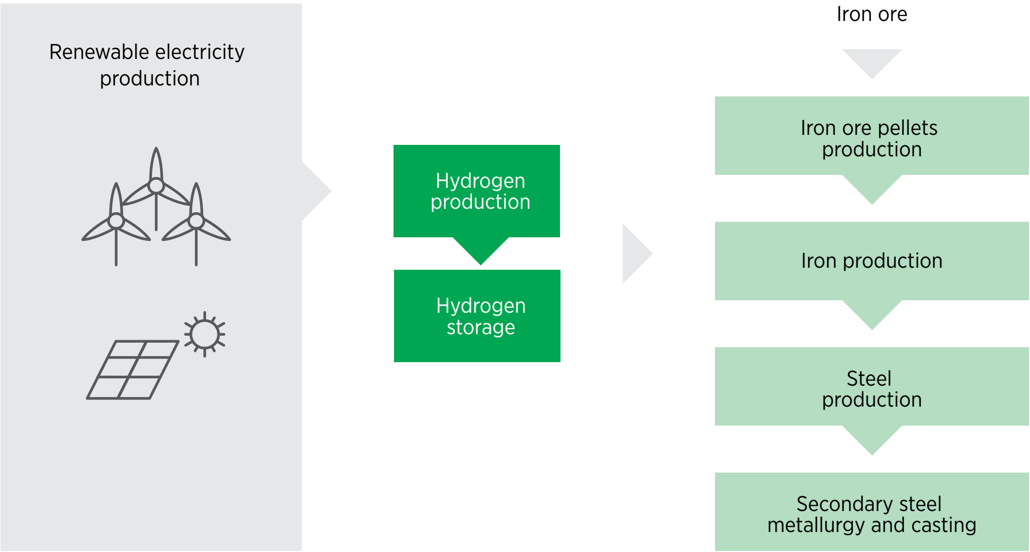
Meanwhile, hydrogen-based direct reduced iron (H_2-DRI) can replace fossil fuels with green hydrogen as a reducing agent (Figure 15), and the technology is reaching commercial maturity. Renewables-powered fully green H_2-DRI production can add CO_2 emissions reductions of 80-95% compared with the traditional BF-BOF route (IRENA, 2020). There are already numerous H_2-DRI projects in the pipeline, indicating increased confidence from industrial players in this production process (refer to Table 4).

Box 5 Capturing carbon from iron and steel production processes

Iron and steel production can be decarbonised using other available technological pathways apart from green-hydrogen-based direct reduced iron. IRENA's 1.5°C Scenario highlights a small yet significant role of carbon capture, utilisation and storage (CCUS) in this industry (IRENA, 2023). CCUS can be potentially retrofitted to existing traditional fossil-fuel-based steel production assets.

Meanwhile CCUS technologies can provide a short-term option for the partial decarbonisation of existing fossil-fuel-powered production facilities, while renewables-based technologies provide a long-term solution for emissions-free steel production.

Figure 15 Hydrogen-based ironmaking and steelmaking



Based on: (Pei *et al.*, 2020).

Drivers for H_2-DRI deployment

- **Demand for carbon-neutral steel products**

  Several private sector businesses have turned their attention to the hydrogen-based green steel method owing to its high decarbonisation potential and technological readiness. For instance, H2 Green Steel has signed 1.5 Mt of pre-orders from several steel end users, for example, BMW, Marcegaglia and Electrolux (H2 Green Steel, 2022). Marcegaglia has a seven-year advance supply agreement with H2 Green Steel (H2 Green Steel, 2023). Volvo has announced that it will use the steel produced by SSAB's green hydrogen steel production facilities for its heavy electric trucks (Volvo Trucks, 2022). These investments and purchase commitments are driven by stringent corporate governance measures demanded by shareholders and consumers.

- **Public sector push and pull**

  The adoption of long-term decarbonisation targets, combined with increased regulatory pressure through carbon pricing in some jurisdictions, creates a strong signal for industry to explore low-carbon solutions (Hall *et al.*, 2021). Industries anticipating further tightening and new regulations are taking steps to transform their operations using cleaner fuels, renewable electricity and production methods that release less emissions.

  Further, increased government participation in green steel procurement through various initiatives, such as the Industrial Deep Decarbonisation Initiative,[6] creates the necessary demand for the steel produced using lower-emission methods.

- **Falling costs of renewable energy generation**

  The electricity input accounts for a significant share of green hydrogen's production cost. New utility-scale solar PV projects, onshore wind projects and offshore wind projects commissioned in 2021 saw a significant decrease in their average weighted levelised cost of electricity, with solar PV witnessing a 88% decrease since 2010 while onshore and offshore wind witnessed 68% and 60% declines, respectively (IRENA, 2022). Markets are increasingly recognising the falling costs of renewable energy sources, which is making green hydrogen production increasingly attractive to iron and steel producers as a pathway for reducing iron. While the cost of producing green hydrogen is currently higher than that for unabated hydrogen, it is anticipated to decrease owing to the falling costs of renewable energy generation and expected cost reductions in electrolyser technology.

Challenges to H2-DRI deployment

- **Scaling the supply of renewable hydrogen**

  Hydrogen-based steel production will be a major green hydrogen consumer in the more circular steel sector. Transitioning to green hydrogen-based steel production will pose major challenges in the form of deploying the required electrolyser and renewable supply capacity. The green H_2-DRI–EAF route requires substantial electricity consumption – particularly for producing hydrogen. As a rule of thumb, 1 Mt/year of hydrogen production capacity requires about 10 gigawatts (GW) of electrolyser capacity and at least 20 GW of renewable power to supply electricity. To put this in perspective, transitioning all iron-producing plants in the European Union to H_2-DRI would require up to 5.3-5.5 Mt/year of renewable hydrogen and up to 370 terawatt hours per year of additional renewable electricity generation, which is four times the electricity that the sector consumes currently (Hydrogen Europe, 2022; Medarac, Moya and Somers, 2020).

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[6] *The Clean Energy Ministerial Industrial Deep Decarbonisation Initiative, started in June 2021, is a collaboration between public and private organisations that aims to stimulate the demand for industrial materials with a small carbon footprint.*

An uninterrupted supply of hydrogen will be critical to the operations of steel production plants. Also, reliable steel production will require hydrogen storage, which will allow building buffer capacity for periods of low renewable generation, ensuring security of supply and minimising price volatility. One option for developing large-scale storage capacity can be converting existing salt caverns, which can potentially provide large storage capacity at relatively low cost. However, the planned project pipeline indicates a lack of advanced stage projects to cater to the demand of the iron and steel industry. These projects also face lengthy permitting and construction periods, which are detrimental to these resources' development (IEA, 2022) Moreover, the geographic misalignment of underground storage resources and existing steel production assets can hinder the development of hydrogen-based steel. Converting hydrogen into ammonia for hydrogen storage could potentially alleviate the challenges of absence of underground storage the production sites, with the caveat of large energy losses at different conversion steps. In future, green ammonia could potentially be used directly (without the need for reconversion into hydrogen) to reduce iron ore (Ma *et al.*, 2023).

- **Costs of production**

Steel produced from the first announced renewable-hydrogen-based DRI plants will have an estimated 20-30% cost premium compared with the steel produced by conventional production methods (RMI, 2019). This cost differential is a key barrier for adoption, since steel is an internationally traded commodity and steel producers operate under tight profit margins. In the absence of (globally agreed) environmental externality pricing, or other supportive policies, steel producers adopting cleaner, costlier technologies can be priced out of the market.

While the cost differential for crude steel is substantial, the cost impact on some higher-added-value end products can be relatively low. For instance, a 20% higher steel cost translates into an estimated 1% increase in a car's overall cost (Cordonnier and Saygin, 2022; Vogl, Åhman and Nilsson, 2018). This opens the door to create a sizeable initial demand for renewables-based steel from end-consumer brands aiming to fulfil their environmental, social and governance commitments.

Steel production costs are highly sensitive to the cost of electricity generation for producing hydrogen, a cost that represents about one-fifth of final steel production costs (Cordonnier and Saygin, 2022). Regions with inexpensive, abundant and high-quality renewable energy and iron ore resources are in a better position to make hydrogen-based iron ore reduction more competitive. This could have a significant impact on future trade flows and creates an opportunity for international co-operation to reduce the costs of the sector's transition globally. Iron ore exporters with abundant and low-cost renewables could capture more value in the supply chain by exporting processed iron. Importing countries, on the other hand, could reduce the overall costs of decarbonising their domestic industries while retaining steel production within their borders. Gielen *et al.* (2020) state that relocation of the energy-intensive ironmaking sector to such regions could reduce global sector emissions by nearly a third, with an estimated carbon price of USD 67/tCO_2, making the green H_2-DRI–EAF cost-competitive with BF-BOF routes.

- **Changes to existing operational parameters and layouts**

  A shift to a 100% renewable H_2-DRI pathway requires changes to both the process and the operational setup compared with existing natural gas or gasified coal-based DRI plants. These include changes to the melting temperature, addition of equipment to maintain slag, among others. The nature and extent of the changes required to adapt to the new method will be unique to each facility. Moreover, the absence of carbon with the renewable H_2-DRI process can lead to incomplete metallurgical reactions, increased unwanted residues and reductions in process yield (Astoria, 2022).

- **Need for high-grade iron ore**

  The DRI route for ironmaking is more sensitive to iron ore grades than the traditional BF production process. Several companies, for example, ThyssenKrupp and BlueScope, are working on solutions to reduce reliance on high-grade iron ores by adding a melting stage after the DRI stage and retaining the BOF process to achieve the necessary steel quality levels using iron reduced from low-quality ores (Nicholas and Basirat, 2022). POSCO is developing a demonstration project based on fluidised bed hydrogen reduction technology, which can use low-grade iron ore (POSCO, 2023). However, these technologies have not yet seen wide commercial adoption.

  The project pipeline for DRI-grade iron ores shows potential supply constraints in response to growing demand. Estimates show a five-fold increase in demand for high-grade ores, pushing the supply-demand gap to 350 Mt by 2050 (Wood Mackenzie, 2022). A supply deficit could be a barrier to the transition towards the DRI production route.

Box 6 Direct electrification of iron ore reduction processes

Electrification refers to the process of reducing a metal ore to its primary metal using electricity as the main energy source. Electricity is already used commercially to reduce bauxite and lithium ore to produce aluminium and lithium metal. The deployment of a similar method to reduce iron ore to iron could accelerate the decarbonisation of primary steel production by enabling the use of renewable power as the primary energy source and eliminating the need for a reducing agent besides the electricity input.

Iron ore can be reduced directly to metallic iron via high- or low-temperature electrolysis. However, these production routes are still in the early stages of technological development.

Several initiatives are working towards demonstrating commercial steel production through direct electrification. For instance, SIDERWIN (funded by the European Commission and a consortium led by ArcelorMittal) has demonstrated the feasibility of iron production via electrolysis at 110°C (European Commission, n.d.[a]). On the other hand, Boston Metal uses high-temperature electrolysis. It aims to see commercial plant deployment by 2026 (Boston Metal, n.d.).

Table 4 List of hydrogen-based ironmaking and steelmaking projects (non-exhaustive)

COMPANY	STAGE	SCALE	(EXPECTED) YEAR OF OPERATION	COUNTRY	LOCATION	IRON PRODUCTION CAPACITY (MTPA)	STEEL PRODUCTION CAPACITY (MTPA)
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
ArcelorMittal	Feasibility	Commercial	2028	CAN	Hamilton	2.5	2.4
Baowu Group	Construction	-	-	CHN	Zhanjiang	-	1
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	-
Fortescue Metals	Announced	Commercial	2023	AUS	Pilbara	-	-
GravitHy	Announced	-	-	FRA	Fos-sur-Mer	2	-
H2 Green Steel	Construction	Commercial	2024	SWE	Svartbyn	-	5
H2 Green Steel	Announced	Commercial	2025	ESP	Iberia	-	2
HBIS Group	Announced	-	-	CHN	Xuanhua	-	1.2
Jindal Steel & Power Ltd	Announced	Commercial	2026	OMN	Muscat	-	5
Liberty Steel	Feasibility	Commercial	-	FRA	Dunkirk	2	2
Liberty Steel	Announced	-	-	ROU	Galati	-	4
LKAB	Announced	Commercial	2030	SWE	Kiruna, Malmberget, Svappavaara	5 by 2030, 24.4 by 2050	-

Table 4 (continued)

COMPANY	STAGE	SCALE	(EXPECTED) YEAR OF OPERATION	COUNTRY	LOCATION	IRON PRODUCTION CAPACITY (MTPA)	STEEL PRODUCTION CAPACITY (MTPA)
POSCO	Announced	Commercial	-	KOR	Pohang	-	1
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	-
Salzgitter	Construction	Pilot	2022	DEU	Salzgitter	1	-
SSAB	Operational	Pilot	2021	SWE	Luleå	-	-
SSAB	Construction	Pilot	2026	SWE	Gällivare	1.3, 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	-	-

Note: 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; Mtpa = million tonnes per annum; 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.

The table includes plants using green hydrogen and plans to transition to green hydrogen from natural gas.

3. ACCELERATING PROGRESS TOWARDS A MORE CIRCULAR STEEL SECTOR

3.1 PROGRESS TO DATE

The iron and steel sector has made progress towards circularity in the value chain of steel products over the past few decades. Steel scrap recycling is a common practice, with established networks to sort scrap metal from waste and make it available for steel producers. Meanwhile, lightweighting, product durability, modularity and reparability are increasingly becoming critical considerations in product design. Also, the adoption of progressively more energy-efficient technologies and measures has reduced specific energy consumption at some of the newest production sites. We are also witnessing announcements, demonstrations and pilots for several renewables-based steel production projects in development in different regions around the globe.

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Governments are critical enablers of a transition towards a more circular steel sector and can use economic and regulatory mechanisms that are aligned with their development priorities. They have done so in the past using environmental regulations; carbon pricing and standards; energy efficiency and material efficiency policies; and research, development and demonstration programmes, among other instruments. They have also played a critical role in knowledge sharing, skill training and capacity building for the steel industry.

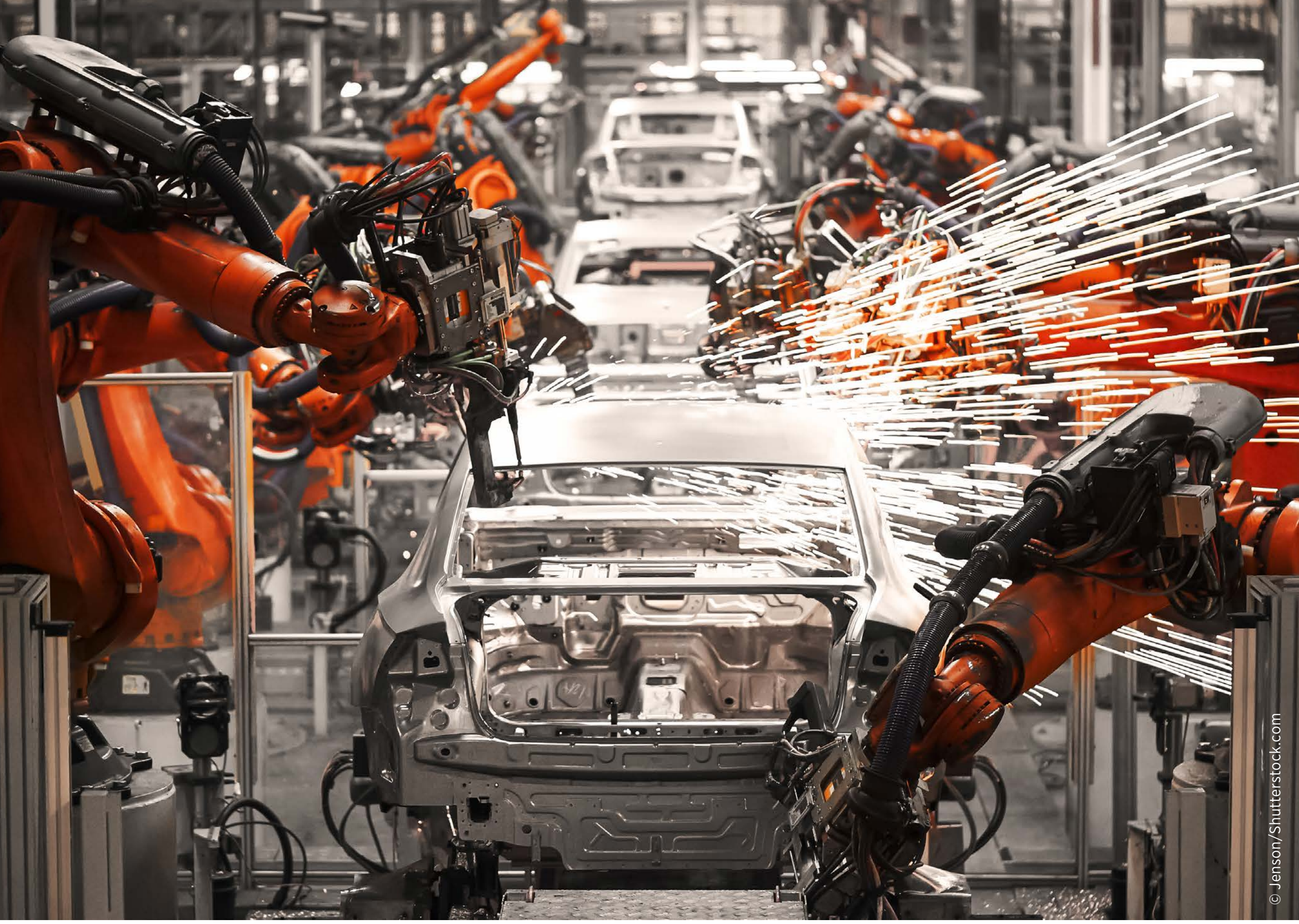
The private sector also plays a vital role in advancing the circular economy for steel. Several steel producers and product manufacturers are leveraging partnerships and research to pioneer material efficiency and renewables-based steelmaking pilots and commercial-scale projects. These include public-private sector research and development initiatives for low-carbon steelmaking, such as ULCOS, and the Clean Steel Partnership and Low-Carbon Metallurgical Innovation Alliance (China Baowu Group, 2021; ESTEP, n.d.; European Commission, n.d.[b]). Automotive and construction associations have been researching methods for lightweighting and alternative materials through partnerships with other manufacturers and research institutes.

Financial institutions have also started applying sustainability criteria to investments in iron and steel production assets. For instance, the Sustainable STEEL principles, launched by a consortium of lenders, helps banks align their steel lending portfolios towards 1.5°C climate targets (Center for Climate Aligned Finance, 2022). Similarly, the Climate Bonds Initiative has recently launched criteria for iron and steel production, which will guide banks and investors to invest in the sector’s sustainable activities and incentivise the development of regulations.

International initiatives are starting to create a demand for sustainable steel from the public and private sectors. Purchase commitments under these collaborations have increased significantly, potentially covering more than 5% of total steel production by 2030 (IEA, IRENA and UNCC HLC, 2022). These initiatives include the Clean Energy Ministerial Industrial Decarbonisation Initiative, SteelZero and the First Movers Coalition (FMC) (CEM, n.d.; SteelZero, n.d.; World Economic Forum, 2021). Additionally, the World Economic Forum and the Energy Transitions Commission launched the Net-Zero Steel Initiative under the Mission Possible Platform. It aims to mobilise industry to support policies for low-emission steel.

3.2 ENABLING FRAMEWORK TO ACCELERATE PROGRESS

A transition towards a fully sustainable and climate-neutral steel sector will require decisive action to continue advancing all levers of circularity. Key steps include improving material efficiency, increasing the share of recycled steel (as more scrap becomes available over time) and making steel production processes more efficient.



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While all the above measures can make important contributions, they will not be enough on their own to make the sector environmentally sustainable in the long run. Addressing the global climate change challenge will require a shift towards sustainable energy sources for producing steel. Central to achieving this objective will be the scale-up of renewable energy use in the sector.

Action is needed in several areas, including policies and regulations, technology development, finance, skill and capacity development, and business innovation. Table 5 offers an overview of these areas, key recommended actions and key stakeholders expected to take a leadership role. Table 6 provides an overview of more detailed short- and long-term actions that different actors can potentially pursue for a more circular steel sector. The short-term actions can help build momentum and support longer-term actions by showing the benefits of the circular economy, whereas the long-term measures can help establish a clear vision for the future of the circular industry.

Table 5 Main areas of action for a circular steel industry

	RECOMMENDATIONS	MAJOR BARRIERS ADDRESSED	LEADERSHIP ROLE
Policies and regulations	Developing regulatory and legal frameworks (push) and clear incentive structures aligned towards circularity (pull)	Uncertainty in investments. Cost barriers to the adoption of circular economy measures. Absence of data, standards and monitoring programmes. Absence of incentives for energy efficiency or incentives that do not align with energy conservation goals.	Government
Technology development	Moving towards environmentally sustainable production routes	Lack of renewable H_2-DRI production capacity. Labour- and cost-intensive scrap collection and sorting processes.	Steel industry, hydrogen and renewable energy industry, government
Finance	Designing financial programmes specific to the needs of each circular economy lever	Access to (international) finance for energy efficiency; research, development and demonstration; infrastructure; and renewable H_2-DRI.	Government and financial institutions
Skill and capacity development	Re-training and capacity building	Knowledge gap between current and best available technologies. Lack of awareness and capacity building for designing and/or implementing circular economy measures.	Government and steel industry
Business innovation	Reorienting existing supply chains and forging new supply chains, business models and technology integrations	Scrap recovery and recycling losses. Inefficient design and use of steel products. Inefficiencies in steel products throughout their value chains. Missing actors in the scrap collection supply chain.	Government; Steel industry

Note: H_2-DRI = hydrogen-based direct reduced iron.

Table 6 Role of different stakeholders in a circular steel economy

CIRCULAR ECONOMY PILLARS	HORIZON	ACTORS AND TARGETED ACTIONS			
		NATIONAL AND SUBNATIONAL GOVERNMENTS (POLICY OPTIONS)	INTERNATIONAL PARTNERS	STEEL PRODUCERS AND PRODUCT DEVELOPERS	FINANCIAL ACTORS
Reduce steel demand through increased material efficiency	Short term	🟠 Mandates, standards and targets aimed at producers 🟠 Preferential policies aimed at consumers 🟠 Standardising life cycle assessment (LCA) nationally	🔵 Knowledge sharing 🔵 Co-ordination for international standardisation of LCAs	🟣 Lightweighting, modular designs, among others 🟣 LCA of embodied emissions of products 🟣 Slag recycling for other industries 🟣 Improve the reporting of material use	
Maximise the potential of recycled steel	Short term	🟠 Price- or quantity-based policy 🟠 Regulating landfills 🟠 Declassification of scrap as waste 🟠 Public provision of separated recycling 🟠 Extended producer responsibility 🟠 Criteria for the public procurement of recycled content 🟠 National scrap inventories for improving scrap management and trade 🟠 Scale-up of low-carbon steel markets 🟠 Regulatory mechanisms	🔵 Capacity building on best practices for industry 🔵 Facilitate dialogue for removing trade barriers	🟣 Improve scrap supply chains to collect and sort scrap 🟣 Increase data gathering for scrap consumption and generation 🔴 Use technology to identify and remove contaminants	🟢 Invest in scrap collection and sorting infrastructure

🟠 Policies and regulations 🔴 Technology development 🟢 Finance 🔵 Skill and capacity development 🟣 Business Innovation

Table 6 (continued)

CIRCULAR ECONOMY PILLARS	HORIZON	ACTORS AND TARGETED ACTIONS			
		NATIONAL AND SUBNATIONAL GOVERNMENTS (POLICY OPTIONS)	INTERNATIONAL PARTNERS	STEEL PRODUCERS AND PRODUCT DEVELOPERS	FINANCIAL ACTORS
Improve process efficiency in steel production	Short term	🟠 Regulatory mechanisms to encourage retrofit 🟠 Scale-up of low-carbon steel markets 🟠 Phasing out fossil fuel subsidies 🟢 Financial incentives to encourage efficient equipment and retirement of inefficient assets	🔵 Capacity building for industry and financial actors to prioritise energy efficiency 🟢 Lending to government for energy efficiency funds and de-risking investments	🟣 Energy audits to identify efficiency opportunities 🟣 Implementing energy efficiency retrofits	🟢 Support mechanism to lower barriers to access to finance
Renewable H_2-based steelmaking	Medium to long term	🟠 Grants for research and development and funding for demonstration projects 🟠 Scale-up of low-carbon steel markets 🟠 Capacity building and training for operations 🟠 Acceleration of permitting processes for renewable energy projects and related infrastructure 🟢 Public sector finance for the development of new infrastructure and upgrading existing assets 🟢 Financial support for first-of-a-kind projects 🔵 Co-ordinate domestic and international innovation and collaboration efforts	🔵 Capacity building for regulations and technical capacity building 🔵 Lending mechanisms for low- and net-zero-carbon steel plants 🟢 De-risking investments	🔴 Undertake research, development and demonstration projects 🟠 Engage with government in developing policies for support and regulatory certainty 🟢 Using corporate finance for project development 🟣 Adhering to standards and certifications for low-carbon steel	🟠 Develop taxonomies to encourage climate-friendly investments, credit guarantees 🟢 Financing for variable renewable energy projects and grid upgrades

🟠 Policies and regulations 🔴 Technology development 🟢 Finance 🔵 Skill and capacity development 🟣 Business Innovation

3.3 RECOMMENDED AREAS FOR INTERNATIONAL CO-OPERATION

Global transformation of the steel sector will not only require action at the national level – which is fundamental – but also international dialogue and co-operation in the G20, which will be key in advancing progress aligned with all pillars of circularity.

Iron and steel is a global industry. Steel is produced in substantial quantities in about 90 countries and consumed all over the world. The G20 countries, which are the world's largest economies, produce about 85% of the world's steel and are responsible for consuming about 80% of it. Co-ordinated action by the G20 countries can address the challenges and opportunities of the sector, enabling its transition towards a more circular steel industry.

In terms of material efficiency, blueprints exist for the smarter, more optimal use of steel in key consuming sectors such as construction and automobile production. National regulatory frameworks can act as drivers for the more efficient use of steel.

- **Recommended collaboration area:** Co-operation in the G20, to identify and scale best practices in the major steel-consuming sectors, through mutual learning and exchange of regulatory experience, can contribute to the more efficient use of steel worldwide.

  Steel scrap recycling is at the core of a shift towards greater circularity in the steel sector. But the availability of scrap is a limiting factor, since steel products have long lifespans. About 30% of the steel produced today comes from recycling scrap.

  The role of steel recycling will continue to grow over time as more scrap becomes available in emerging economies, resulting in larger shares of recycled steel, and thereby progressively reducing the need for primary production. By 2050, about half of the world's steel production could come from recycled scrap.

  National governments can make a difference by adopting and enforcing regulations that ensure environmentally sound and thorough steel scrap collection and sorting processes. Adopting such good practices in the recovery of end-of-life steel products is also crucial to minimise scrap's contamination by other materials, for example, copper, thereby enabling the use of scrap as input for higher-quality steel specifications.

- **Recommended collaboration area:** Dialogue and co-operation in the G20 can contribute towards removing the barriers to international scrap trade, allowing scrap to be transported and used where it creates the most economic and environmental value.

  A more circular and sustainable steel sector can also be achieved through making steel production processes more efficient, with widespread adoption of the best available technologies across the G20.

- **Recommended collaboration area:** G20 members can facilitate the exchange of best practices among national policy makers and regulators. These discussions may focus on preventing market distortions that disincentivise investments in energy efficiency projects. Implementing best practices can make the industry more competitive and provide sufficient incentives to invest in improving efficiency in domestic steel industries.

  A shift from fossil-fuel-based steel to renewables-based steel will be crucial in a transition towards a more sustainable iron and steel sector. Renewables already supply a substantial fraction of the power used for secondary steel production in EAFs today. However, primary steel production, which accounts for about 70% of global steel output, still relies almost exclusively on fossil fuels.

  A transition towards renewables-based steel will require decisive policy support at the early stages of technology adoption. Policy action at the national level can help create the conditions for investment by defining roadmaps for the sector's transformation, and the adoption of supporting measures. However, since steel is an internationally traded commodity, multilateral co-ordination will be vital.

- **Recommended collaboration area:** G20 members can accelerate a transition towards renewables-based steel by co-operating in several areas, including dialogue towards internationally agreed definitions, standards and certifications for low-carbon steel; initial demand creation through multilateral public procurement commitments; knowledge exchange on technology research and development and professional skills needed for the transition; technical and financial assistance to developing countries, among others.

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APPENDICES

APPENDIX 1: STEEL SCRAP AVAILABILITY PROJECTIONS

Figure 12 presents a range of estimates of future steel scrap availability. These estimates, as well as the sources, are presented in Table A1.1. The scrap availability figures represent the sum of home, prompt and end-of-life scrap.[7]

Table A1.1 Scrap availability: An overview of estimates from literature

MILLION TONNES[a]	2020	2030	2050
Xylia *et al.*, 2018	770	1 000	1 550
WSA, 2018a	800	1 100	1 320
Gauffin, 2015	870	1 050	1 350
IEA,[b] 2020 STEPS	865	-	1 480
IEA, 2020 SDS	865	-	1 250

Notes: [a] It is worth highlighting that the values represent scrap generated at different levels of steel demand, and they include the impact of material efficiency measures.

[b] International Energy Agency scrap numbers reflect 2019 values and not 2020 values.

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[7] *Home scrap refers to the scrap generated during the steel production and downstream processes. Prompt scrap is generated during the production of steel products. Home and prompt scrap are high-quality forms of scrap with known compositions. Old scrap (or post-consumer scrap) is generated at the end of a steel product's life.*

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