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Review

Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options

Jinsoo Kim [a,*], Benjamin K. Sovacool [b,c,**], Morgan Bazilian [d], Steve Griffiths [e], Junghwan Lee [a], Minyoung Yang [a], Jordy Lee [d]

[a] Department of Earth Resources and Environmental Engineering, Hanyang University, Republic of Korea
[b] Science Policy Research Unit (SPRU), University of Sussex Business School, United Kingdom
[c] Center for Energy Technologies, Department of Business Development and Technology, Aarhus University, Denmark
[d] Colorado School of Mines, CO, United States
[e] Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates

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ABSTRACT

The iron and steel industry is the largest coal consumer and the most greenhouse gas intensive industry. It consumes about 7% of global energy supply, and conservative estimates report that it is responsible for 7–9% of global greenhouse gas emissions. Decarbonization of the iron and steel industry is thus vital to meet climate change mitigation targets and achieve a sustainable future for the industry. This paper presents a comprehensive and systematic review that considered more than 1.6 million pieces of literature and analyzes in depth a shortlist of 271 studies on the iron and steel industry's decarbonization. Applying a sociotechnical lens that investigates raw materials, iron and steel making processes, steel products making and usage, and waste and recycling, the review identifies the climate footprint of the iron and steel industry. The review also assesses current and emerging practices for decarbonization, identifying 86 potentially transformative technologies. The benefits of decarbonizing the iron and steel industry are considered through energy and carbon savings, financial savings, and other environmental and public health benefits. Barriers to decarbonization are considered across financial, organizational, and behavioral aspects. The review also discusses various financial tools and policy instruments that can help overcome the barriers. Lastly, research gaps are outlined.

1. Introduction

Modern life is surrounded by iron and steel. Buildings, skyscrapers, bridges, power transmission towers, airplanes, vehicles, and ships all use significant amounts of iron and steel in their construction. As a result, iron and steel demand has increased more than threefold since 1970, and accounts for 95% of all metal produced annually in the world [1]. Iron and steel are also an essential ingredient for energy transitions and decarbonization. Renewable energy sources such as wind turbines are 71–79% steel, and solar panels, geothermal plants, and electric vehicles also depend heavily on iron and steel products.

As steel is essential for modern economies and developing technologies, steel demand is expected to grow substantially in the coming years due to its direct relationship to population, GDP growth, and overall industrialization [2]. Economic expansion of emerging economies in India, ASEAN countries, and Africa will add to the demand trends already exhibited by the US, Europe, and China. Iron and steel production will therefore play an essential role in ensuring that billions of people will be able to improve their quality of life in the coming decades.

In the manufacturing of these essential goods, iron and steel, necessitates huge energy inputs. As Fig. 1 indicates, the iron and steel sector used 33.57 Exajoules of energy in 2018 [3], and energy cost constitutes a significant portion of steel manufacturing costs, ranging from 20% to 40% [4], which explains why many decarbonization options are related to energy saving. Critically, the iron and steel industry is the second largest consumer of coal, next to electricity generations. Coking coal is used for chemical reactions in furnaces to make steel from iron ore, so up to 75% of the energy content used in steel production is consumed in the blast furnace. The remaining 25% offers heat at the sinter and coking plants [5].

* Corresponding author.
** Correspondence to: B.K. Sovacool, Science Policy Research Unit (SPRU), University of Sussex Business School, United Kingdom.
E-mail addresses: jinsookim@hanyang.ac.kr (J. Kim), B.Sovacool@sussex.ac.uk (B.K. Sovacool).

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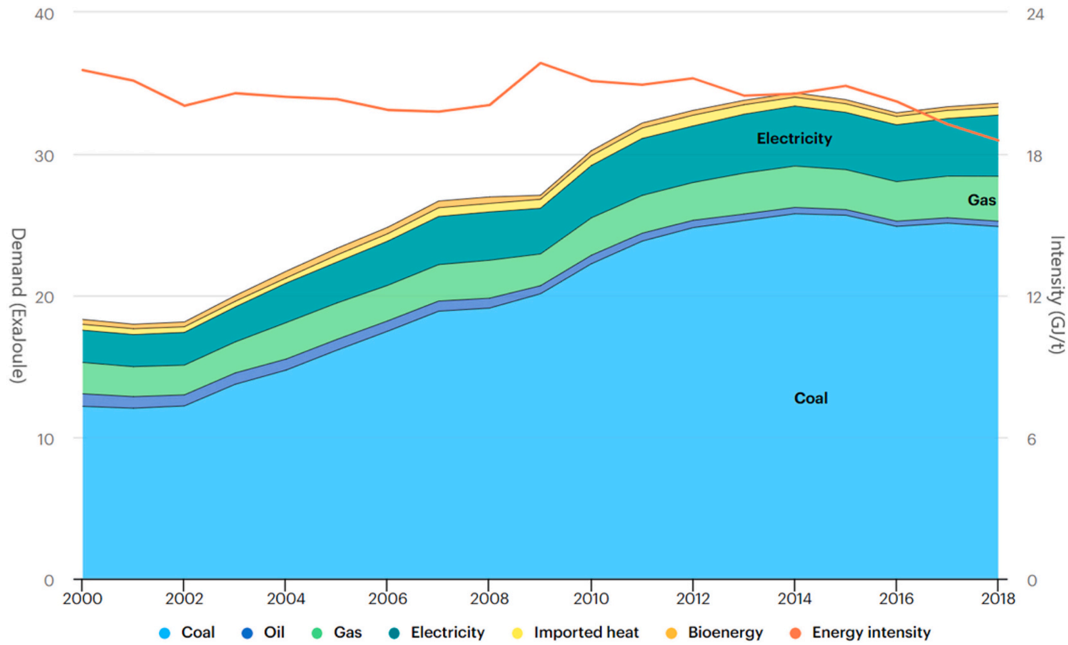

Fig. 1. Energy demand and intensity of the global iron and steel industry (2000–2018).
Source: [3].

Thus, it is perhaps inevitable that the iron and steel industry is highly responsible for global greenhouse gases (GHGs) emissions and thus contributions to climate change. The iron and steel sector emits 2.6 Gt CO_2e annually, which is 7% of the global emissions from the energy use and 7–9% of global anthropogenic CO_2 emissions—the highest among heavy industries [6].

Iron and steel are also considered as one of hardest industries to decarbonize due to high heat requirements, using carbon as a process input, low profit margins, high capital intensity, long asset life, and trade challenges. There are no easy ways to create large amounts of heat energy for many iron and steel processes without also releasing CO_2 emissions, and coal is often used both as a source of heat and as part of the production processes. Similarly, the decades-long life cycles of iron and steel plants, the lack of clear financial incentives for decarbonization, and price volatility make it difficult to incorporate carbon reducing technologies.

Many institutions, such as the International Energy Agency (IEA) [6], European Steel Association [7], Lawrence Berkeley National Laboratory [8], Boston Consulting Group [9], and WSP and Parsons Brinckerhoff/DNV GL [10], have published carbon mitigation options and technology roadmaps for the industry's decarbonization.

When outlining their 2020 technology roadmap towards more sustainable steelmaking, the IEA suggested four core technology groups; carbon capture, utilization and storage (CCUS), hydrogen, direct electrification, and bioenergy [6]. Hydrogen would be effective for CO_2 mitigation in various iron and steel processes, such as BF (blast furnace), DRI (direct reduced iron), smelting reduction, and ancillary procedures [11,12]. Electrolysis [13], torrefied biomass [14], and charcoal [15] are also good options for the decarbonization of steelmaking processes.

Because of the iron and steel industry's energy-intensive nature, pursuing efficiency and energy-saving has been the top priority of the industry. Unfortunately, the iron and steel industry's potential for decarbonization is through process efficiency alone is limited since current iron and steelmaking processes have been efficiently operated (from an industry standpoint) close to their thermodynamic limits [9,16]. Thus, it is quite natural that there is only a small room to improve energy efficiency and related decarbonization. Moreover, Chinese blast furnaces, which account for over 50% of all ironmaking facilities, are heavily reliant on CO_2-intensive coal electricity and are relatively young, around 12 years old on average [6], so replacing them with more efficient equipment is not economical.

The combination of iron and steel's importance in modern society and the difficult of decarbonizing steel supply chains necessitate a comprehensive review of decarbonization efforts within the iron and steel industry through a systematic review and rigorous interdisciplinary approach. It asks: Which options are available and promising for the decarbonization of the iron and steel industry, and thus make the industry more climatically sustainable? What are the key factors of the industry's energy consumption and GHG footprints? What are the benefits from the decarbonization of the iron and steel industry, and what barriers will be faced? To answer these questions, we undertake a critical, in-depth review of 269 studies shortlisted from more than 1.6 million studies on the topic of iron and steel decarbonization. Based on the review results, we propose a new sociotechnical lens to examine the industry's decarbonization options—raw materials, iron and steel making processes, steel products manufacture, recycling, and use—, and identify promising innovations, benefits, barriers, policy options, and future agendas using this lens.

Although there are insightful reviews for the decarbonization of the iron and steel industry, focusing on energy saving [17], blast furnace [18], and specific projects [19], for example, the systematic search and critical review process presented in Section 3 make our review more comprehensive. Moreover, the sociotechnical lens can provide an organized perspective of the promising decarbonization options for the whole value chain of the industry and related society. Thus, our review can contribute to the literature by providing an informative review framework and extensive decarbonization innovations.

Also, our review results identify that many effective decarbonization options across the four sociotechnical systems can make the iron and steel industry carbon-neutral and sustainable. In particular, 86 emerging breakthroughs and transformative innovations (Section 5.5) and cross-cutting solutions (Table 10 and Fig. 26) have great potential for the low carbon future of iron and steel production. Still, there are economical, organizational, and behavioral barriers (Section 7) to iron and steel decarbonization despite being technologically feasible and having substantial benefits (Section 6). We conclude our review by showing the interventions, benefits, barriers, and policies for decarbonizing the iron and steel system in a single figure (Fig. 30).

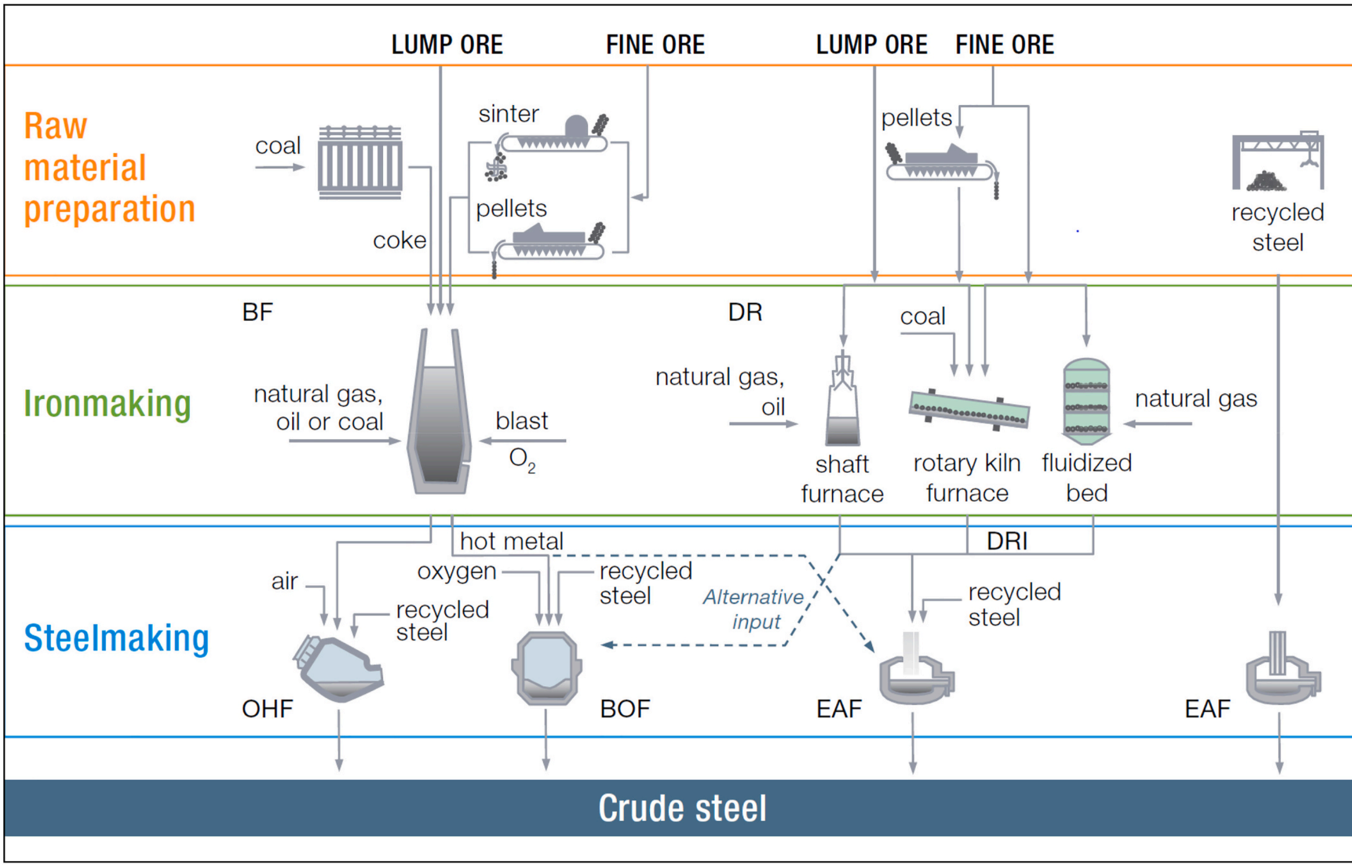

Fig. 2. Iron and steelmaking routes.
Source: [5]. Note: BF is blast furnace, DR is direct reduction, BOF is basic oxygen furnace, EAF is electric arc furnace, OHF is open hearth furnace, and DRI is direct reduced iron.

Table 1
Crude steel production by route (major steel producing counties, 2018).

Country	Production (million tonnes)				% of total production			
	BOF	EAF	OHF	Total	BOF	EAF	OHF	Total
China	893.3	103.2		996.5	89.6	10.4		100
India	48.7	62.7		111.4	43.7	56.3		100
Japan	75.0	24.3		99.3	75.5	24.5		100
USA	26.6	61.2		87.8	30.3	69.7		100
Russia	45.9	24.1	1.7	71.7	64.0	33.7	2.3	100
South Korea	48.7	22.7		71.4	68.2	31.8		100
Germany	27.7	11.9		39.6	70.0	30.0		100
Total	1165.9	310.1	1.7	1477.7	78.9	21.0	0.1	100

Source: Compiled by the authors from [22]. Note: BOF, EAF, and OHF are basic oxygen furnace, electric arc furnace, and open-hearth furnace, respectively.

Section 2 provides background for the iron and steel industry, while Section 3 summarizes the research design for a systematic literature review. Section 4 depicts energy and emission profiles, and Section 5 examines promising decarbonization options. Section 6 describes the benefits in three categories, and Sections 7 and 8 discuss barriers and policy instruments. Section 9 presents research gaps and future agendas, and Section 10 concludes.

2. Definitions and attributes of the iron and steel industry

2.1. Definitions and terms

Modern steelmaking procedures can be divided into four routes: blast furnace/basic oxygen furnace (BF/BOF), electric arc furnace (EAF, direct reduction), smelting reduction, and direct melting of scrap in an EAF [8,20]. BF/BOF accounted for about 65% of the world steel production in 2010, and the EAF route accounted for about 30% in 2010 [8]. In Europe, 58.3% of steel was produced by the BF/BOF, whereas 41.7% were from the EAF [21]. Fig. 2 shows simplified iron and steelmaking routes, and Table 1 presents crude steel production by the route.

Our review covers the iron and steel industry from raw materials to waste/recycling of steel products. It does not examine the mining industry for iron ore, coking coal, or alloying elements required for steel production. Although the overall GHG emissions from mining industries have little attention than the other heavy industries [23], there could be effective options to mitigate carbon emissions, such as clean haul truck powertrain technologies, shovel operator efficiency improvements, and high-pressure grinding rolls technology for iron mining. One study reported that applying these decarbonization technologies can reduce 10% of the total cumulative GHG emissions from the Canadian iron

Table 2
Overview of the iron and steel making processes.

Process	Sub-components	Description
Raw material preparation	Sintering	Sintering is a combustion process with a mixture of iron ore fines, iron-bearing wastes, and coke dust. In a blast furnace (BF), the mixture is converted into coarse lumps (sinter) through incipient fusion.
	Pelletizing	For the iron-rich ore preparation, the iron ore must be crushed and grounded to remove impurities in the pelletizing process. After removing impurities, the iron-rich ore is mixed with a binding agent, and heating them makes durable marble-sized pellets. We can use these pallets in both BFs and direct reduction.
	Coke Making	Coke, made by the thermal distillation process of coal at high temperatures without air, has a high carbon content. Coke is a fuel in a BF, while provides a reducing atmosphere.
Ironmaking	Blast Furnace (BF)	Iron ore, coke, and limestone are fed into the top of a giant shaft furnace, blast furnace. The materials constitute “alternating layers” in the BF supported by an intense coke bed. Iron is refined in the BF by the following processes: Hot air passes through the porous bed from the furnace's bottom to the top, and the air ignites the coke, which produces additional heat and carbon monoxide (CO) gas. The high heat melts the materials, and the CO gas eliminates the iron ore's oxygen, making hot metal. The hot metal, flowing to the bottom of the BF, is regularly tapped, and transported to the basic oxygen furnace, and then refined into steel.
	Direct Reduction	Direct reduction is the process that removes oxygen from solid-state iron ore. Natural gas and coal are common reducing agents, but different reducing agents, feedstocks, and furnaces could be utilized for direct reduction. Direct reduced iron (DRI) is the end-product of this process.
	Smelting Reduction	As an alternative to the BF, smelting reduction iron (SRI) produces liquid iron. SRI can also reduce energy-intensive materials such as coke and sinter. Instead, smelting reduction is aimed at using coal and iron fines. COREX, FINEX, and ITmk3 are representative examples of SRI.
Steelmaking	Basic Oxygen Furnace (BOF)	The transported hot liquid metal from the BF is converted into steel in the BOF. Oxygen is added to eliminate carbon from the hot liquid metal in the process. There are extensive metallurgical processes for BOF to improve steel quality.
	Electric Arc Furnace (EAF)	When producing steel from DRI, pig iron, or ferrous scraps (recycling), an electric arc furnace (EAF) is mainly applied. Carbon electrodes in the furnace roof move up and down to provide the necessary energy in the EAF. The EAF consumes much lower energy (electricity) than the other processes since the energy-intensive iron ore reduction is not required. The EAF can also be utilized for various scrap types.
Casting, Rolling, and Finishing		The crude, molten steel from BOFs or EAFs is transferred to the (continuous) caster and formed into semi-finished steel. In rolling or finishing mills, this semi-finished steel is processed into final steel products, such as coil, sheets, or strips (see Fig. 3).

Source: Authors compilation and modification from [6,8,20].

mining industry for 2018–2050 [24].

Table 2 offers an overview of the four classifications of iron and steel production and their sub-components.

The “crude steel” in Fig. 2 is the steel in its first solid form after casting in the final furnace—BF or EAF. As shown in Fig. 3, liquid steel is commonly continuously cast into slabs (semi-finished steel products cut into various lengths, flat products), billets (semi-finished steel products with a square cross section up to 155 mm × 155 mm), and blooms (semi-finished steel products with a square cross section above 155 mm × 155 mm) [25]. These semi-finished products may be transported to other sites for further processing, or converted to finished steel products in processing plants, often in a separate facility or company. Conversion to finished products can involve various processes such as rolling, forming, pressing, cutting and bending, with some finished products requiring more steps than others (for example, successive rounds of rolling—hot and cold—and coating). Key finished products include coil, sheets, strips, wire, bars, rods, tubes, pipes, rail and plated/coated versions of each of these products [6].

2.2. Industry revenues and structure

The iron and steel sector is a globally extensive, and massive socio-technical system with a significant impact on our modern life. It directly employs more than six million people and engages a total of 40 million indirect jobs if counting supportive positions throughout the whole supply chain [27,28] with 5.8– 7.9 multipliers for jobs [29]. The iron and steel industry generates about $2.5 trillion in global revenue, which is 3.0% of global Gross Domestic Product [6]. Also, steel products are one of the most widely traded commodities in the global market. Fig. 4 depicts steel production by product and demand segment, indicating that buildings and infrastructure account for about half of steel demand [6].

As presented in Table 1, China accounts for over 53% of the world steel production, followed by India, Japan, the USA, Russia, South Korea, and Germany. The top seven producer countries account for about 79% of global production [22]. Fig. 5 illustrates existing iron and steel making infrastructure by production route and region. This China-dominated production split is a natural result of the fact that over 50% of the existing production equipment is in China, followed by India at around 5%. Fig. 5 also depicts the average age of iron and steelmaking equipment, and shows that Chinese blast furnaces, which account for over 50% of all facilities, are relatively young at around 12 years on average [6]. This is because the expansion of the iron and steel industry in China began around 20 years ago, and thus replacing the furnaces and equipment with new, efficient equipment would not be economically viable.

2.3. Distinguishing attributes

Apart from its energy and carbon intensive nature, the iron and steel industry is distinguished from other industries by four features. It is a consolidated industry, produces intermediate goods for other sectors, has a high recycling rate, and needs high temperatures compared to the other manufacturing industries, including primary metals [30].

The iron and steel industry has economies of scale that often require consolidation and agglomeration [10,31]. This increasing returns to scale attribute makes the industry consolidated. Consequently, most iron and steel is coming from only a few players/countries, as shown in Fig. 5. The top 50 companies in the industry produced 58.5% of crude steel (1060.2 million tons) in 2019 [32].

Typically, end-users do not consume the iron and steel products—-crude steel, slab, billet, or bloom—directly. These steel products are supplied to automobile, shipbuilding, plant, pipeline, and building and construction sectors as intermediate goods. Therefore, the iron and steel industry's decarbonization has great potential to reduce indirect emissions from those other industries [33,34].

A high recycling rate is another distinguishing attribute of the iron and steel industry [35–37]. According to World Steel Association [38],

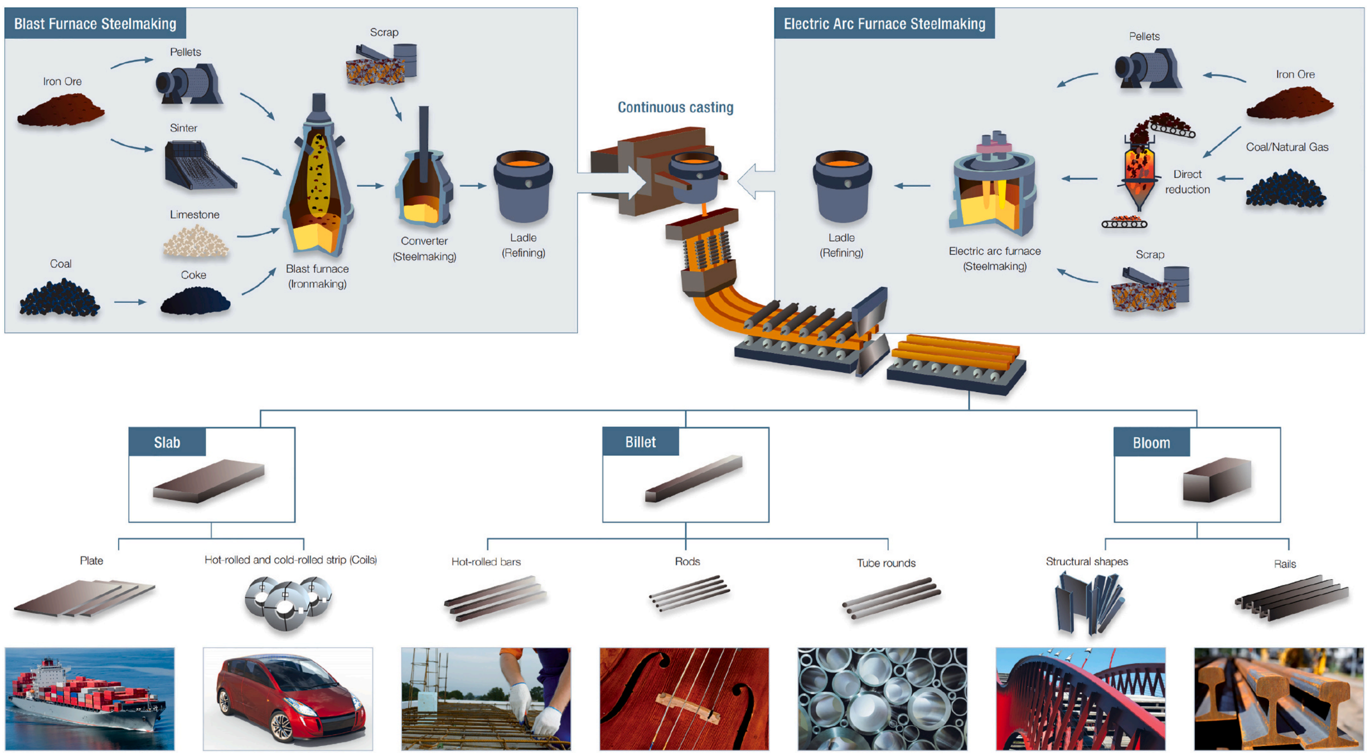

Fig. 3. Iron and steelmaking routes.
Source: [26].

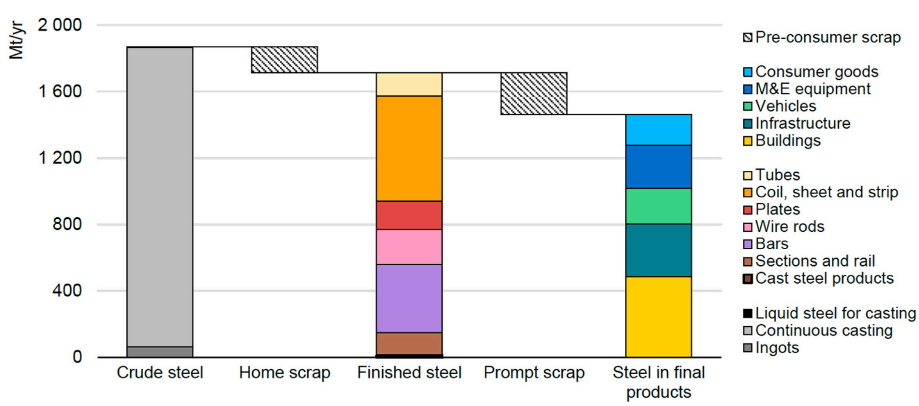

Fig. 4. Global steel production by product and demand segment in 2019.
Source: [6].

the recovery rates of steel are estimated at around 90% for automotive and machinery, 85% for construction, and 50% for electrical and domestic appliances, globally. In the U.S., for example, 33.1% of steel wastes (70.9% of steel cans) were recycled, which is third after paper and paperboard (68.2%) and other nonferrous metals (67.3%, including lead) in municipal wastes [39]. This high recycling rate can yield various benefits in terms of economy and environment, and we will visit this issue in Chapter 6.

Lastly, the industry needs very high temperatures, unlike those industries that use low-grade heat, such as machinery or electrical manufacturing. From Raw Material Preparation to Casting, Rolling, and Finishing, all processes require very high temperatures. For example, a low-temperature in sintering means "lower than 1,300 °C," [40] and BOF and EAF are generally operated around 1500– 1600 °C [41]. This attribute makes the iron and steel industry energy- and carbon-intensive, resulting in it being the most carbon-emitting among industries.

3. Research design and conceptual approach for a sociotechnical review

3.1. *Critical and systematic review approach*

Similar to our previous review for the decarbonization of food and beverages [42] and F-gases [43], we characterize this review as critical and systematic. A critical review aims to demonstrate that a "research team has extensively scoured the literature and critically evaluated its quality." [44]. We've made this review systematic, following the guidelines from [45,46]. A critical review includes evaluation of pieces of evidence quality and research gaps derived from the literature. It offers [42]:

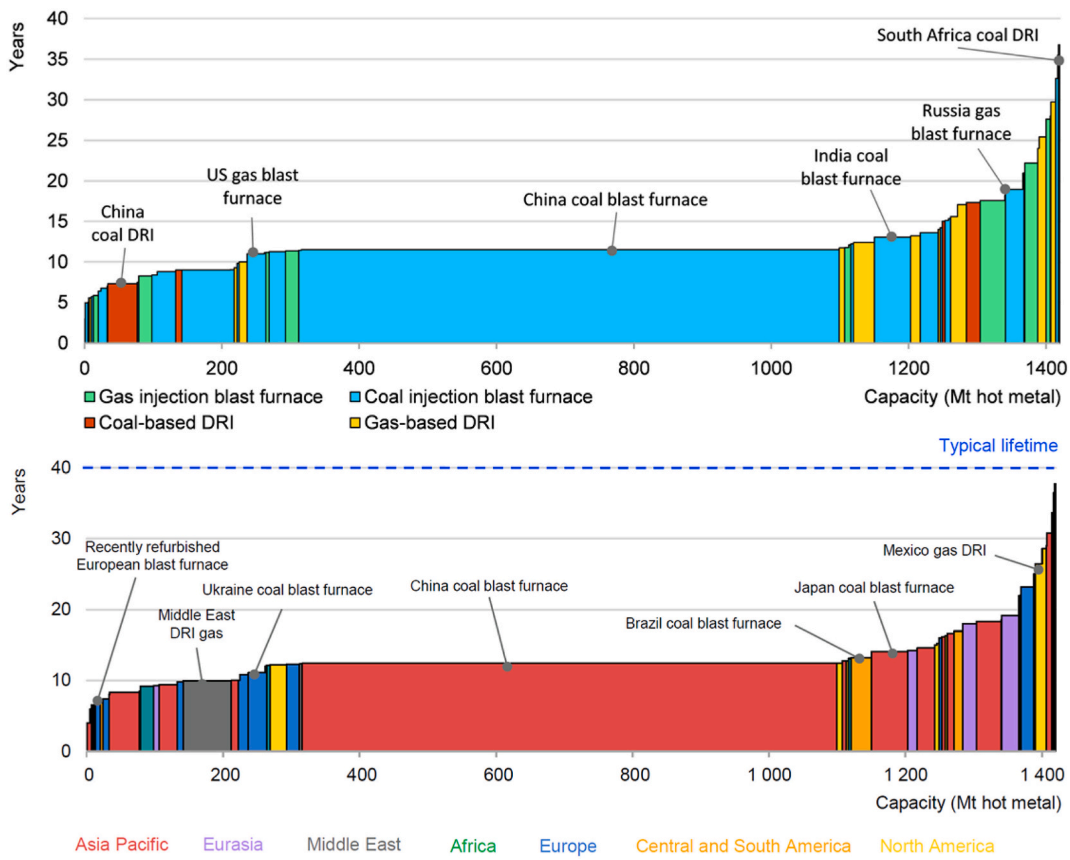

Fig. 5. Geographic distribution and the average age of iron and steel making equipment by production routes (top panel) and regions (bottom panel).
Source: [6].

- *a chance to "take stock" and evaluate what is of value within a given field, or across varying bodies of evidence, in relation to a particular topic or research question;*
- *both a "launch pad" for conceptual novelty, as well as an empirical "testing" ground to judge the strength of evidence.*

Unfortunately, a critical review is not necessarily systematic. That is why we try to make our review systematic as well as critical. A systematic approach can minimize any unintentional bias, such as self-citations or reviewing only for friendly groups, while promoting a review's diversity. It also offers [43]:

- *a focused exploration, which avoids excessively wide-ranging discussion and inconclusive results;*
- *the avoidance of the selective and opportunistic selection of evidence;*
- *replicability through the documenting of study inclusion;*
- *the ability to discriminate between sound and unsound studies, thus assessing methodological quality; and*
- *increased transparency, which reduces subjectivity and bias in the reporting of results.*

For these reasons, the systematic review has also been widely applied in energy, environmental, and climate change fields [47,48]. As introduced in the following subsections, we developed a searching protocol,

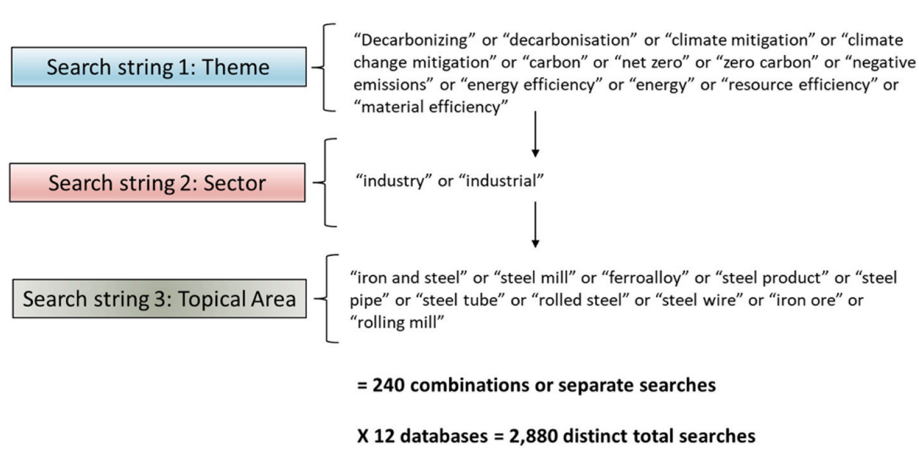

Fig. 6. Summary of critical and systematic review search terms and parameters.
Source: Authors.

Table 3
Summary of critical and systematic review search results and final documents.

Database	Main topical area of database	Initial search results	Deemed relevant after screening titles, keywords and abstracts	Deemed relevant after scanning full study	Number of duplications	Total
ScienceDirect	General science, energy studies, geography, business studies	139,812	344	128	–	128
JSTOR	Social science	21,204	22	12	0	12
Project Muse	Social science	20,129	7	3	0	3
Hein Online	Law and legal studies	28,766	30	9	0	9
PubMed	Medicine and life sciences	1000	29	12	5	7
SpringerLink	General science, business and area studies	106,534	62	38	1	37
Taylor & Francis Online	General science	27,726	24	14	0	14
Wiley Blackwell (Wiley Online Library)	General science, area studies	33,448	26	15	0	15
Sage Journals	General science, area studies	5079	8	2	0	2
National Academies Publications (nap.edu)	General science	383,167	6	3	0	3
Targeted internet searches	White papers, reports, grey literature (e.g., International Energy Agency, International Renewable Energy Agency, World Bank, UN agencies, and the online OECD library)	48,588	41	28	0	28
Google scholar	General science	837,257	148	34	21	13
Total		1,652,708	745	296	27	271

Source: Authors.

analytical parameters, and an analytical frame of sociotechnical systems to keep our review systematic and critical.

3.2. Searching protocol and analytical parameters

As Fig. 6 summarizes, we utilized three explicit classes of search terms for the critical and systematic review. This resulted in 240 distinct search combinations for twelve separate databases or repositories produce 2880 search strings in total. This systematic search protocol can capture state-of-the-art research in terms of academic and policy.

Table 3 displays our results. Since the "iron and steel" with "industry" and "carbon" is a widespread word in academic or policy articles, the generic search result is counted in more than 1.6 million potentially relevant documents. However, after applying three screening protocols, which are identical to our previous review [42,43], that enormous number fell into a shortlist of 271 studies. The three screening protocols are Recency (published after 2000), Relevance (address the specific topics of decarbonization), and Originality (results after eliminating duplicates). We cite many of these studies throughout the review.

3.3. Analytical frame of sociotechnical systems

The analytical frame of sociotechnical systems is applied for those 271 final studies to help guide and structure the review results [49,50].

Although a sociotechnical system for the iron and steel industry would be less complicated than the other sectors for consumer goods, such as food and beverages [42] and glass [citation, if possible], it includes not only iron and steelmaking processes, including material preparation, but also raw materials such as iron ore and coal, waste and recycling, and even the ways of steel use and regulations, including efficiency and safety (see Fig. 7). To be clear, Fig. 7 visualizes elements of the system in a non-hierarchical way. That is, we do not argue that each dimension of the system is on the same level, but they are all a part of the system in some way.

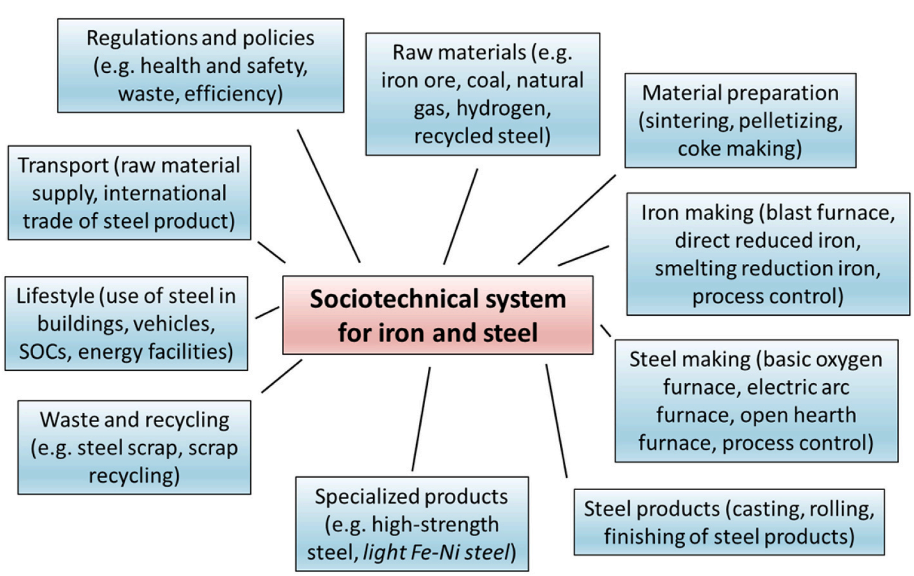

Fig. 7. Framing iron and steel as a sociotechnical system.
Source: Authors.

Table 4
Final energy use in iron and steel making in 2015.

Source	Energy use (EJ/year)	Share (%)
Coking coal and coke	24.1	70.0
Other coal	6.1	17.6
Blast furnace gas and coke oven gas	−3.3	−9.6
Natural gas	2.3	6.7
Oil	0.4	1.2
Biomass	0.1	0.4
Electricity	4.0	11.8
Heat	0.6	1.9
Total	34.4	100.0

Source: [52,53]. Note: Negative energy use represents recovered energy in the iron and steel making processes.

Although not all studies in our sample fall under this rubric of a sociotechnical system, we utilize it throughout the study to organize results and return to it in the conclusion.

4. The energy and climate impacts of iron and steel industry

In 2020, the IEA projected global steel demand will increase by more than a third by 2050, particularly as emerging economies continue to grow, industrialize, and require more energy [6]. The COVID-19 pandemic gives a demand shock in the iron and steel industry, resulting in 5% decrease in global crude steel output in 2020 [6] (see Section 9.3 for more discussions). However, the steel industry is also projected to return to a robust growth path in IEA [6]'s baseline projections after overcoming the demand slump in the near term. Thus, without adequate measures and innovations to reduce GHG emissions from the industry, the emissions are projected to 2.7 Gt CO_2 per year by 2050, which is 7% higher than today [6].

4.1. Energy and carbon intensive processes in the iron and steel sector

When investigating the industry's climate impacts, describing the energy-intensive processes in the industry is the first and efficient way for a review. The iron and steel industry emits GHGs from raw materials and processes, combustion sources, and indirect emissions, such as electricity consumption in EAFs [51]. Table 4 shows the share of each energy source in iron and steel making processes.

The primary sources of CO_2 emissions in the iron and steel making processes are raw materials, including cokes, and fuel combustion. Ovens, boilers, stoves, furnaces, and other miscellaneous equipment in the processes from the sintering to the final steel product manufacturing in Table 2 can be CO_2 emissions sources. Fig. 8 depicts the profile of CO_2 emissions in a typical BF/BOF integrated steel plant. Among 1.8 t CO_2 emissions per ton of rolled coil in a typical integrated steel plant, 1.7 t CO_2 is associated with coal use, and the remaining 0.1 t CO_2 is responsible for lime use [8].

Three reasons make the DRI carbon content critical when used in an electric arc furnace: 1) the presence of carbon is necessary to complete the metallization of the iron in the EAF, 2) carbon represents an additional source of energy in the EAF because burning the carbon by injecting oxygen reduces the electricity consumption, consequently enabling a faster melting of the charged materials, 3) carbon enables the formation of a foamy slag in the EAF [15].

4.2. Estimating greenhouse gas emissions

The most of carbon footprints in the iron and steel industry are energy-related emissions. The IEA predicted the iron and steel industry would account for about 25–30% of direct industrial carbon emissions by 2050, even in the IEA Sustainable Development Scenario in which the GHG emissions of the iron and steel sector are reduced by 54% by 2050. As presented in the right side of Fig. 9, Asia Pacific is the key region because of this dramatic reduction of carbon emissions [6].

Our review finds many articles assessing country-specific GHG emissions in the iron and steel sectors. For example, one study revealed direct and indirect GHG emissions in the Chinese iron and steel industry using the Material Flow Analysis. The work showed that China emitted 77.2% of GHG emissions directly in 2011, and most of them were coal-fired emissions (Fig. 10).

Other studies examined the CO_2 emissions projections of the iron and steel sector for the UK perspective [56,57], Japan's pathways towards 2030 [58], China with carbon audit evaluation [59], Thailand by 2050 [60], Europe considering future scenarios on energy efficiency [61], Taiwan [62], or even for global projections [63,64]. Recent estimation of GHG emissions from Chinese stainless steel production shows 1.44–

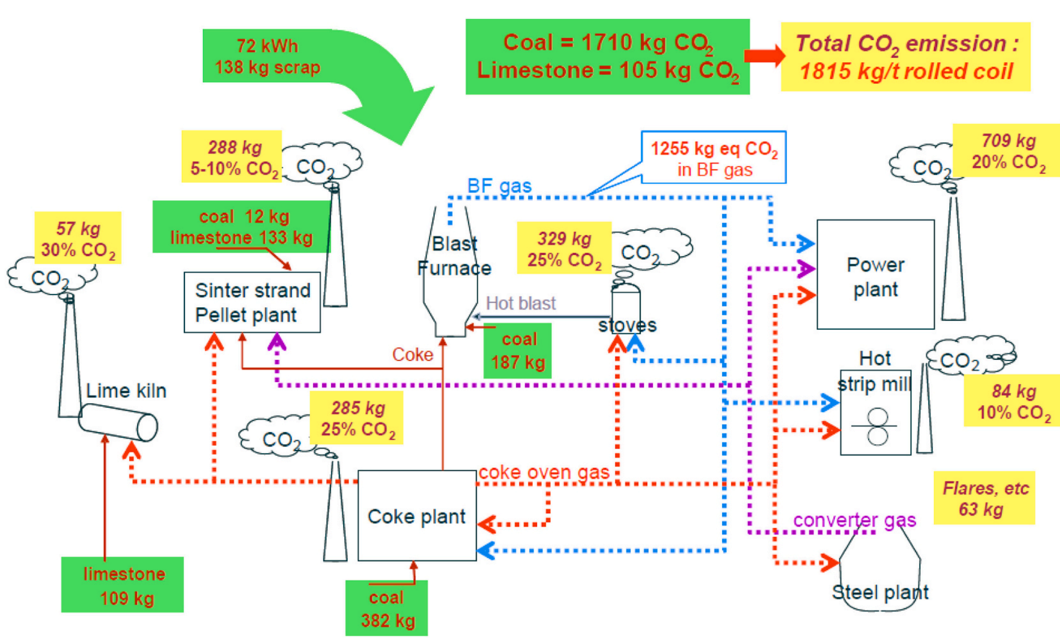

Fig. 8. CO_2 emissions from a typical steel mill.
Source: [54].

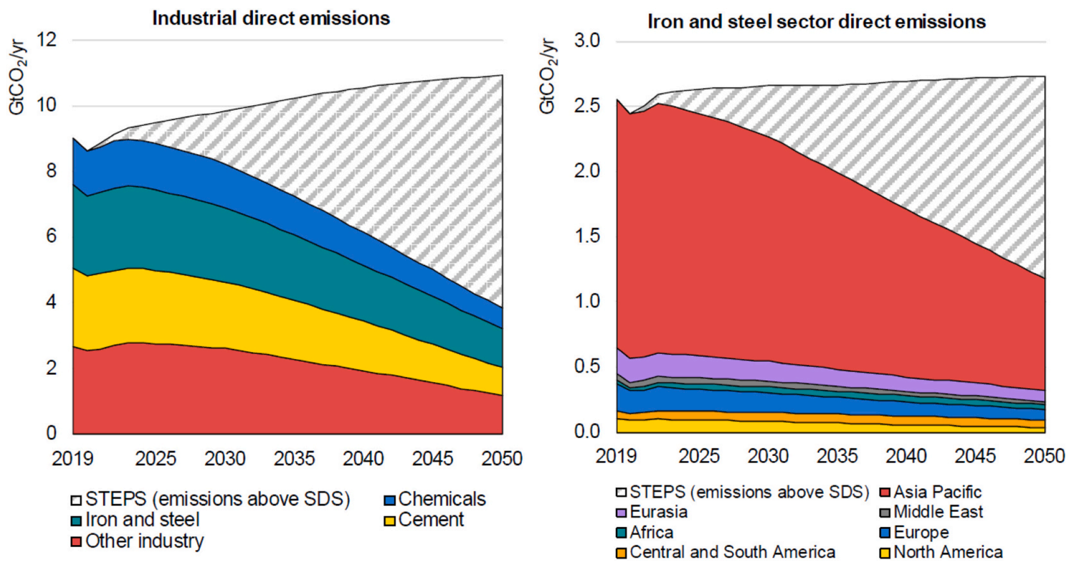

Fig. 9. The contribution of the iron and steel sector to direct industrial CO_2 emissions by scenario.
Source: [6]. Note: STEPS is the IEA Stated Policies Scenario and SDS is the IEA Sustainable Development Scenario.

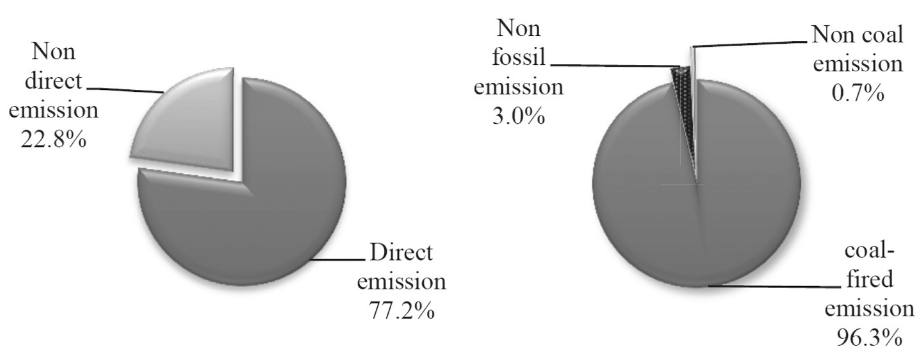

Fig. 10. The ratio of GHG emissions from iron and steelmaking systems of China in 2011.
Source: [55].

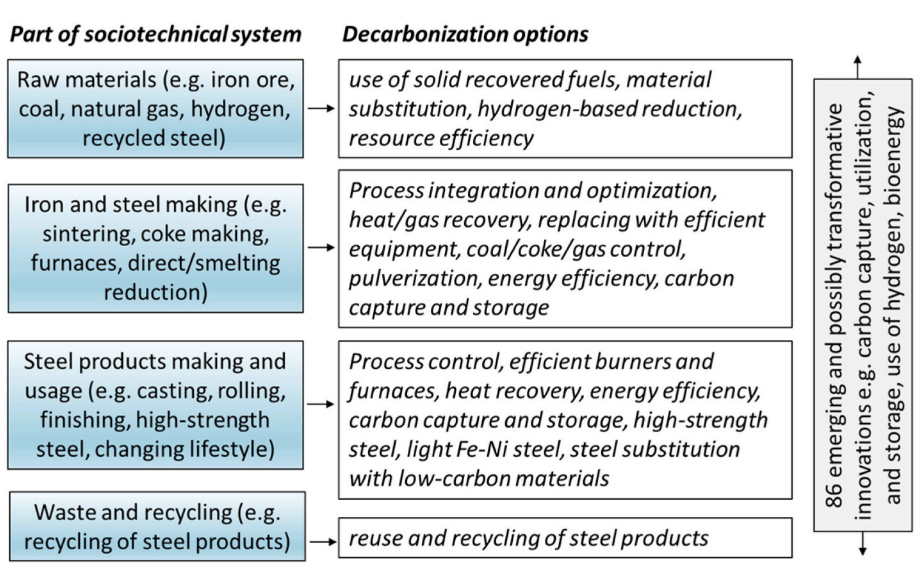

Fig. 11. Sociotechnical options for decarbonizing the iron and steel industry.
Source: Authors.

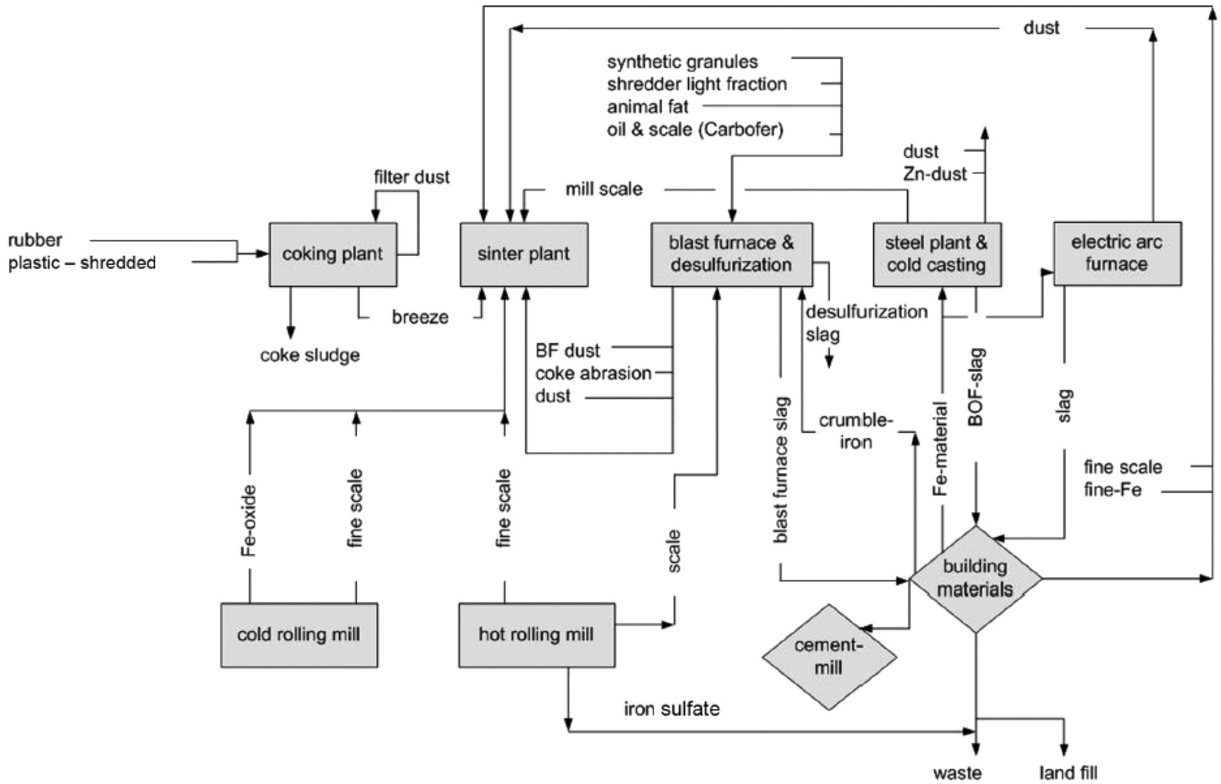

Fig. 12. Recycling of waste materials for a metallurgical plant.
Source: [66].

1.76 kg CO_2 per kg stainless steel in terms of life cycle emissions [65]. As shown in these studies, the energy- and carbon-intensive nature of the iron and steel industry has aroused continuous interest to appraise decarbonizing technologies and resulting GHG emissions.

5. Current and emerging technologies and practices for decarbonization

Five distinct classes of technological practices and innovations for the decarbonization of the iron and steel industry are described in this section. Fig. 11 depicts an overview for the four classes—raw materials for the iron and steel making, iron and steel making processes, steel products making and usage, waste and recycling of iron and steel—and the fifth class, 86 emerging breakthrough and potentially transformative technologies, is described in Section 5.5.

5.1. Options for raw materials

The iron and steel sector uses carbon intensive raw materials for steel production. It is the largest consumer of coal, and DRI needs hydrogen, typically via natural gas, as a reducing agent. Thus, substantial amounts of carbon from the raw materials can be mitigated by using low-carbon hydrogen solid recovered fuels, or bioenergy sources, as the reducing agent.

Manufacturers can use *solid recovered fuels* (SRF) in steel production instead of reducing agents such as coke, coal, or natural gas. Using SRF may not be effective to reduce greenhouse gas emissions, but it could reduce landfill waste disposal, which is one of the major sources of methane emissions. Also, SRF has good properties for iron and steel making as it contains high carbon and hydrogen contents, which are necessary for strengthening steel. The steel plants in Austria, Germany, and Japan have used SRF as reducing agents [66], and Fig. 12 presents the flows of recycled wastes usage in a metallurgical plant.

Hydrogen could also be used directly as a reducing agent in the steel making process and therefore has excellent potential for CO_2 reduction. Many steel producers are trying to develop this option. We can identify the following initiatives [52]:

- The hydrogen subproject of the ULCOS (Ultra-Low CO_2 steelmaking) program, run mostly from France (Université de Lorraine) [67,68]
- Hybrit project, SSAB, Sweden [69]
- SuSteel, VoestAlpine, Austria [70]
- Salcos-Macor, Salzgitter, Germany [52]
- ArcelorMittal Midrex plant, Germany [21]
- Flash iron making, the United States [71]

Decarbonization potential using hydrogen in the iron and steel industry is substantial. A simulation result indicates that the hydrogen-based direct reduction process can reduce up to 91% of direct CO_2 emissions relative to using natural gas [21]. Moreover, hydrogen-based technologies are a representative cross-cutting option for decarbonization [72] (see Section 9.2). It is, however, noticeable that the hydrogen production routes have a diverse nature, such as green, blue, and grey, and their carbon intensities are also widely ranged. Thus, the decarbonization of the iron and steel industry via hydrogen must be supported by the hydrogen produced from a low-carbon route (see Section 5.5 and Fig. 18).

Sintering is the second largest energy-consuming process in the iron and steel industry [73]. Thus, it is quite natural that there have been continuous efforts to decarbonize sintering, and energy saving by *process optimization* is one of those efforts. Process optimization by integrating a hybrid just-in-time learning soft sensor [73] and thermodynamic optimization [74] could be applied for saving energy during the sintering process.

5.2. Options for iron and steel making

The iron and steel making processes are the major carbon emissions

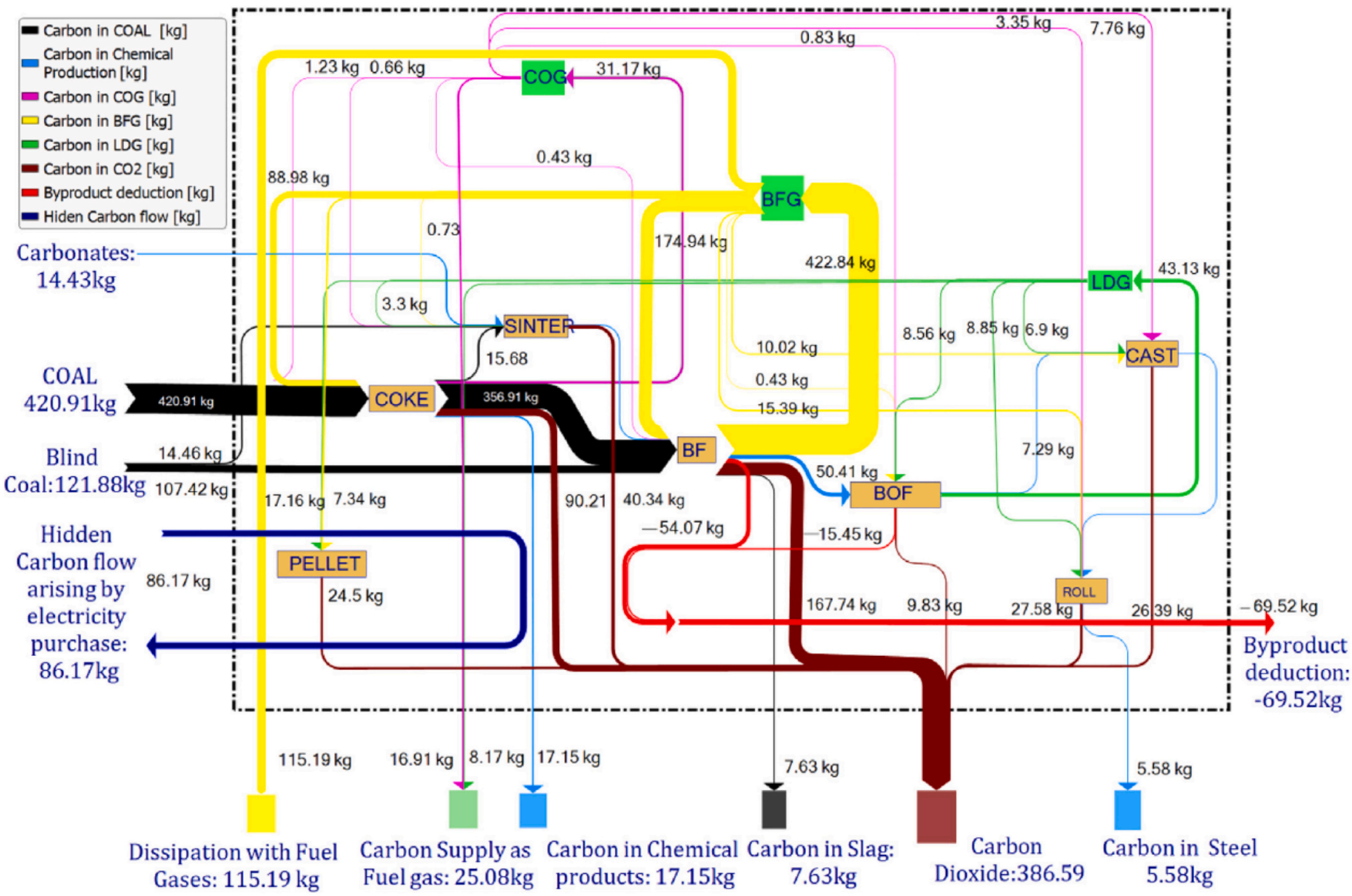

Fig. 13. A carbon flow chart for BF/BOF steel processing.
Source: [79].

source in the iron and steel industry. According to China's example of 2004, the iron making process is the most energy-consuming process among all steel industry processes, accounting for 70% of the total energy use of the iron and steel sector [75]. Because of the complexity and different steelmaking routes, there are many options for decarbonizing iron and steel making processes. They include energy efficiency, adoption of renewable sources or fuel switching, waste heat recovery technologies, process integration and optimization, carbon capture and storage, and hydrogen use.

Energy efficiency is vital for the sustainable future of the iron and steel industry. As mentioned in the Introduction, energy cost takes 20– 40% of steel manufacturing costs [4], and, naturally, there is a strong incentive to save energy consumption in the process. Many countries have tried to improve the energy and resource efficiency of iron and steel production. The U.K. steel sector has recorded a steady improvement in resource efficiency but suffered a decline in the economic output per energy consumption [76]. One study reveals that the Swiss metals sector, which is responsible for about 14% of the industry's total final energy demand, has the maximum energy efficiency potential at 19% with the current best available techniques. The economic potential, however, decreases in the range of 11%–15%, and the corresponding CO_2 abatement potential is 6% [77]. Another study [78] suggested that the whole iron and steel-making process energy utilization efficiency was 47.6%, which means 52.3% of total purchased energy was lost in the process. A case study for China [79] gives us an excellent picture of the overall carbon flow in the iron and steel process (Fig. 13). According to this case study, producing one ton of crude steel emits 1418.78 kg of carbon dioxide. The study decomposed this direct CO_2 emission by process—422.75 kg from fuel gas dissipation, 28.00 kg in slag, 62.94 kg in chemical products, for example. This decomposed carbon flow identified that enhancing power generation efficiency using the combined cycle could eliminate 134.43 kg CO_2 [79].

Other studies also presented energy efficiency options, impacts, and case studies, such as energy efficient technologies dissemination for the German steel industry [80], energy efficiency potential in India [81], and an EU27 case study considering different payback periods of efficiency investment [82].

The adoption of renewable sources or fuel switching from fossil fuels in the iron and steel making processes can reduce substantial greenhouse gas emissions. Adopting biomass in the processes is the first option for the iron and steel industry [83,84]. Biomass could replace fossil-based reducing agents and has the potential to decrease CO_2 emissions up to 50% in the integrated steelmaking process [14]. Biochar can be used in the sintering process, and charcoal is a promising substitute in blast furnaces [84]. Besides biomass, the other renewable sources can also mitigate carbon emissions since the industry uses electricity and heat for steel making [85–87].

Due to the energy intensive nature of steelmaking processes, the integration of lower-emission energy sources in high-producing geographic regions can also significantly lower global steel emissions. Coal currently accounts for 60% of China's electricity generation, which raises embodied steel emissions relative to regions that have integrated lower-emission electricity sources and renewables [85–87]. Similarly, almost one-fifth of all steel is expected to come from India by 2050 (compared to around 5% today), who's electricity gird is also heavily dependent on coal [88]. Renewable-based electricity and heat supply combining low-carbon hydrogen and CCUS could be a powerful option for decarbonization [86,89], especially as these nations continue to

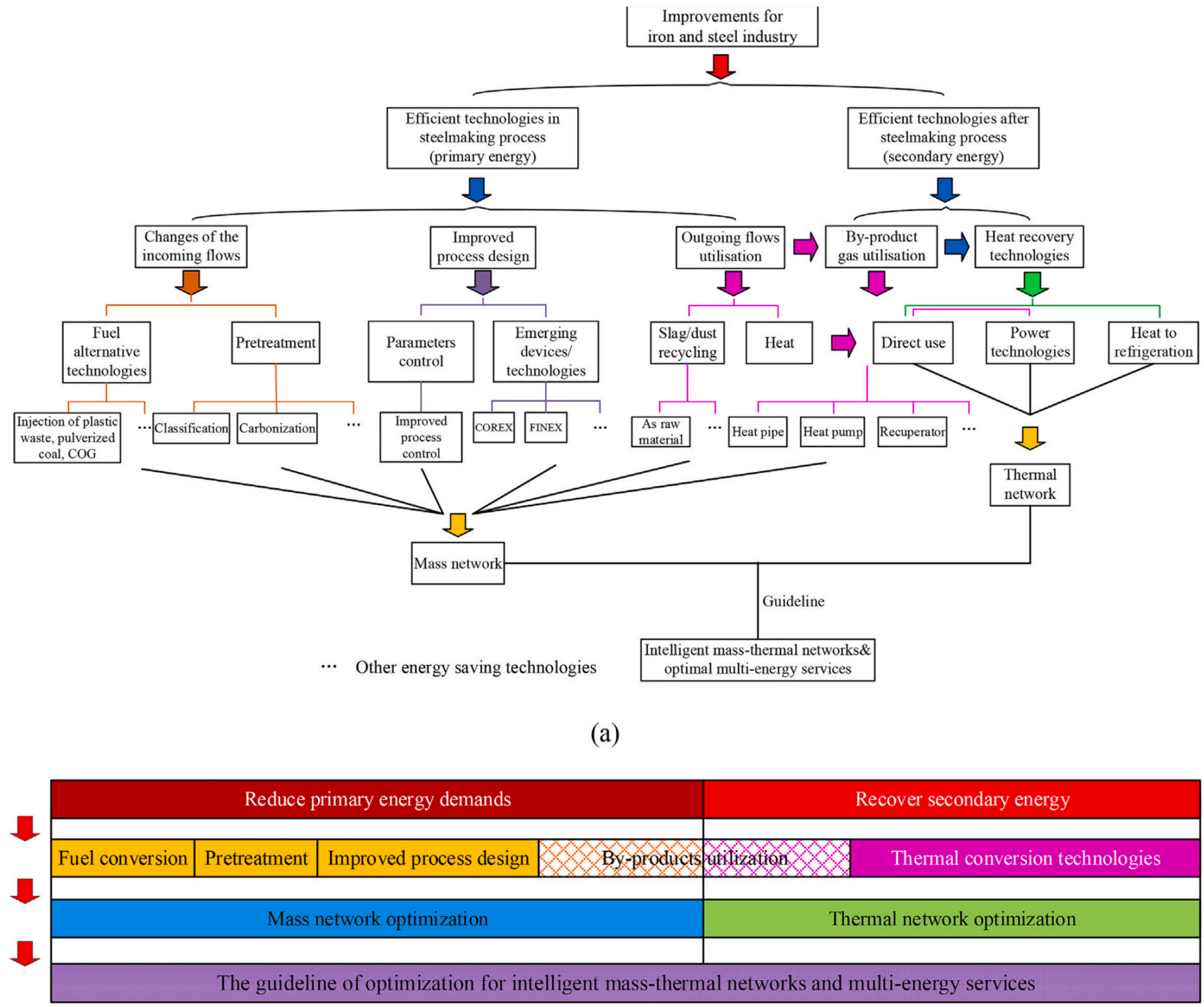

Fig. 14. Roadmap of efficient use of energy in iron and steel industry (top panel (a): main concepts, bottom panel (b): general summarization).
Source: [17].

account for larger percentages of steel production [90].

Waste heat recovery technologies also have great potential for the decarbonization of the iron and steel industry. Coke oven gas (COG) or coke gas is a byproduct of the coke-making process in the iron and steel industry. COG is a complicated mixture of CO, CO_2, H_2, CH_4, and N_2, and volatile coal produces COG in the coking process. COG also contains around 30 wt% tar [91]. COG, including tar, has very high energy content that could meet approximately 4.1% of the global demand for power generation [92]. Therefore, the hot COG utilization (recovery) can contribute considerable energy savings.

Various COG utilization approaches, such as power generation [93], H_2 production [94], and methanol [95] or CH_4 production [96], have been developed. The integrated COG-based DRI plant is another promising and efficient option. In this process, the hot DRI reacts with sulfur (in-situ desulfurization) before the fuel is injected into the reformer. Purified COG can also be converted into a reformed gas that can produce DRI [91].

Molten slag is another promising source for waste heat recovery. It is exhausted with a very high temperature around 1450–1550 °C [97]. For the heat recovery from molten slag, traditional technologies, such as water quenching, is not appropriate because it consumes a considerable amount of water. POSCO, the steel company in the Republic of Korea, developed an energy-efficient technology to recover slag heat in 2012. It recorded a 50% recovery rate at a temperature of 460 °C in a field test of a prototype [98].

Process integration and optimization is another good option to decarbonize the iron and steel industry. Various optimization techniques have been applied for the iron and steel sector, such as an integrated steel plant system [99], energy intensity optimization [100], and material-energy nexus flow combination [101]. One study [17] illustrated the concept of mass-thermal network optimization and summarized their classifications, which gives us valuable insights into the decarbonization options (Fig. 14). As shown in this figure, process optimization can reduce energy demand as well as recover energy use. Thus, the optimal integration of various process optimization techniques has excellent potential as a promising decarbonization option for the iron and steel industry, and that's why a practical roadmap is necessary.

Carbon capture and storage (CCS) or Carbon capture, utilization, and storage (CCUS) technology is one of the key options to mitigate carbon emissions and hence could be helpful for the iron and steel industry [91]. For example, there are vigorous efforts to develop effective sorbents for CCS from materials and by-products of the iron and steel

Table 5
Life cycle GHG emissions for lightweighting scenario. (unit: kg CO_2-eq.).

Options	Production			Use		End of life	Total	
	Low	Mid	High	Low	High		Low	High
Baseline vehicle	1670	3590	4100	38,248	57,753	147	40,065	62,000
6% lightweight HSS	1620	3630	4200	35,547	54,178	138	37,305	58,516
19% lightweight HSS	1563	3700	4820	29,500	44,544	100	31,171	49,472

Source: [113]. Note: HSS represents high-strength steel.

making process, such as a mixture of magnetite (Fe_3O_4) and iron (Fe) [102] and direct gas-solid carbonation of steel slag [103]. Also, CCUS includes "off-gas hydrogen enrichment and/or CO_2 removal for use or storage," "converting off-gases to fuels," "converting off-gases to chemicals" for blast furnaces (BF), and "natural gas-based with CO_2 capture" for direct reduced iron (DRI). Because of its versatile nature, CCS can be applied for most processes in the sector: sintering, pelletizing, coking, iron and steel making, and casting and rolling [104].

An increase in CO_2 costs in the market, i.e., the EU Emission Trading Scheme, can make CO_2 capture options economically feasible in the iron and steel industry. Note that iron and steel manufacturing is an extensive production process with high CO2 concentrations and recoverable heat

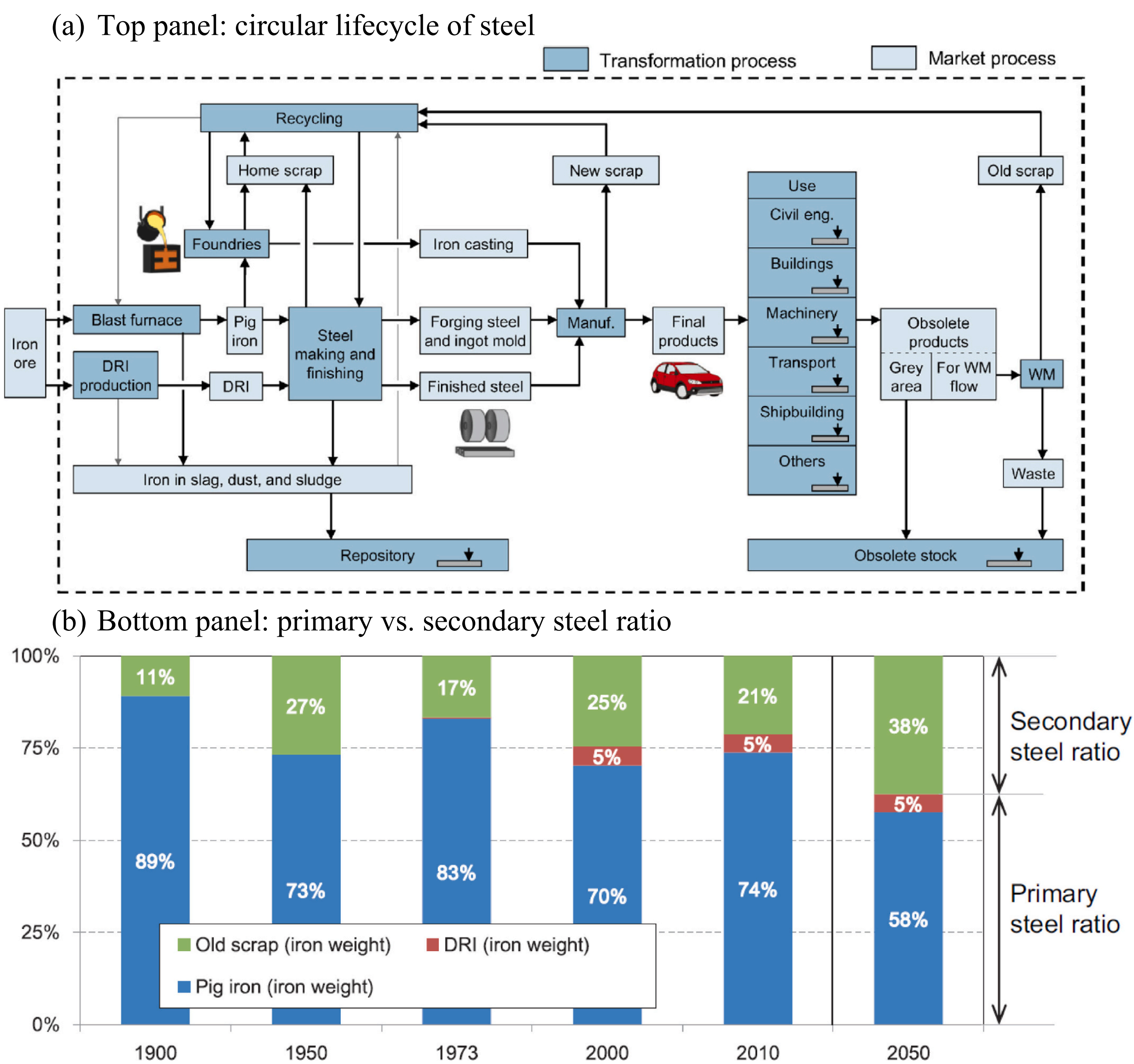

Fig. 15. Steel scrap recycling and the expansion of secondary steel.
Source: [116].

Table 6
86 commercially available, emerging, and experimental innovations for the iron and steel industry.

Level of sociotechnical system	Commercially available but not yet widely utilized (as of 2020)	Emerging soon with working prototypes (as of 2020)	Experimental and likely only after 2025
Raw materials	1. Solid recovered fuels for use as reducing agents 2. Heat recovery from sinter cooler 3. Single-chamber-system coking reactors	1. Primary Energy Melter	1. Low-carbon hydrogen-based direct reduction 2. Charcoal in the sintering process 3. Torrefied biomass
Iron and steel making	4. Use of recuperative burners 5. Replacing existing equipment with more efficient ovens, burners, kilns, and furnaces 6. Process modification of kilns 7. Optimization of furnace 8. Waste heat recovery 9. Use of ceramic ladles instead of cast iron pipes 10. Efficient ladle preheating 11. Radiation recuperators for ladle furnace 12. Coal moisture control 13. Coke dry quenching 14. Injection of pulverized coal 15. Top-pressure recovery turbines 16. Recovery of BF/BOF gas 17. Charging carbon composite agglomerates	2. Advanced control of heating walls in coke ovens 3. Hot oxygen injection 4. Tecnored 5. Cyclone converter furnace 6. Continuous horizontal sidewall scrap charging 7. Converting off-gases to fuels (BF) 8. Converting off-gases to chemicals (BF)	4. Plasma blast furnace 5. Off-gas hydrogen enrichment (BF) 6. CO_2 removal for use or storage (BF) 7. Electrolytic H_2 blending (BF) 8. Natural gas-based DRI with high levels of low or zero-carbon electrolytic H_2 blending 9. Natural gas-based DRI with CO_2 capture 10. DRI based solely on low or zero-carbon electrolytic H_2 11. Paired straight hearth furnace 12. Molten oxide electrolysis 13. Suspension hydrogen reduction of iron oxide concentrate 14. Ironmaking using biomass and waste oxides 15. New scrap-based steelmaking process 16. In-situ real-time measurement of melt constituents 17. Continuous steelmaking for EAF
Steel products making and usage	18. Near net shape casting (thin slab) 19. Bottom stirring/stirring gas injection 20. Use of foamy slag practices 21. Use of oxy fuel burners 22. DC arc furnace 23. Scrap preheating and continuous charging 24. Flue gas monitoring and control 25. Eccentric bottom tapping 26. Improved process control 27. Ultra-high-power transformer 28. Twin shell furnace 29. Hot charging 30. Recuperative or regenerative burner 31. Use of ceramic low thermal mass insulators for reheating furnace 32. Controlling oxygen level and variable speed drive on combustion air fans 33. Efficient drives in rolling mill and machining 34. Waste heat recovery (cooling water, annealing, and compressor) 35. Reduced steam use for pickling 36. Automated monitoring and targeting systems 37. Thermal insulation for plating bath 38. Automated bath cover 39. Compressed air network modification 40. Reducing air extraction across heating solution 41. Efficient compressors 42. Optimizing the process solution temperature 43. Use of high-strength steel	9. Energy monitoring and management system in casting 10. Preventative maintenance in steel mills or EAF plants 11. Variable speed drives for flue gas control, pumps, fans in integrated steel mills 12. Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills 13. Additive manufacturing	18. Smelting reduction with CCUS 19. low or zero-carbon H_2 for high-temperature heat (ancillary processes) 20. Next-generation system for scale-free steel reheating 21. Thermochemical recuperation for steel reheating furnaces 22. Oxygen-rich furnace System 23. Integrating steel production with mineral sequestration
Waste and recycling	44. Rotary hearth furnace dust recycling system 45. Injection of plastic waste	14. Recycling basic oxygen furnace slag 15. Recycling of stainless steel dust 16. Regeneration of hydrochloric acid pickling liquor 17. Recycling of waste oxides in steelmaking furnace	24. Geological sequestration of carbon dioxide using slags

Note: The detailed description of each innovation is presented in Table A1: in the Appendix.
Source: Authors compilation and modification from [8,18,21,66,77,113,124–139].

[105,106]. Higher carbon price thus makes the CCS applications in the iron and steel industry economically feasible.

Despite the challenges to meet economic feasibility, it is evident that CCS will be (and must be) an effective and cross-cutting option for the decarbonization of the iron and steel sector. As many steelmaking practices have already reached close to their maximum thermodynamic limits [9,16] and emerging decarbonization options are primarily focusing on incrementally lowering emission, carbon capture is one of the few technologies to offer scalable reductions that rival steel's economic importance and need for decarbonization. Several studies discuss its technical concept [106,107], application design [108,109], and potential [110,111] as a promising decarbonization option.

5.3. Options for steel products and usage

Steel products making, from crude steel to the finished products such as coil, sheets, strips, wire, bars, or pipes, also require substantial energy inputs. Similar approaches—process control and optimization, efficient burners and furnaces, heat recovery technologies, and carbon capture and storage—could also be applied for decarbonization. However, the practical application of those approaches differs from that in iron and steel making since they are “distinct” processes (see Table 6, for example).

The World Steel Association launched a global initiative to exchange knowledge from regional activities, entitled “CO_2 Breakthrough Programs,” in 2003 [112]. The research and investment covered in these programs are taking place in [91]:

- The EU (ultra-low CO_2 steelmaking, or ULCOS I and ULCOS II)
- The US (American Iron and Steel Institute)
- Canada (Canadian Steel Producers Association)
- South America (ArcelorMittal Brazil)
- Japan (Japanese Iron and Steel Federation)
- South Korea (POSCO)
- China (Baosteel) and Taiwan (China Steel) and
- Australia (BlueScope Steel/One Steel CSIRO coordination)

Considering the local constraints and cultures, the decarbonizing innovations, economic feasibility, technical feasibility at various scales—from lab scales to commercial implementations—were discussed in the CO_2 Breakthrough Programs [112].

One good option to mitigate CO_2 emissions is the *weight lightening of vehicles* with high-strength steel products. Lightweight vehicles will consume less energy than heavier cars per vehicle-mile traveled. Table 5 reveals that the life cycle GHG emissions of vehicles made with 19% high-strength steel (HSS) are 20.2– 22.2% lower than a for a baseline vehicle [113].

Similarly, according to the World Steel Association, advanced and ultra-high-strength steel can reduce steel applications' weight by up to 40%. It also reduces the number of raw materials and energy used to produce steel products. HISTAR® by ArcelorMittal, for example, weighs 32% less than a standard grade steel beam of the same length and thickness, saving around 30% on material [114].

5.4. Options for waste and recycling

Reducing wastes in the steel making processes and recycling steel products can substantially reduce energy use in the iron and steel sector [115]. The World Steel Association reveals that the steel industry has globally recycled over 22 billion tons of steel since 1900, resulting in the iron ore (28 billion tons) and coal (14 billion tons) consumption reduction globally [114]. Another study showed that global secondary steel using steel scrap may expand to 38% of total steel production by 2050 (Fig. 15) [116]. Since steel production from scrap uses much lower energy than the primary steel from iron ore [117,118], the expansion of secondary steel can be an impactful decarbonization option.

Iron recovery from metallurgical slags is also noteworthy and E-wastes, such as refrigerators, computers, and TV, also provide secondary ferrous resources for recycling [119]. Comminution (for size reduction and surface area increase) and separation [120], carbothermic smelting reduction [121], carbothermic reduction, flotation, or leaching [122], and aluminothermic smelting reduction [123] technologies have been applied for the iron recovery from slags.

Recycling steel for use as a raw input, or for the creation of recycled steel through EAF production routes can also lower the emissions intensity of steel by 62–90%. The amount of emissions reduced is primarily based on the electricity grid of the country that is responsible for recycling the steel [90], the steel process route, and is heavily dependent on the availability of scrap steel. Because of this dependency, and steel's use in products with long lifetimes, the use of recycled steel has not been able to match growing steel demand, although many of the IEA's ambitious climate scenarios show large increases in the creation of scrap-base steel [6] and a decline in blast-furnace primary steel production.

5.5. Emerging breakthroughs and transformative innovations

The last category of decarbonizing options for the iron and steel industry is *breakthrough and emerging innovations*. Our systematic review revealed possibly transformative options for the near future, as summarized in Table 6. Likewise the former review on the decarbonization options for the other industries [42,43], we classified the 86 innovations for the iron and steel industry across the sociotechnical system into three groups—commercially available but not yet widely diffused (as of 2020); emerging soon with working prototypes; and those at the experimental and likely only after 2025. Interestingly, more innovations are commercially available (45) than are both emerging (17) or in experimental stages (24).

The decarbonization innovations, including the emerging ones above, could also be categorized using a decision tree (Fig. 16) or by the popularity in the reviewed literature (Fig. 17). If we consider decarbonization of the iron and steel industry using just existing materials and fuels, then recycling more and enhancing resource/material efficiency would be the sole options [140]. Considering new materials and fuels as well, however, expands the decarbonization options and existing processes can be kept or changed with more efficient equipment or entirely new techniques, such as hydrogen-based direct reduction.

Fig. 17 depicts the frequency of decarbonization options among the reviewed literature in this study. The frequency and level of academic interest could be an indicator of promising innovations, although it does not necessarily represent the true potential of each technology. We organized the frequency by the iron and steel industry's value chain and assigned colors for the type of each innovation.

One early stage but promising and powerful decarbonization option is low-carbon *Hydrogen*. Hydrogen from renewable or other low-carbon sources could be used as a reducing agent in the steel making process and has the potential to mitigate more than 3 Gton of CO_2 annually at a cost of less than USD$ 60/ton CO_2 mitigated [141]. HYBRIT, one of the companies developing hydrogen-based DRI has further shown that each ton of hydrogen used in a DRI process that replaces a blast furnace saves 24–32 kg of CO_2 [142].

A simulation result indicates that the hydrogen-based direct reduction process can reduce up to 91% of direct CO_2 emissions than the reduction using natural gas [21]. Incorporating a biomass-based polygeneration system in the iron and steel making process could also be a good option for the iron and steel industry's sustainable future. One study suggested a 34.15% reduction of carbon emissions and a 1.81% enhancement of the annualized capital cost in the best scenario [137]. Considering its impact, potential [72,143], and developers, such as SSAB [144], POSCO [19,145], ArcelorMittal [146], Voestalpine [147], Salzgitter Flachstahl [52], hydrogen-based DRI would become the long-term winner for low/zero carbon steel.

The ULCOS (Ultra-Low Carbon Dioxide Steelmaking) project also presents hydrogen as a breakthrough technology for the iron and steel sector [67]. It suggests replacing coal with hydrogen and electricity in hydrogen reduction. A pure hydrogen-based steel making process is also possible. Many studies have developed practical models with pure H_2 as a reducing agent in the direct reduction process [11,148–150]. Hydrogen could also be combined with CCS technologies [151] and CCU technologies [152] to reduce carbon emissions in steel making processes (Fig. 18).

The cost reduction of renewable electricity could be a game-changer

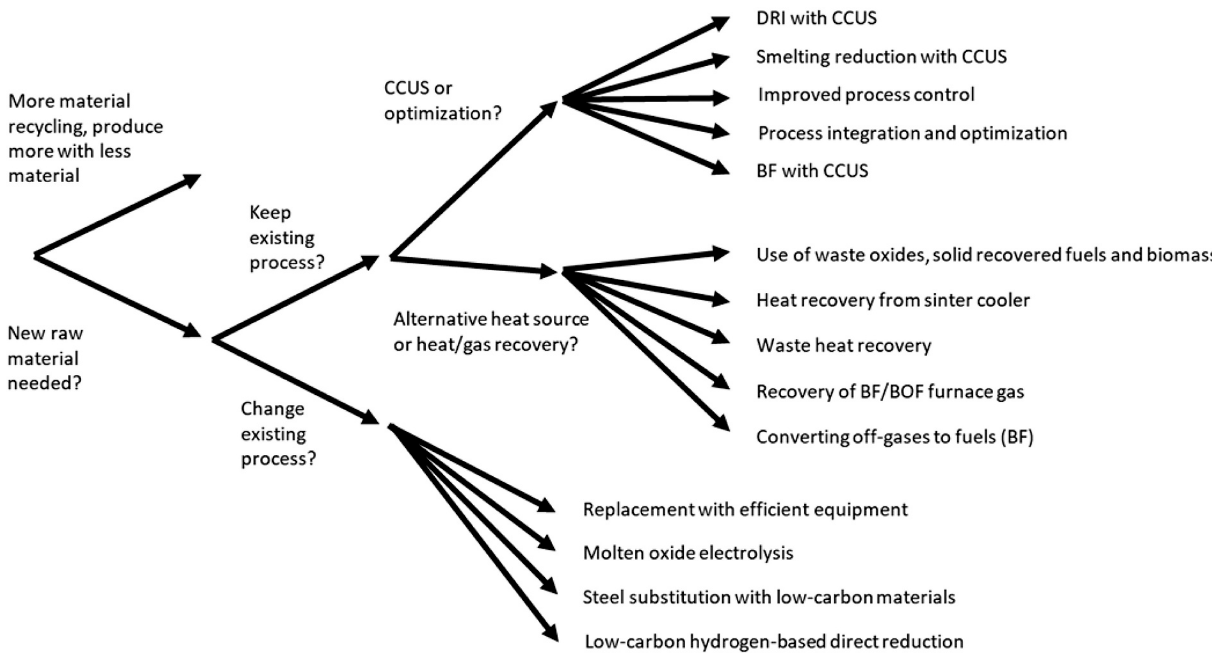

Fig. 16. Decision tree of decarbonization choices for the iron and steel industry.
Source: Authors modification based on the framework in [130].

	Raw material preparation	Ironmaking	Steelmaking	Casting, rolling, finishing
Frequently mentioned ⇧	Heat Recovery from Sinter Cooler	Direct-reduced Iron	Electric Arc Furnace	Heat Control
	Improved Process Control	Coke Control	Heat Recovery of BOF Gas	Improved Process Control
	Solid recovered fuels for use as reducing agents	BF Gas Recovery	Open Hearth Furnace	Monitoring and Management System
⇩	Charcoal in the Sintering Process	Heat Control	Ladle Control	Recuperative Burner
Barely mentioned	Single-chamber-system Coking Reactor	Recuperative Burner	Improved Process Control	Oxy-fuel Burner

Fig. 17. Promising decarbonization innovations by value chain.
Note: Crosscutting options, such as hydrogen and CCUS, are incorporated in processes or equipment. For example, hydrogen and CCUS can be applied in both direct-reduced Iron and Electric Arc Furnace. Orange color denotes the options related to heat, blue indicates the one for process/equipment, and green is for material/fuels.
Source: Authors.

for low-carbon hydrogen production. One study suggested that Australia could supply hydrogen for East Asia, especially Japan and Korea, at USD 3.23 per kg by 2025. This study also revealed that the 2025 export potential of 25– 345 PJ could grow to 621– 3180 PJ in 2040, with the production cost range of USD 1.70– 4.95 per kg H_2 [52]. Electrolysis efficiency is currently at around 77%, and approximately 85% is the thermodynamic limit [153]. Electricity cost is thus the driver of renewable hydrogen production cost.

Molten oxide electrolysis (MOE) is another potentially game changing technology as it completely changes the steel manufacturing process [19]. Unlike traditional steel production, MOE produces no carbon emissions and can be zero-carbon if powered by zero-carbon electricity sources (Fig. 19).

6. The benefits of decarbonizing iron and steel industry

Decarbonizing the iron and steel industry gives clear benefits that we categorize into three areas: energy and carbon savings, cost savings, and other environmental co-benefits.

6.1. Energy and carbon savings

Although steelmaking processes operate close to their thermodynamic limits using current technologies [9], our review reveals compelling decarbonization innovations (see Table 6). Those innovations can yield financial benefits from energy and carbon savings across multiple levels of the sociotechnical system.

Regarding emissions reductions, one study reveals that energy saving technologies, such as coal moisture control and high temperature air

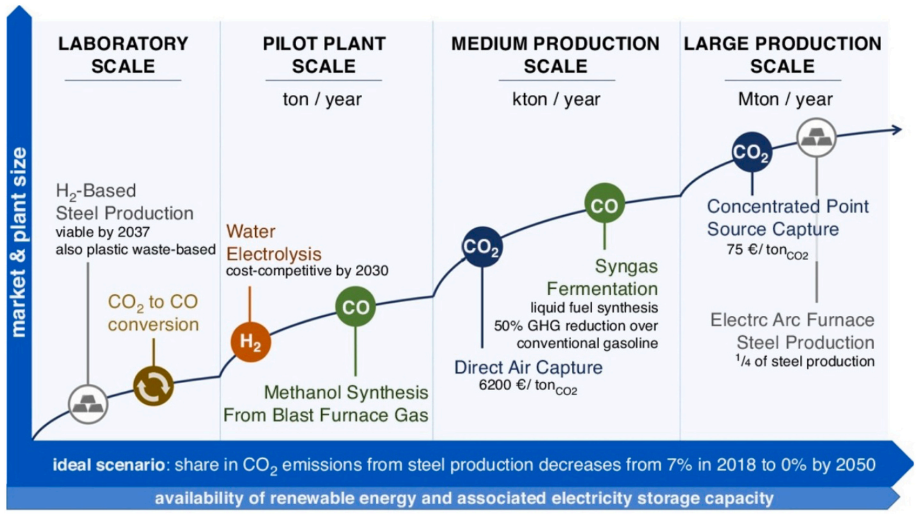

Fig. 18. Green hydrogen production and its applications in steel production.
Source: [152].

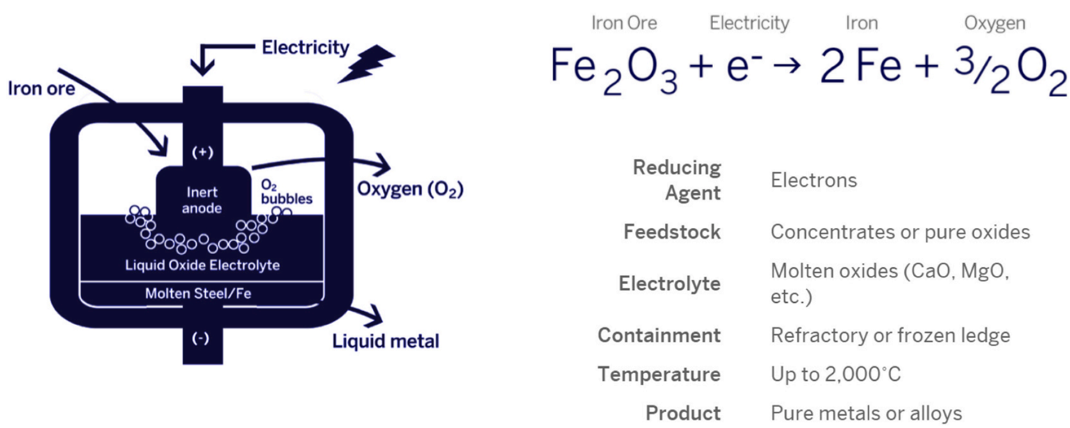

Fig. 19. Molten oxide electrolysis.
Source: [154].

combustion, can reduce almost half of the CO_2 emissions from the Chinese steel sector, reducing the emissions from 1469 Mt in 2015 to 710 Mt by 2050 [155]. Another case study assessed that the cost-effective energy saving potential of the German iron and steel industry is up to 11.7% for fuel, 2.2% for electricity, and 12.2% for CO_2 emissions when applying a plant-specific bottom-up approach [156].

Despite the fact that decarbonization of the iron and steel industry would be a challenging journey, a sustainable future in terms of the environment and economic output could be achieved through effective technologies and policies. According to Hasanbeigi [7], the maximum decarbonization potential would be about 15% between 2010 and 2050, considering the CO_2 intensity decrease of power sectors and the increase in scrap availability. Fig. 20 gives valuable insight into investigating where the energy savings by decarbonization technologies originated. This case study indicates that traditional production processes, such as hot rolling, blast furnaces, and coke ovens (top three in Fig. 20), have great potentials for energy saving in China when applying fuel changes and low-carbon devices [157]. Well-known decarbonization options, such as regenerative burners and pulverized coal, identified in Section 5.5, are also effective for China's iron and steel industry. Quantifying the contribution to energy savings of each innovation via scenario analysis could support development of a decarbonization policy.

6.2. Cost and financial savings

Because of the iron and steel industry's energy-intensive (uses high-temperature) nature, reduced energy inputs will result in significant financial savings as well as social cost savings through reduction of the negative externalities imposed by coal and natural gas consumption [158]. One study, for example, estimated that efficient technologies for integrated casting and rolling would reduce operations and maintenance costs by 20–25% [136]. Another study presented 14 efficiency measures in the industry that could save \$0.11–\$6.27 per tonne of steel [159] (Table 7). Thus, taking the total global steel production, 1477.7 million tonnes in 2018 (Table 1), into account, 14 efficiency measures could save a total of \$26.76 billion per year.

6.3. Other environmental co-benefits

Many of the decarbonizing options reviewed in this paper can also save water usage, minimize wastes, and make other positive benefits, such as air quality improvements [162–164]. One study noted that the optimization of water usage and recovery could yield considerable water and energy savings in the iron and steel making processes. For example, case studies on the optimizing the water network of steel plants in China and Italy resulted in reduced freshwater intake in the plants by 20%

Fig. 20. Energy savings contributed by each technology in China's iron and steel industry.
Source: [157]. Note: Positive values denote energy savings, and negative values represent energy increments.

[165]. Another study also reveals that decarbonization of China's iron and steel industry can significantly improve the ecological environment of the Beijing-Tianjin-Hebei region, Yangtze River Delta region, Henan, and other places that have frequently suffered from pollution haze [166].

As discussed already, the recycling ratio of steel is very high, close to 95%, making steel the most recycled material [165]. While the high recycling ratio is mainly for economic reasons, it gives us other environmental benefits that include less energy use and fewer carbon emissions. The scrap-based EAF is greener than the other steel making processes starting from raw materials. The 4-Rs "circular economy" concept by the World Steel Association successfully depicts the co-environmental benefits of reuse and recycling (Fig. 21).

Applying decarbonization options for the iron and steel industry can

Table 7
Fourteen efficiency measures in the iron and steel industry and productivity benefits.

Efficiency measure	Productivity benefit	Cost saving (US$/tonne)
Electric steelmaking		
Oxy-fuel burners	Reduces tap-to-tap times	1.00
Scrap preheater—FUCHS shaft furnace	Reduces electrode consumption, improves yield, saves waste handling costs	0.80
Bottom stirring—stirring gas injection	Improves yield, cuts need for inert gas purchases	0.22
Improved process control	Reduces electrode consumption, improves yield, saves maintenance costs	0.90
DC-arc furnace	Reduces electrode consumption, reduces tap-to-tap time	0.13
Scrap preheater—CONSTEEL	Reduces electrode consumption, improves yield	0.38
Scrap preheater—twin shell	Reduces tap-to-tap time	0.11
Foamy slag	Reduces tap-to-tap time	0.63
Integrated steelmaking		
Injection of natural gas—140 kg/thm	Decreases coke use; O&M and material cost savings at the coke battery	0.36
Pulverized coal injection—130 kg/thm	Decreases coke use; O&M and material cost savings at the coke battery	1.43
Pulverized coal injection—225 kg/thm	Decreases coke use; O&M and material cost savings at the coke battery	0.27
Adopt continuous casting	Saves equipment/handling costs, reduces material losses	5.36
Hot charging	Reduces material losses, improves productivity	0.25
Both electric and integrated		
Thin slab casting	Improves productivity, reduces material losses	6.27

Source: [160]. Note: kg = kilogram. THM = tons of heavy metal. "Tap-to-tap" time is the time from the beginning of charging to the end of tapping (emptying) the furnaces [161].

also reduce air pollutants, such as particulate matter. One study interestingly formulated the relationship between CO_2 reductions, PM2.5 reductions, and related costs through a triangular diagram [167] (Fig. 22). It is noteworthy that the balance between cost, carbon emissions reduction and particulate emissions reductions varies by technology combinations with the BF-BOF being inexpensive but very environmentally unfriendly and the combination of EAF-CCS-fabric filter and desulfurization being expensive but very environmentally friendly (color is the figure).

7. The barriers to decarbonizing iron and steel industry

The potentially attractive benefits identified in the previous section may give enough incentives to invest in the decarbonization innovations for the iron and steel industry. Unfortunately, those benefits are often vague to decision-makers, whereas the investment cost for decarbonization is regarded as an impending salient loss. Also, we usually face an insidious set of barriers and challenges exist disturbing that can disturb the achievement of decarbonizing investments. As the authors' of a previous review [42] addressed, the UK Department of Energy and Climate Change, and Department for Business, Innovation and Skills identified a number of general barriers to industrial decarbonization [10]:

high capital cost and long investment cycles, limited financing, risk of not meeting required product quality or changing character, risk of production disruption, shortage of skilled labor, shortage of demonstrated technologies, and lack of reliable and complete information.

The barriers to energy efficiency investments and improvements can be categorized into seven dimensions—technology related, information related, economic, behavioral, organizational, competence related, or awareness related [168] or using simplified three groups—market related barriers, organizational and behavioral barriers, and policy barriers [169]. Our review also identified three distinct barriers to decarbonizing iron and steel industry: financial and economic, organizational and managerial, and behavioral.

7.1. Financial and economic barriers

Although the benefits are evident, the decarbonization of the iron and steel industry needs substantial initial investment [108,170]. For many metals companies, it is extremely difficult to justify large upfront capital costs for decarbonization projects that have limited deployment and proven operational data [171]. The long life-cycles of steel plants (Fig. 5) and price volatility also make it difficult to integrate decarbonization efforts into steel operations when sites and projects are being initially built and developed [10]. Retrofitting operations is similarly difficult, as overhauling processes to accommodate new technologies without widely accepted carbon costs or a low-carbon steel market make it difficult to justify increased operational costs. Steelmakers in 2021 already faced challenges regarding supply chain disruptions, which added $200–250 per ton to steelmaking costs [172].

Existing efforts to transition towards a sustainable iron and steel industry in Central-East Europe, including Russia and Ukraine could already face a financial barrier. For example, Russia has abundant and cheap fossil fuels and is the only country that uses OHF among major steel producing countries (see Section 2.2), although the share of steel production in OHF dropped from 22% in 1992 to nearly zero today [173]. Thus, it is not a simple matter to simply restructure the iron and steel industry with modern, more efficient equipment for Russia (we return to this issue in Section 9.1). Thanks to the cost-saving benefits of the iron and steel sector's decarbonizing measures, there are economical and impactful options in the industry, such as continuous casting, cogeneration, and recuperative burners. However, many robust decarbonization measures—coke dry quenching and heat recovery annealing, for example—are still expensive and are beyond carbon prices in current ETS markets [174] (Fig. 23).

7.2. Organizational and managerial barriers

The iron and steel sector is a consolidated industry (see Section 2.3). A fragmented industry is inclined to have organizational and managerial barriers such as difficulties in sharing innovations and best practices [42]. One might think that giant, multinational firms can readily implement innovations for decarbonization. However, the capital intensive and oligopolistic nature of the iron and steel sector hinders the low-carbon transformation of the industry, although it is true that the companies can invest in big research and development projects [175,176].

One study categorized the steel industry in India, the world's third-largest producer, as "low" market concentration but "high" government concentration from a GHG emissions perspective. In terms of techno-economic assessment, India's iron and steel industry has access to so-called "best available technologies" for decarbonization, but they are not economical without further support measures [177]. This is one piece of evidence that the iron and steel sector's decarbonization is a matter of organizational and economic feasibility and not just technological or market related.

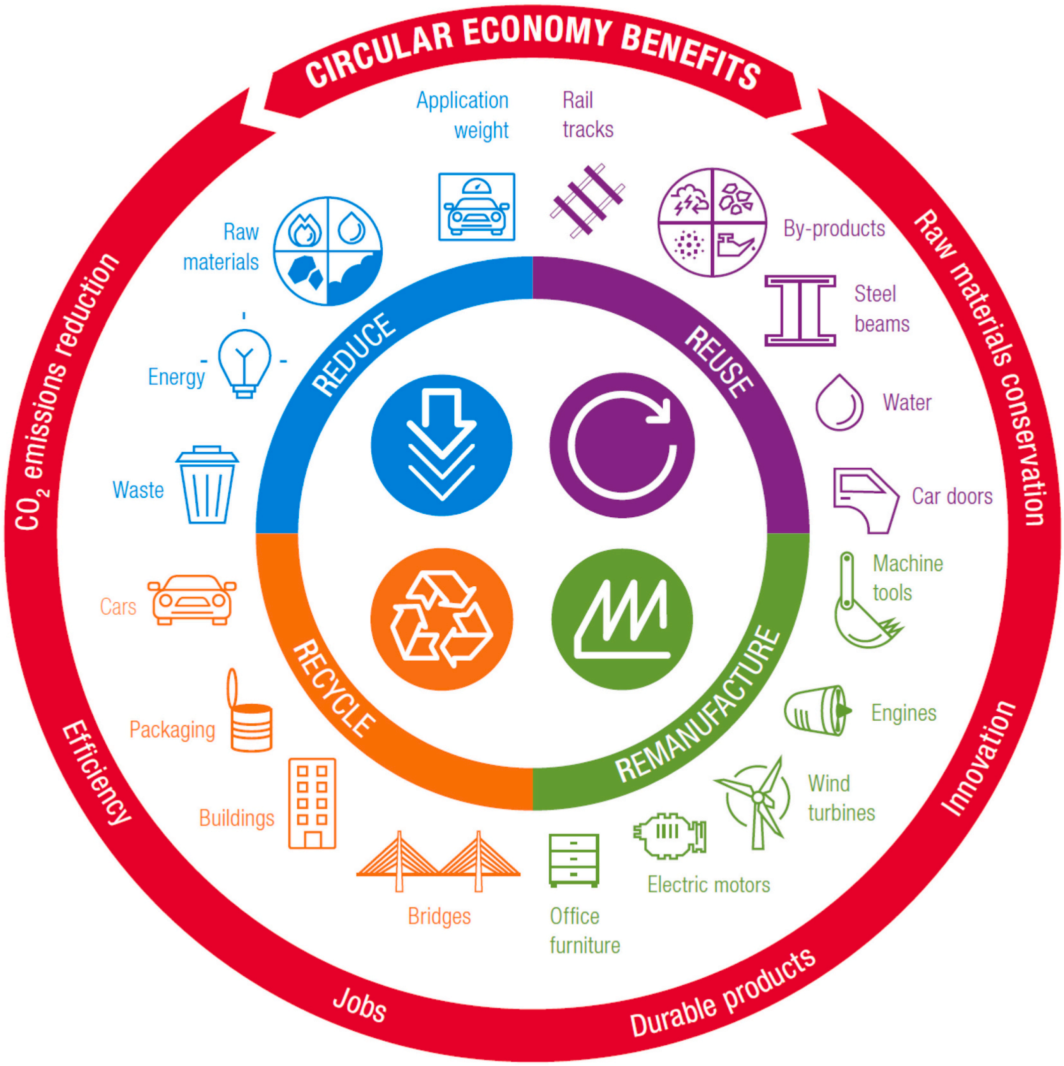

Fig. 21. Steel in the circular economy: the 4Rs.
Source: [114].

Uncertainty and risks also prevent an active investment for decarbonization. One study revealed that decision-makers in large steel producers of Bangladesh are concerned with "high perceived risk due to uncertainty about future energy prices, slow rate of return and others," "poor information quality regarding energy efficiency opportunities," "uncertainty regarding hidden costs," and "technical risk" when they decide on decarbonization or energy efficiency investments [178].

7.3. Behavioral barriers

Urbanization, modern city lifestyle, skyscrapers, and even wind turbines need more steel than in the past. We cannot blame the industry for this final class of barriers—convenient, safe, and even clean life generally take us in the direction of becoming more carbon intensive, rather than less. Moreover, steel products are durable—have a relatively long lifetime relative to other consumer goods. We may wait a hundred years or more to recycle or replace the steel in buildings, bridges, and infrastructure. Fig. 24 well describes the predominance of long service life steel products around us [114]. Only some metal products for daily life, such as steel cans and iron bars, have short service life. Thus, recycling, replacement, and secondary steel naturally have a time lag and hence are limited in their ability to serve as decarbonization options, although they have significant overall potential.

8. Policy instruments to overcome the barriers

Because of the consolidated nature of the iron and steel industry, relatively few players and countries provide the majority of global steel supply. The top six steel producing countries produce approximately 80% of steel globally, and the top 50 companies in the industry made 58.5% of the crude steel in 2019 (see Table 1 and Section 2). Consequently, there has been little attention to developing effective financing and business models for decarbonization since big players have enough capital to invest if the measures and innovations offer attractive returns.

However, there is a need for policy instruments to overcome the barriers and harness the dissemination of innovative, cross-cutting options for the industry's low-carbon future. Table 8 presents a collection of policy instruments from the literature to address the challenges to decarbonizing the iron and steel industry [6,179–187].

UK Climate Change Committee's recent report of net zero [188] suggests more proactive policy efforts as well as other well-known measures, such as energy and resource efficiency and CCS, across a mix of different industries, including iron and steel. Carbon taxes and regulatory standards could also be an effective measure for the decarbonization of the iron and steel industry [189,190] (Table 9), and *border-tariff adjustments* could minimize the risks of leakage and give a signal to other sectors, resulting in the price increase of carbon-intensive

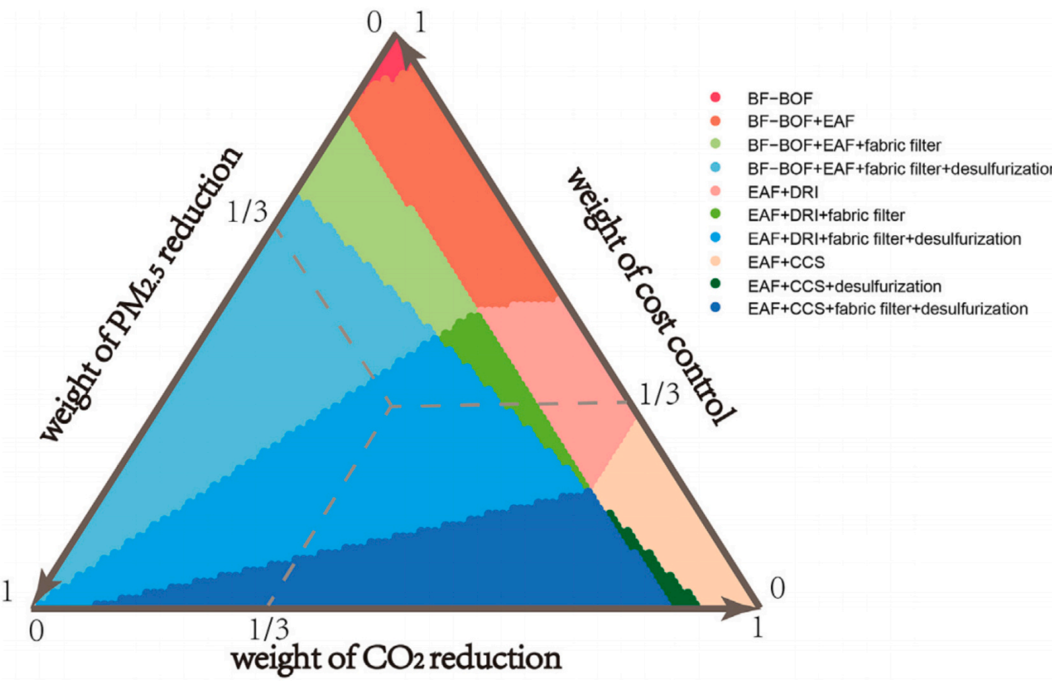

Fig. 22. Relationship between CO_2 reductions, PM2.5 reductions, and related costs of the iron and steel sector.
Source: [167].

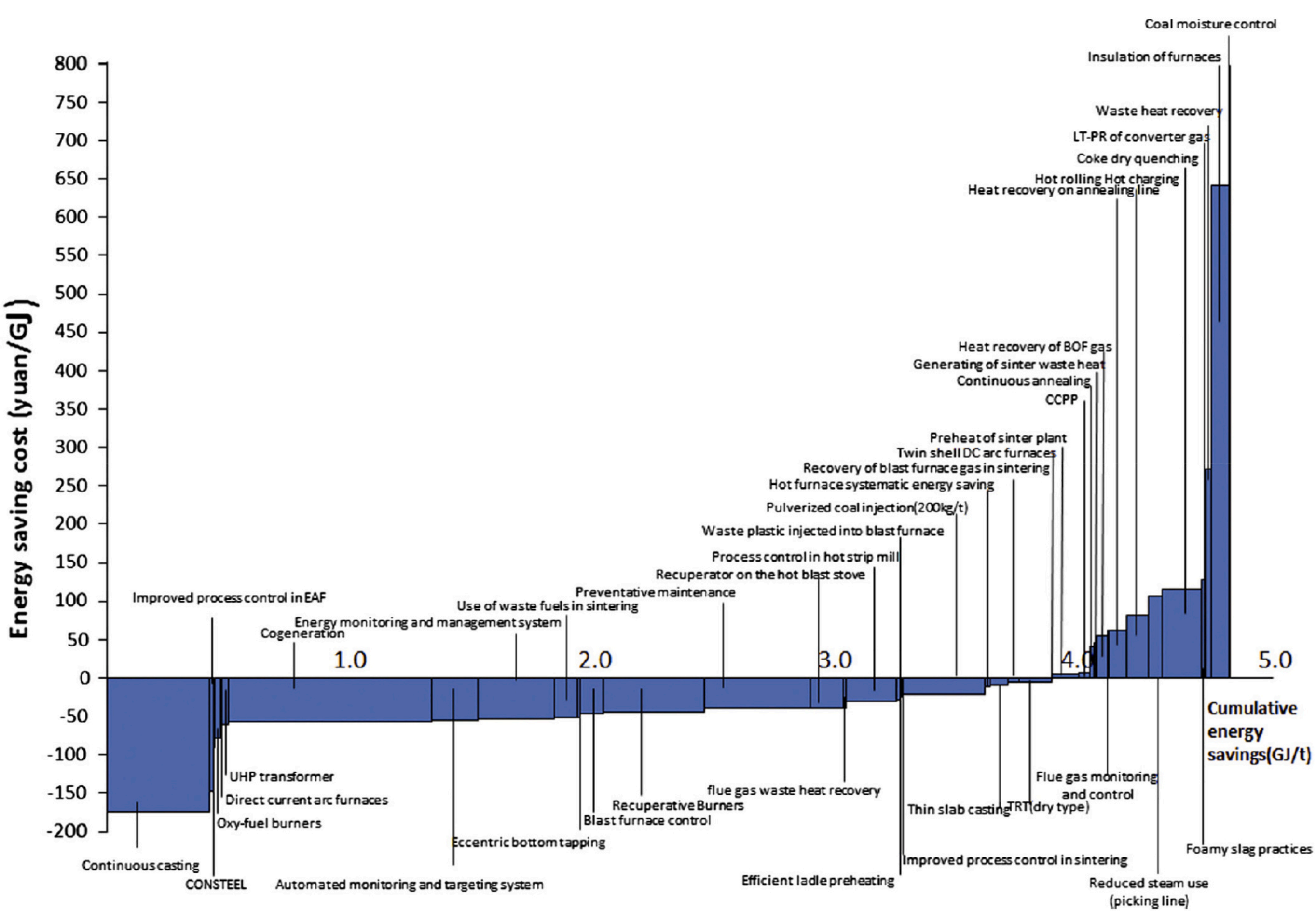

Fig. 23. Energy conservation supply curve with the discount rate 20%.
Source: [174].

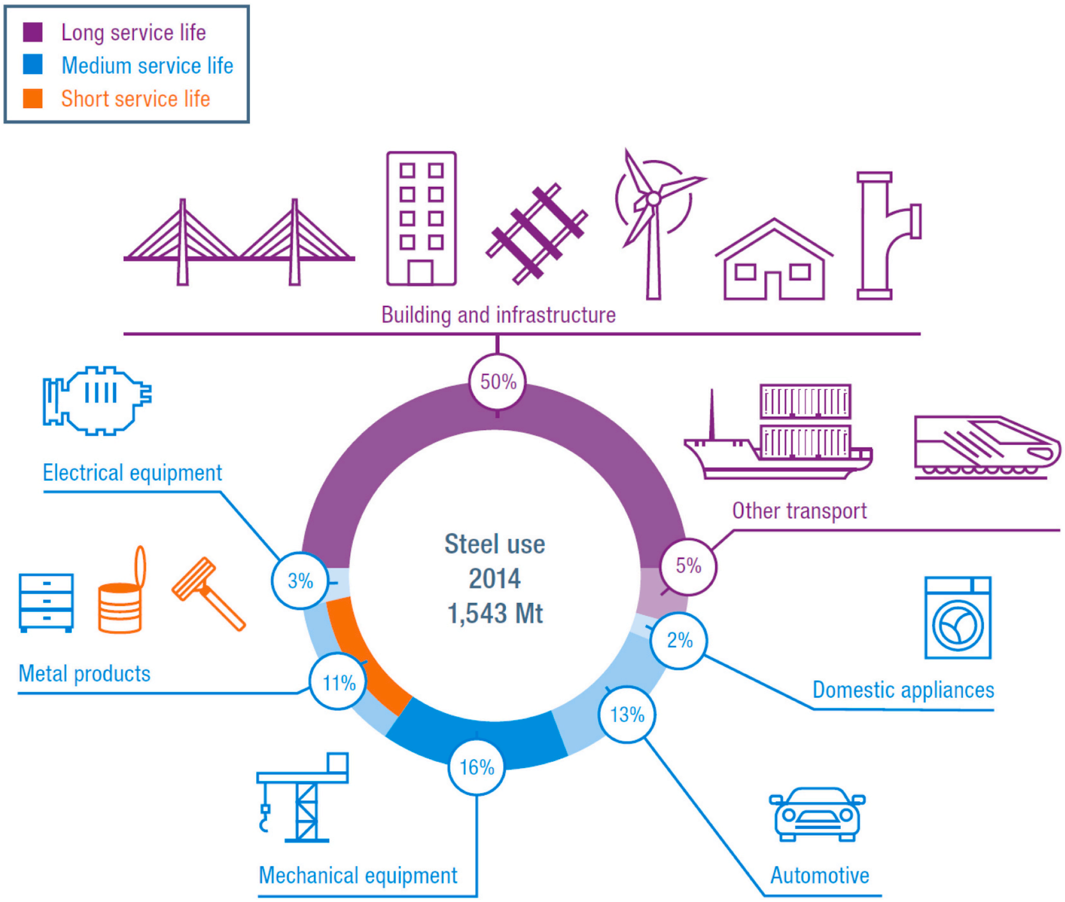

Fig. 24. Steel products and durability.
Source: [114].

imported goods.

Research & development of low-carbon technologies is an excellent answer to mitigate the climate crisis. For example, there is still potential to cut down the energy intensity in China's ferrous metal industry, especially in the S&P (smelting and pressing of ferrous metals) subsector. Compared with the international average standard, the energy intensity in the S&P industry is relatively high. Specifically, several measures can be used to reduce the energy intensity of China's FMI, i.e., increasing R&D subsidies for energy-saving and climate-friendly technologies and encouraging the diffusion of advanced equipment and technologies [191]. One research study also assessed decarbonization pathways for iron and steel through the 40 reviewed roadmaps and pathways (Fig. 25) [170]. Similar to our diagram for promising decarbonization options (Fig. 17), furnaces related to heating are the most mentioned topic for decarbonization R&D of the iron and steel sector.

One UK ERC study [192] reported the steel industry in the Republic of Korea as a representative example of policy-driven innovation. POSCO, a state-owned company in the past (not now), has adopted innovations in the iron and steel industry based on a clear strategy, R&D support for a university (POSTECH) and a research institute (RIST), and market creation under the Korean government's strategy [193]. Also, active transfer of innovative decarbonization technologies is essential. As one study [194] stated, a policy framework to support energy and industry transition could enable the environment for the transfer, such as hydrogen-based steel making. Simulations and assessments of the anticipated results for the decarbonization policies could also support investment and government intervention. One study presented the economic and environmental effects of China's national energy efficiency target [195], and another study appraised the economic benefits of the "STeel Environmental Assessment Program" in Japan [196].

Table 8
Policy mechanisms for the industrial decarbonization of iron and steel sector.

Instrument	Description
Carbon pricing	National and/or regional pricing on carbon emissions, including direct carbon taxes and emissions trading schemes to establish markets for carbon permits that can also be traded and sold, with some free allowances given
Voluntary and mandatory energy efficiency schemes	National and subnational programs and voluntary initiatives intended to promote energy efficiency practices and processes
Regulations on GHG emissions	Emission restrictions, such as relining ban of blast furnaces
Renewable energy incentives and guarantees	Direct government incentives for industrial scale renewable energy applications such as heat pumps, biogas, or biomass
Creation of low-carbon markets	Government created markets to offer premium prices for low-carbon products
Border-tariff adjustments	Restrictions placed on traded and imported carbon intensive goods, intended to carbon reduce leakage
Industry roadmaps	The creation of industry roadmaps to guide firms with decarbonization efforts

Source: Compiled by the authors. Note: Any general renewable energy support policies (i.e. FITs) are not included.

Table 9
Policy evaluation criteria for the iron and steel sector.

Criteria	Existing Clean Development Mechanism (CDM)	Harmonized carbon tax	Incremental emissions tax or intensity-based rewards	Regulatory standards
1. Short term: improve efficiency and CO_2 intensity of coal DRI and BF/BOF units	+	++	+	++
2. Medium term: encourage shift from coal DRI and small BF to large efficient BF units	−	+	−	++
3. Long term: encourage substitution of steel with low-carbon-intensive materials	−	+	−	N/A
4. Overall effectiveness	−	++	−	++
5. Ease of implementation	+	++	−	+
6. Ease of monitoring and verification	++	+	−	+

Source: [189]. Note: +++ is very good and — means worst.

	Iron & steel	(Petro)-Chemical	Cement	Pulp & Paper	Ceramics	Glass	Food
1. Most mentioned	Furnaces	Catalytic Processes	Alternative Feedstock	Industrial Ovens	Furnaces	Furnaces	Process Heat Provision
2.	Electrolysis	Heat Recovery	Biomass & Bio-based Waste	Heat Recovery	Heat Recovery	Heat Recovery	Industrial Ovens
3.	Flue Gas Recycling	Membrane Separation	CCS	CCS	CHP	Pre-Heater	CHP
4.	CCS	CHP	Furnaces	Biomass & Bio-based Waste	Biomass & Bio-based Waste	Oxyfuels	Biomass & Bio-based Waste
5. Least mentioned	Heat Recovery	CCS	Heat Recovery	Process Heat Provision	Alternative Feedstock	Recycled Primary Materials	Membrane Separation

Fig. 25. Decarbonization R&D pathways for manufacturing industries.
Source: [170]. Notes: Orange color denotes the options related to heat, and green indicates alternative feedstock or fuels. Blue is the technology about chemical and mechanical processes, and CCS/gas recycling is marked in grey.

9. Gaps and future research agendas

The last finding of our systematic review considers gaps in current research. Three distinct areas—cross-cutting solutions, interconnection to other systems, and the long-term impacts of COVID-19—are developed to discuss gaps and future research agendas.

9.1. Identification and pursuit of cross-cutting solutions

The decarbonizing practices and innovations collected for the iron and steel industry in Section 5 are narrowly focused on a single process such as sintering or blast furnaces. Also, because of the industry's concentrated nature—the top seven countries account for about 79% of global production—most of the research is only for limited players and countries [22] (see Table 1). Consequently, just a few studies attempted to identify *cross-cutting* measures that generally seemed across different subsectors or countries. Table 10 presents those cross-cutting options and examples specified.

A relatively short list of seven options in Table 10 and the visualized relationship between those options and the sociotechnical system

Table 10
Crosscutting options for the decarbonization of the iron and steel system.

Crosscutting option	Relevant for	Example(s)	Identified by
Energy efficiency	Raw material preparation, iron and steelmaking, steel products making, use of steel products	Efficient ovens, burners, kilns, furnaces, and compressors, efficient ladle preheating, top-pressure recovery turbines, efficient drives in rolling mill and machining	[56,78,136]
Fuel switching	Raw material preparation, iron and steelmaking, steel products making	Substituting coal and oil with renewables or natural gas	[66,197,198]
Process control and optimization	Iron and steelmaking, steel products making	Process modification of kilns, optimization of furnace, flue gas monitoring and control, improved process control, optimizing the process solution temperature, preventative maintenance	[17,73,74,99]
Heat recovery	Raw material preparation, iron and steelmaking, steel products making	Waste heat recovery from cooling water, annealing, and compressors	[91,199,200]
Recycling and resource efficiency	All processes and systems of the iron and steel sector	Solid recovered fuels for a reducing agent, injection of pulverized coal, rotary hearth furnace dust recycling system, hot oxygen injection, recycling basic oxygen furnace slag, recycling of stainless steel dust, new scrap-based steelmaking process	[114,201,202]
Hydrogen	Raw material preparation, iron and steelmaking, steel products making	Low-carbon hydrogen-based direct reduction, off-gas hydrogen enrichment, electrolytic hydrogen blending, natural gas-based with high levels of electrolytic hydrogen blending, hydrogen for high-temperature heat (ancillary processes)	[52,72,203,204]
Carbon capture, utilization, and storage	Raw material preparation, iron and steelmaking, steel products making	CO_2 removal for use or storage (BF) Natural gas-based with CO_2 capture (DRI) Smelting reduction with CCUS	[91,102,104,111,128]

Source: Compiled by the authors.

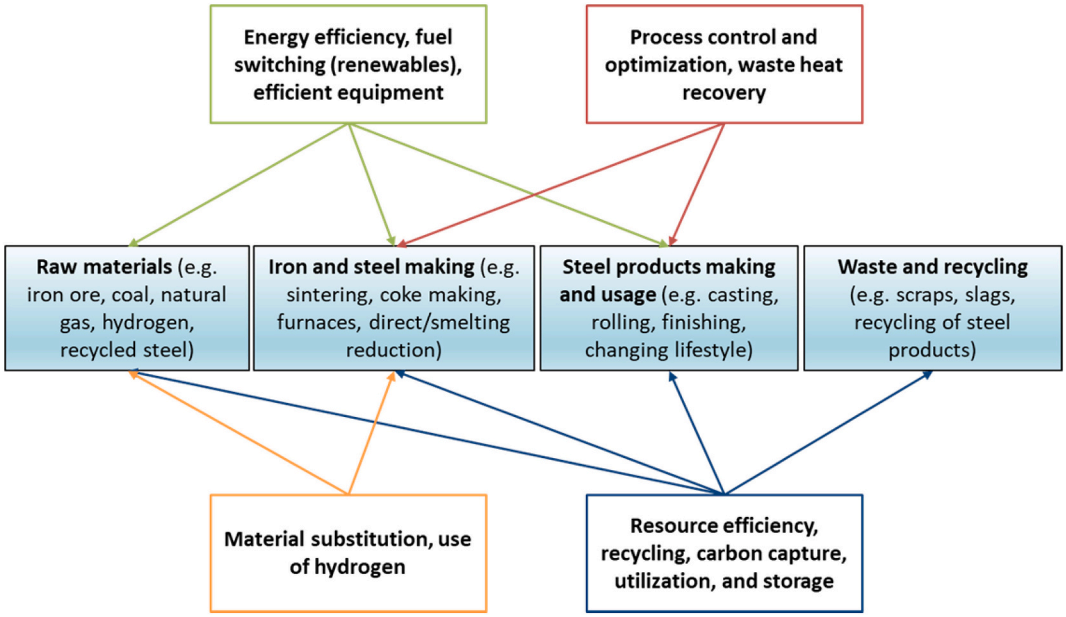

Fig. 26. Visualizing crosscutting options for the decarbonization of the iron and steel system.
Source: Authors.

(Fig. 26) indicate a clear insight—we already have practical and widely applicable options to achieve the decarbonization of the iron and steel industry. Policymakers, stakeholders, and investors can make a vivid vision for decarbonization based on these cross-cutting solutions as well as commercially applied options now. Table 10 is not exhaustive but rather a starting point for a better understanding of options moving forward. We thus believe "more work on cross-cutting options" should be pursued.

In particular, CCUS plays an essential role as a crosscutting option for iron and steel systems' decarbonization [86,205]. Ramírez-Santos et al. [126] give us great insight into the progress of gas separation technologies in the iron and steel industry. The largest CO_2 emission source in an integrated steel plant would be a power plant. The power plant can receive all kinds of available residuary gases. However, the study also indicated that the original source of most of the CO_2 emissions is BF, around 69% of the overall CO_2 emission [126].

9.2. Interconnection to other systems and industries

The global iron and steel system does not exist alone. Like many other industries, it is coupled to other sociotechnical systems [42]. Fig. 27 depicts the interconnections between the iron and steel industry and the other noticeable sociotechnical systems. The energy system including fossil fuels and renewables, transport, military and aerospace, buildings, mining, civil infrastructure, machinery, electronics, and even waste (scraps) needs iron and steel products.

These interconnections can create compelling dependencies, but also result in synergies that are rarely examined in research. Material Flow Analysis (MFA) [206] and Life Cycle Assessment (LCA) [207] approaches could be helpful to elaborate the synergies. For example, one study assessed the feasibility of material and technical efficiency improvement in the life cycle of steel products [118] by combining MFA and LCA. Applying the hybrid approach suggested in [118], the impact of synergies could be assessed, such as an HSS regulation in infrastructure. We note, however, that significant data collection and modeling would be necessary for the analysis.

The importance of exploring these synergies is also evident in the growing role that electric arc furnaces and recycled scrap play in steel production and decarbonization efforts. Many of the institutions that have published carbon mitigation options and technology roadmaps

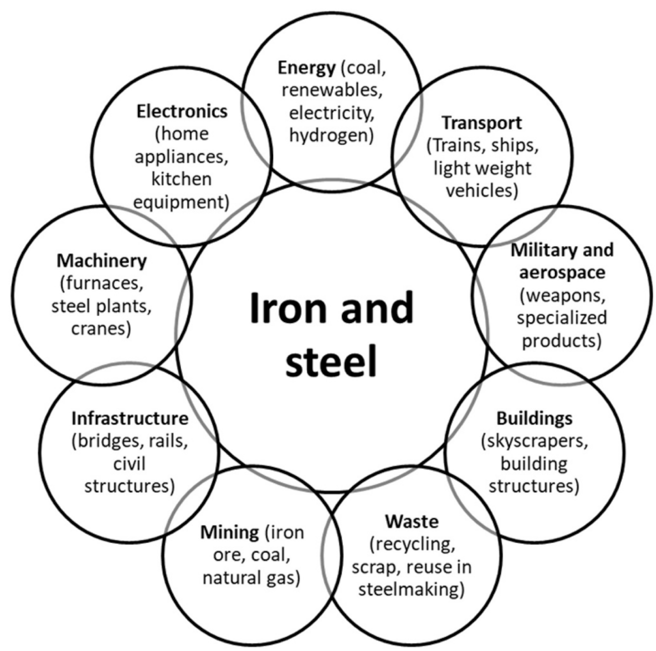

Fig. 27. Compelling interconnections of iron and steel to other sociotechnical systems.
Source: Authors.

[6–10] highlight the importance of EAF and iron/steel scrap. Therefore, the interconnections between the iron and steel industry and the other noticeable sociotechnical systems can highlight the future viability of an EAF based system, the availability of scrap steel, and steel's general ability to meet shifting sociotechnical needs.

In terms of sectoral carbon emissions, one study reveals that the embodied carbon emission of the steel bar and other steel products are the largest component of total embodied carbon emissions for the residential buildings in China with an estimated at 25– 31% share [208]. Another study claimed that the construction sector was the largest embodied energy consumption sector with a figure of 842.6 million tons

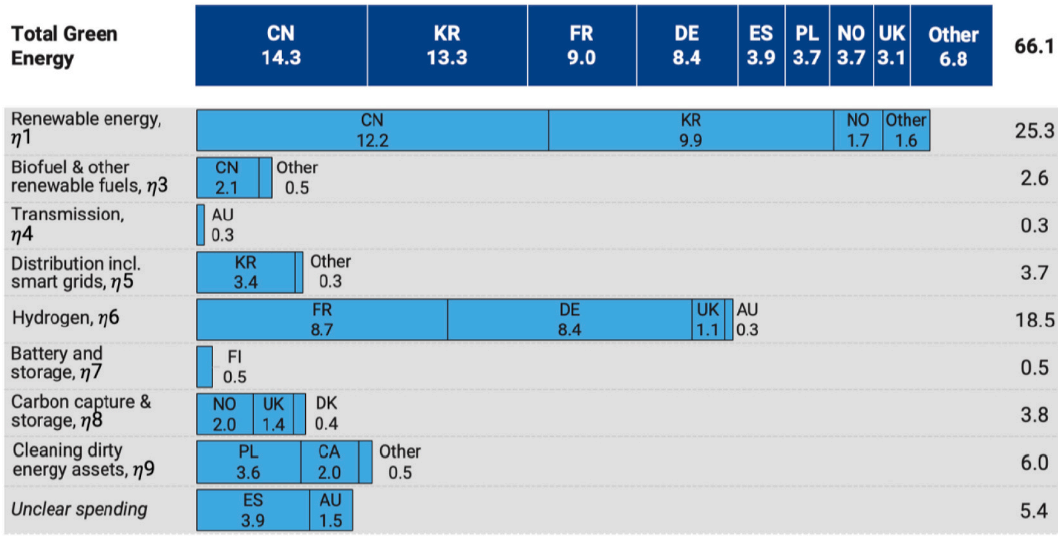

Fig. 28. Compelling total green energy spending by country and sub-archetype (Unit: billion US$).
Source: [210], Global Recovery Observatory. Notes: For each sub-archetype, the largest contributors are listed by name, with smaller spenders categorized as "other." AU: Australia, CA: Canada, CN: China, DE: Germany, DK: Denmark, ES: Spain, FI: Finland, FR: France, KR: South Korea, PL: Poland, NO: Norway, UK: United Kingdom.

of CO_2e, accounting for 52.7% of total embodied emissions in China [209].

9.3. *Research into the long-term impacts of COVID-19*

A novel Coronavirus (COVID-19) emerged in early 2020 with significant demand and even production impacts on the iron and steel industry as well as the overall energy sector.

A multitude of factors contribute to uncertainty in the global outlook for the steel industry, affecting forecasters' ability to anticipate prices, future levels of demand, employment and many other aspects. Many of these factors are persistent, such as uncertainty about the future rate of growth in the global economy, or the levels of consumer demand in a given downstream market. But the current levels of uncertainty for the short-term outlook for the sector, like all other sectors of the economy, may well be unprecedented, largely relating to the unknown future impacts of the Covid-19 coronavirus pandemic.

The outbreak triggered a series of confinement procedures, and several downstream industries (construction, automotive etc.) have seen reductions in output. However, China's crude steel output has remained robust, with a 2.2% year-on-year increase to 503 Mt per year (in the first half of 2020). Stagnating and declining demand levels in its domestic and export markets indicate a significant accumulation of inventory during this period of strong production growth.

In production centers elsewhere the virus has had a much more profound impact on production levels. In the first half of 2020 steel production in Europe declined by 13% relative to the same period in 2019, by 17% in North America and 24% in India [6].

The longer-term impacts of the virus outbreak are even more uncertain. The way that other countries besides China respond to the outbreak, in terms of the duration and extent of confinement policies, and the level to which demand in various economies is restored—including the extent to which stimulus packages are aimed at infrastructure and other steel-intensive sectors—are the key determining factors that will affect the steel industry's outlook in the coming years [6].

Although stimulus packages have been generally disappointing regarding allocation of funds to sustainability-related investments, several European countries have earmarked investment for hydrogen and CCS, both of which are cornerstone technologies for iron and steel decarbonization [210]. As shown in Fig. 28, USD$18.5 billion has been allocated to hydrogen infrastructure with Germany and France leading the way. A further USD$3.5B has been invested in CCS infrastructure with Norway and the UK each contributing more than USD$1 billion.

Stimulus spending on R&D for industrial sustainability is also an opportunity. As shown in Fig. 29, USD$29 billion has been committed to "green" R&D as part of stimulus packages, with USD$5.5 billion focused on industry [210]. As shown in Fig. 29, South Korean leads this investment, which is consistent with the country's focus on "Innovation in the Green Industry" as part of its Green New Deal COVID-19 stimulus efforts [211]. One would expect the iron and steel industry to benefit from this stimulus given that South Korea is a major global steel producer and, as noted previously in this paper, serves as an example of a country that has undertaken policy-driven innovation in the iron and steel industry.

The need for target COVID-19 stimulus in the iron and steel industry has been highlighted by the IEA with particular focus on direct electrification of primary steelmaking [212]. We've discussed in this paper the breakthrough potential of molten oxide electrolysis to eliminate the need for direct use of fossil fuels in steel production and perhaps COVID-19 will lead to the necessary support for the technology to reach broad deployment.

10. Conclusion

Our modern life is built on iron and steel products. We are working and living in buildings and skyscrapers, and we need airplanes, vehicles, and bridges to move. Even in the sustainable, low-carbon future, there still are buildings, transport, infrastructures, and devices using iron and steel. This essential iron and steel industry is the most carbon-emitting sector among heavy industries and has been efficiently operated close to its thermodynamic limits. Thus, to break the limit, innovative decarbonization efforts are necessary. This is why we have done a critical and systematic review of the sociotechnical systems of iron and steel. Fig. 30 summarizes our review showing interventions, benefits, barriers, and policies for decarbonizing the iron and steel system.

Fig. 30 also reveals practical low-carbon interventions (shown in green). These range from material substitution in raw materials to reuse of steel products are part of the broader circular economy. These available technologies and approaches can coexist with no less than 86 current and breakthrough technologies and cross-cutting solutions such as hydrogen-based steel production and CCUS technologies (see Section

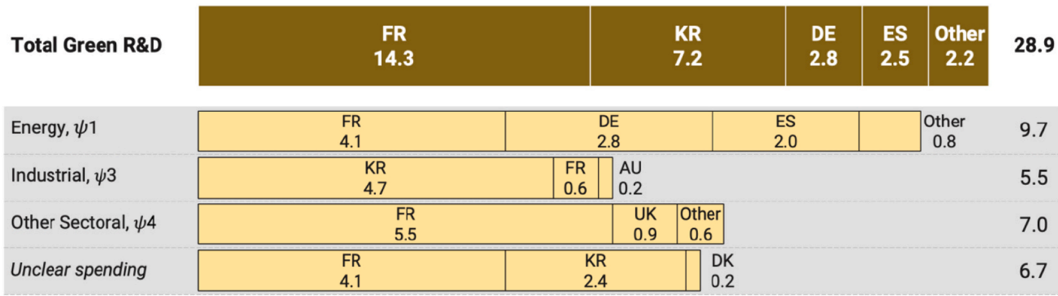

Fig. 29. Total green R&D spending by country and sub-archetype (Unit: billion US$).
Source: [210], Global Recovery Observatory. Notes: For each sub-archetype, the largest contributors are listed by name, with smaller spenders categorized as "other." AU: Australia, DE: Germany, DK: Denmark, ES: Spain, FR: France, KR: South Korea.

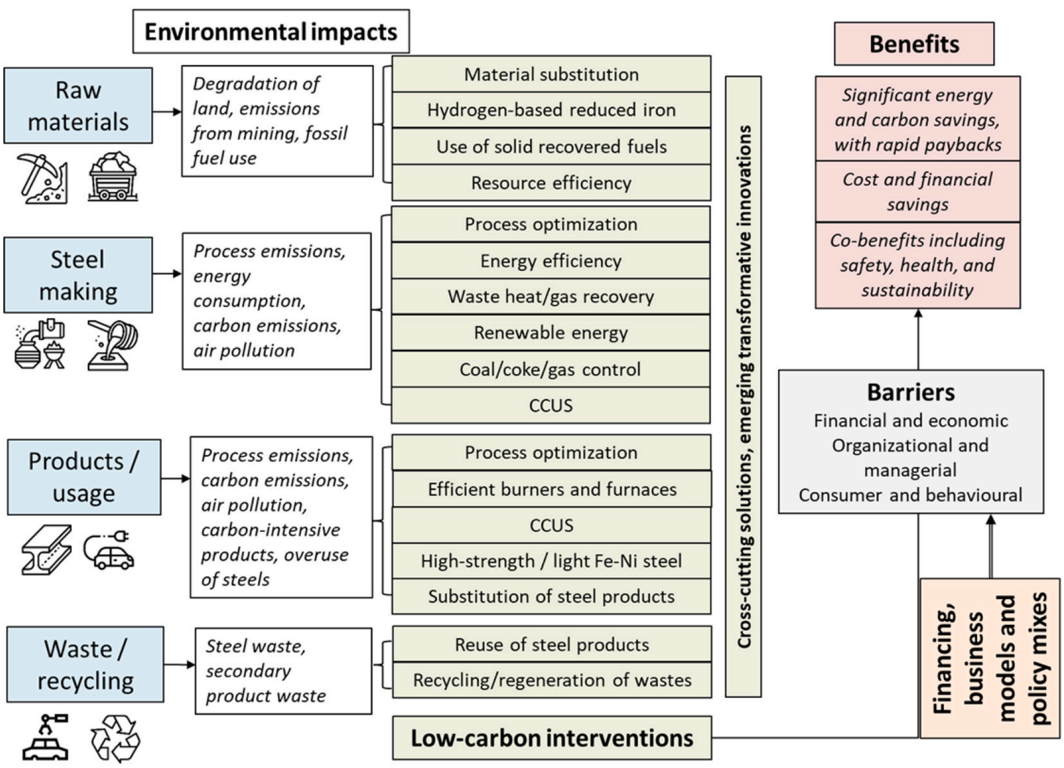

Fig. 30. Interventions, benefits, barriers, and policies for decarbonizing the iron and steel sociotechnical system.
Source: Authors.

9.1).

Although there are barriers (shown in grey) at many levels to decarbonizing the iron and steel industry—financial, organizational and managerial, and behavioral—the benefits (shown in red) of the decarbonization are also considerable. Direct benefits from carbon reduction, energy savings, and financial savings, as well as environmental co-benefits, will shorten the payback period of decarbonization investments. Also, indirect benefits from the interconnected industries (Fig. 27) and policy instruments, financing solutions, and business models (shown in orange) can help tackle the barriers.

When the policymakers, business, and research community begin to address the decarbonizing options, barriers, and solutions more actively, and perhaps with the COVID-19 pandemic as an added catalyst, imminent problems by greenhouse gas emissions from the iron and steel system can be resolved and turned into another opportunity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Description of emerging and potentially transformative innovations for the iron and steel industry.

Innovation	Description
Solid recovered fuels for use as reducing agents	Recovered wastes, such as plastics or granulated rubber, could be used as reducing agents (producing CO and H_2) in blast furnaces.
Heat recovery from sinter cooler	There are two potential reusable waste heat in sinter plants—exhaust gas from sintering machines and the cooling air heat.
Single-chamber-system coking reactors	Single-chamber-system (SCS) coking reactors are huge coke ovens with widths of 450–850 mm. The SCS reactors have independent process-controlled modules that allow thinner heating walls to improve heat transfer and design flexibility.
Use of recuperative burners	A recuperator, a gas-to-gas heat exchanger in the recuperative burner of a furnace, can reduce fuel consumption about 10–20% than the furnaces without the recuperative burner.
Process modification of kilns	Process modifications of kilns, such as green balls heated and cooled in a grate-kiln, can cut energy use and CO_2 emissions.
Optimization of furnace	Furnace optimizations using computational fluid dynamics, simulation (virtual furnace), and X-ray diffraction analytical techniques can improve energy efficiency and productivity.
Waste heat recovery	We can recover waste heat in blast furnaces, such as molten slag heat, in three forms—hot air or steam recovery, conversion to chemical energy, and thermoelectric power generation.
Use of ceramic ladles instead of cast iron pipes	In the iron and steel making processes, ladles are often uncovered because lids are heavy and too hot to manage. Thus, closing the lid by using ceramic ladles can save significant energy.
Efficient ladle preheating	Heat losses in the ladle preheating can be reduced by temperature controls, installing hoods, efficient ladle management, or oxyfuel burners.
Radiation recuperators for ladle furnace	Installing recuperators for the ladle can improve fuel efficiency.
Coal moisture control	Moisture control of feed coal in the coke making process improves coke quality and productivity.
Coke dry quenching	Coke dry quenching (CDQ) reduces dust emissions, enhances coke quality, and recovers sensible heat from the high-temperature coke.
Injection of pulverized coal	Coke making process can be skipped by injecting pulverized coal. Fine coal granules are injected into the blast furnaces to supply carbon sources. Skipping energy-intensive coke making process means substantial energy saving and CO_2 emission reduction.
Top-pressure recovery turbines	If the top gas pressure of blast furnaces is high enough to generate electricity, then applying top-pressure recovery turbines will be an economically feasible option.
Recovery of BF/BOF gas	Carbon monoxide and hydrogen in the blast furnace gas are potential energy sources and can be used as a fuel through enrichment with natural gas or coke oven gas.
Charging carbon composite agglomerates	Applying the carbon composite agglomerates, the mixtures of fine iron ore and carbonaceous materials, in blast furnaces and electric arc furnaces can improve reduction rates and save fuels.
Near net shape casting (thin slab)	Near-net-shape casting is the integrated process of casting and hot rolling. This integration reduces reheating the steel before rolling and thus saves energy.
Bottom stirring/stirring gas injection	Injecting an inert gas to increase stirring in the bottom of the electric arc furnaces can make the heat transfer efficient and save electricity consumption.
Use of foamy slag practices	Heat losses in electric arc furnaces can be reduced by covering the arc and melt surface of furnaces with foamy slag.
Use of oxyfuel burners	Oxy-fuel burners in electric arc furnaces can increase heat transfer (reduces heat losses), help to remove impurities, such as phosphorus and silicon, and reduce electrode consumption.
DC arc furnace	Direct current (DC) based electric arc furnace has high productivity, uses less electricity, consumes less electrode, and needs lower maintenance costs than conventional furnaces.
Scrap preheating and continuous charging	Efficient scrap preheating and continuous charging, such as Consteel, can improve the heat recovery rate and reduce handling costs and time.
Flue gas monitoring and control	Flue gas (oxygen and carbon monoxide) monitoring and control enable the optimization of fuel and air mixture, and this can improve the energy efficiency of the process.
Eccentric bottom tapping	Eccentric bottom tapping in electric arc furnaces enables slag-free tapping and reduces tap-to-tap time and electrode consumption.
Improved process control	Improved process control of electric arc furnaces includes process optimization via (real-time) monitoring and controlling systems with sensors. Optimized steel bath temperature and carbon levels can reduce electricity consumption in the process.
Ultra-high-power transformer	Applying ultra-high power (UHP) transformer for the furnace operation can reduce energy losses and increase productivity.
Twin shell furnace	The twin shell furnace is based on shaft technology. A double (two identical) shaft arrangement can improve the efficiency of preheating.
Hot charging	Charging slabs at a high temperature (hot charging) in the reheating furnaces of the rolling mill can reduce energy use and material losses and improve steel quality and productivity.
Recuperative or regenerative burner	Recuperative or regenerative burners can be utilized not only for iron and steel making processes but also in steel product manufacturing.
Use of ceramic low thermal mass insulators for reheating furnace	Compared to conventional insulation materials, ceramic low thermal mass insulation materials can reduce heat losses in reheating furnaces.
Controlling oxygen level and variable speed drive on combustion air fans	The optimal oxygen (air) level in a combustion process is essential to improve energy efficiency. We can find the optimal level by applying variable speed drives of air fans in the reheating furnace.
Efficient drives in rolling mill and machining	Replacing the air conditioning drives in a rolling mill and machining with high-efficiency motors can save electricity consumption.
Waste heat recovery (cooling water, annealing, and compressor)	We can recover the waste heat from cooling water, annealing, and compressors of the steel product manufacturing processes, such as hot strip mills.
Reduced steam use for pickling	Installing lids and floating balls on the top of the bath in the acid pickling line can prevent heat losses via evaporation.

(*continued on next page*)

Table A1 (*continued*)

Innovation	Description
Automated monitoring and targeting systems	In a cold strip (rolling) mill, an automated monitoring and targeting system can reduce energy demand and effluents.
Thermal insulation for plating bath, Automated bath cover	Automated bath cover and thermal insulation of plating bath can reduce energy losses in strip mills.
Compressed air network modification	Modifying (optimizing) a compressed air network and motor systems in steel product manufacturing can reduce waste heats and energy use.
Optimizing the process solution temperature	A heat treatment process and thermal optimization in steel product manufacturing, such as continuous casting, can reduce energy consumption for the process.
Use of high-strength steel	High-strength steel (HSS) consumes less raw materials compared to standard steel products at similar specifications. Also, light product weight, especially for vehicles, needs fewer fuels to move the same distance. Thus, in terms of lifecycle, the HSS significantly less emits greenhouse gases.
Rotary hearth furnace dust recycling system	Recycling steelmaking dust, including iron and zinc dust, can save raw materials inputs.
Injection of plastic waste	Plastic wastes can replace coke for the reduction reaction in blast furnaces. Although plastics cannot replace all coke functions, such as moving the gases and liquids, we can save substantial energy through the replacement at a certain level.
Primary Energy Melter	Primary Energy Melter (PEM) enables the melting of low-quality scrap and charges it together with hot metals. PEM can thus reduce energy and material consumption.
Advanced control of heating walls in coke ovens	Advanced control of heating walls, such as individual control and diagnostic system, can improve energy efficiency in coke ovens.
Hot oxygen injection	Injecting high-temperature oxygen directly in the blast furnace blowpipe and tuyere can offer better coal dispersion at high oxygen concentrations. Thus, the injection of pulverized coal accompanies hot oxygen injection for optimal performance.
Tecnored	The Tecnored, a Brazilian process, uses agglomerated pellets or briquettes for iron making. With the flexibility of using various types of solid fuels, the Tecnored process can reduce greenhouse gas emissions.
Cyclone converter furnace	The cyclone converter furnace is made of a cyclone for the pre-reduction of the iron ore. Combining this pre-reduction unit with the final reduction process can reduce heat losses.
Continuous horizontal sidewall scrap charging	Continuous horizontal sidewall scrap chargers can mitigate the problems in conventional scarp preheaters, such as frequent maintenance, space constraint, and the need for a post-combustion burner.
Energy monitoring and management system in casting	Energy monitoring and management system in the casting process can make the process more energy-efficient through energy assessment and optimization.
Preventative maintenance in steel mills or EAF plants	Preventative maintenance in steel mills or EAF plants through sensors and data analysis can improve the productivity of the mills and reduce overall energy consumption per unit production.
Variable speed drives for flue gas control, pumps, fans in integrated steel mills	Variable speed drives mentioned above can be applied for not only reheating furnaces but also pumps and (ventilation and combustion) fans in integrated steel mills.
Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills	Cogeneration (or combined heat and power) for the gases in integrated steel mills is an energy-efficient way to use heat and electricity.
Additive manufacturing	A digitalized production process, additive manufacturing, can minimize material losses and facilitate lighter-weight parts design in steel product manufacturing.
Recycling basic oxygen furnace slag	The recycling of slags can reduce the landfill disposal of byproducts from blast furnaces and basic oxygen furnaces. However, it still faces many technical and economic challenges.
Recycling of stainless steel dust	The stainless steel dust in electric arc furnaces can also be recycled by re-injection into the furnaces and improve the energy efficiency of the steelmaking.
Regeneration of hydrochloric acid pickling liquor	The pickling process generates considerable spent pickle liquor, and regenerating it can reduce wastes and energy use because the acid spent pickle liquor should be disposed of after chemical neutralization.
Recycling of waste oxides in steelmaking furnace	Recycling waste oxides in steelmaking furnaces and mills, such as blast furnaces, electric arc furnaces, and rolling mills, can save raw materials and energy.
Low-carbon hydrogen-based direct reduction	Hydrogen-based steelmaking routes offer great potential for decarbonization. However, note that they strongly depend on the carbon footprint of hydrogen production.
Charcoal in the sintering process	Charcoal is an attractive alternative to coke breeze in the sintering process.
Torrefied biomass	Torrefied biomass, biochar, can be used as an auxiliary reductant.
Plasma blast furnace	Plasma technology can be used for heat support for cupola and blast furnaces.
CO_2 removal for use or storage, Natural gas-based DRI with CO_2 capture	CCS and CCUS technologies can be applied to iron and steel making processes. Please see the references in the main body of the text.
Electrolytic H_2 blending (BF), Natural gas-based DRI with high levels of low or zero-carbon electrolytic H_2 blending, DRI based solely on low or zero-carbon electrolytic H_2	Also, low or zero-carbon hydrogen produced by electrolysis (green hydrogen) can be applied to iron and steel making processes.
Paired straight hearth furnace	Paired straight hearth (PSH) furnace is more productive than conventional furnaces. The PSH furnaces are charged with "eight" cold-bonded self-reducing pellets, whereas the traditional rotary hearth furnaces use only two or three.
Molten oxide electrolysis	Molten oxide electrolysis (MOE) could be a game-changer of the steelmaking process. Unlike traditional steel production, MOE produces no carbon emissions if powered by zero-carbon electricity sources.
Suspension hydrogen reduction of iron oxide concentrate	Flash smelting uses hydrogen as a reductant. Iron ore concentrates react with reductants, such as hydrogen, natural gas, or synthetic gas.
Ironmaking using biomass and waste oxides	Replacing fossil fuels, especially coal, in the ironmaking processes with biomass and waste oxides can curtail energy use and CO_2 emissions.
New scrap-based steelmaking process	A new, efficient scrap-based steelmaking process, such as a counter-current reactor, can reduce primary energy use in the scrap heating and melting steps.
In-situ real-time measurement of melt constituents	Off-line molten material analysis to check the composition of melt constituents is time-consuming and expensive. In-situ real-time measurement thus saves time and energy.
Continuous steelmaking for EAF	

(*continued on next page*)

Table A1 (*continued*)

Innovation	Description
	The continuous steelmaking, continuous process from crude steel to the casting mold in EAF, can improve energy efficiency and productivity.
Smelting reduction with CCUS	Carbon capture, utilization, and storage technologies can be applied in a smelting reduction process (i.e., HIsarna process, ULCOS).
Low or zero-carbon H_2 for high-temperature heat	The coal-based high temperature for the iron reduction can be replaced with green hydrogen (ancillary processes).
Next-generation system for scale-free steel reheating	Scale formation hinders gas flow and heat transfer and compromises steel quality. During the steel reheating process, 1–2% of the steel forms scale on the steel surface and furnaces. Thus, scale-free steel reheating can reduce the energy and costs of the process.
Thermochemical recuperation for steel reheating furnaces	Thermochemical recuperators (air heat exchangers) can improve the steel reheating efficiency by recovering sensible heat in the flue gases.
Oxygen-rich furnace system	A low NO_x burner with oxygen enrichment can reduce CO_2 emissions in the furnaces.
Integrating steel production with mineral sequestration	CO_2 sequestration in the form of solid carbonate can be integrated into the steelmaking process. The iron oxides from peridotite ores can chemically bind CO_2.

Source: Authors. The relevant references are provided in the main body of the text.

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