Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(11), 489–501
https://doi.org/10.12913/22998624/209894
ISSN 2299-8624, License CC-BY 4.0

Received: 2025.05.09
Accepted: 2025.09.15
Published: 2025.10.01

Possibilities of reducing greenhouse gas emissions in the steel industry

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ABSTRACT

Steel is a key raw material for many sectors of the economy, including construction, transport and the machinery industry. In 2023, 71 countries produced 1.89 billion tons of steel, and its consumption amounted to 1.763 billion tons. At the same time, the steel industry is responsible for about 7% of global greenhouse gas emissions and 11% of CO_2 emissions. The dominant production technology is the blast furnace process (BF-BOF), which requires the use of coal, and the less emission-intensive electric arc furnace (EAF) method, which uses scrap and electricity. The growing demand for steel forces the search for low-emission production methods. Currently, research focuses on the intelligent use of coal (e.g. PCI method) and CO_2 capture technologies (CCUS), but their full commercialization requires further development. This paper attempts to assess the technological maturity of modern (low emission) steel production methods and the possibilities of their effective application. The idea of decarbonization requires avoiding coal. It is believed that ultimately the best method will be direct reduction of iron ore with hydrogen. To achieve the required effect of decarbonization of the production process, the most important method of steel production will be the use of hydrogen obtained from renewable energy sources.

Keywords: hydrogen, electric arc furnace, blast furnace, steel production technologies, basic oxygen furnace, direct reduced iron, low-emission steel production technologies, decarbonization potential.

INTRODUCTION

Steel is a man-made alloy of iron with carbon (and other elements) – just like cast iron and pig iron. Depending on the carbon content, these alloys are given specific names: steel has up to two percent carbon, iron more than two percent, and pig iron four to five percent (plus other elements). It is an extremely important material for both today's society and tomorrow's low-carbon economy, being an essential component of most EU industrial ecosystems. Its use is ubiquitous, in virtually all areas of human activity.

In 2023 year, 1.763 Mt of steel was used, and especially in buildings and infrastructure (52%), automotive and other transport industry (17%), mechanical equipment (16%), metal products (10%), electrical equipment and household appliances (5%) [WSA, 2024]. Globally, 219 kg of steel was used in new products per person in 2023 [WSA, 2024]. It is estimated that on average in the European Union currently around 12 tons of steel per person is in use [Report, 2019; COM350, 2021].

Steel production and use plays a significant role in the global economy, with revenues exceeding $2.5 trillion and employing around 6 million people worldwide [IEA, 2020]. Total global crude steel production in 2023 was 1,888.2 million tones, almost the same as in the previous year (1,887.6 million tons). Crude steel production in China (2023) was 1019.1 million tons, and in India – 140.2 million tons, in Japan – 87 million tons [Production, 2023].

Steel is not a homogeneous product, and types of steel can be distinguished by their chemical composition, physical form, stage of transformation, and quality [COM350, 2021]. This is why it can be used so widely for different purposes. It is an essential raw material for modern economies, and global demand for it will increase in the coming decades to meet growing social and economic needs. Meeting this demand will be a challenge for the iron and steel sector, which, aware of its significant impact on the environment, and therefore also on the climate, is trying to set a more sustainable path for its development [IEA, 2020].

CURRENT STEEL PRODUCTION TECHNOLOGIES

Steel production is a complex, multi-stage process that requires the involvement of various technologies and skills. During these multifaceted processes raw materials are transformed into finished steel products through several key stages: raw material preparation, ironmaking, steelmaking, secondary refining, casting, and rolling and finishing. The most important ingredient is iron ore, which is obtained from minerals containing iron.

Raw material preparation

The first stage is the acquisition of the necessary raw materials. This initial stage involves preparing the charge for the metallurgical process.

Iron ore processing

Iron ores are rocks and minerals from which metallic iron can be economically extracted. Iron ores differ in their chemical composition and iron oxide content. The most used ores in metallurgy are magnetite, hematite, goethite, limonite or siderite. Iron ore is subjected to beneficiation processes to enhance iron content and eliminate impurities. This involves crushing, grinding, and various separation techniques to produce sinter or pellets suitable for the blast furnace.

Coke production

Metallurgical coal undergoes pyrolysis in coke ovens at high temperatures (~1000 °C) in an oxygen-deficient environment, producing coke. This carbon-rich material is essential for the blast furnace, providing both fuel and a reducing agent**.** In the metallurgical process the metallurgical coal is used, also known as coking coal, which has special parameters different from thermal coal. Thermal coal and coking coal are two different types of coal with different properties and applications. Coking coal is essential in the steel industry, especially in steel production. During the coking process, this coal is heated without access to air, which leads to the formation of coke – a material with a high carbon content and a porous structure. Coke plays a key role in blast furnaces, where it acts as a reducing agent and a heat source in converting iron ore into iron [Ozga-Blaschke, 2020]. The properties of coking coal, such as the appropriate carbon content, low impurity content and the ability to sinter, make it an irreplaceable raw material in metallurgy. Its unique ability to transform into a plastic state during heating and then harden into a porous body is crucial for the efficiency of metallurgical processes [Mertas and Ściążko, 2019].

Coking coal accounts for about 23% of annual global coal production [IEA, 2020; SteelWatch, 2023] and most of the global coal supply is used by the steel sector. Metallurgical coal in the blast furnace acts as both an energy carrier providing heat, as well as a reducing agent – reacting with iron oxide to remove oxygen and providing physical structural support inside the furnace (a kind of grate for the charge) [SteelWatch, 2023]. The heavy reliance of the blast furnace on metallurgical coal results in a significant carbon footprint. Producing one ton of steel using the BF-BOF method requires 0.77 tons of metallurgical coal, which, according to World Steel estimates, is responsible for 2.32 tons of CO_2 per ton of steel and over 3 tons of CO_2e after considering methane from coal mining [SteelWatch, 2023].

Scrap metal preparation

As more and more steel is becoming waste material, the possibility to reuse scrap to produce new steel products becomes increasingly important. Recycled steel is sorted, cleaned, and processed to remove contaminants. Prepared scrap is then sized appropriately for efficient melting in the metallurgical process.

Ironmaking

At this stage, the most common method is using the blast furnace (BF), while there exists also the other route called direct reduced iron method (DRI).

Blast furnace (BF) method

In a blast furnace iron ores are processed into raw steel material – the so called pig iron.

The furnace is charged with iron ore, coke, and fluxes (such as limestone). Hot air (~1200 °C) is blown into the furnace, easing the reduction of iron ore to molten iron (hot metal). The chemical reactions produce slag as a byproduct, which floats atop the molten iron and is removed. As a result of chemical reactions, iron is separated from other impurities. The heat energy to power the furnace can be supplied directly by burning fuel or by providing electrical energy. The most used fuel is hard coal or coke, which function as a reducing agent in the process.

A blast furnace is a continuously operating shaft furnace in which the counter current charge (from top to bottom) and gas (from the bottom of the furnace to the top) exchange heat and mass. From the top, coke and charge, which consists of sinter, lumps, ore and fluxes, are charged in alternating layers using a dumping device. The charge materials move by gravity. In the lower part of the furnace, hot air from the heaters is blown through the tuyeres and reacts with the coke. Carbon monoxide is produced, which reduces iron oxides in iron ores. Molten metal is collected at the bottom. In addition to hot metal, slag is formed, which, due to its lower density, floats on the surface of the hot metal bath. The products of the blast furnace process are pig iron, slag, blast furnace gas and exhaust dust.

Pig iron is an intermediate product in a production of iron and steel. Typically, it contains about 3–4% carbon, and other impurities such as silicon, manganese, sulphur, and/or phosphorus.

Slag and flue dust can be treated as waste or used to produce building materials. Blast furnace flue gases consist mainly of carbon, oxygen and sulphur compounds, which form sulphur dioxide and carbon dioxide, a greenhouse gas. Flue gases also include nitrogen compounds, as well as water vapor and argon [Lanzerstorfer et. al., 2019]. These compounds pose a threat to the environment. This is the main reason that steelmaking is one of the most carbon emission-intensive industries. As of 2020, steelmaking was responsible for about 10% of greenhouse gas emissions. The industry is seeking significant emission reductions [Hoffman et al., 2019].

Scientists and technologists are looking for methods to reduce the emission of this process. Coal dust can be injected into the BF furnace – this is the so-called pulverized coal injection (PCI) technology. Some steelmakers are conducting tests to replace fossil coal with biochar, which is produced by biogreen pyrolysis and carbonization of raw biomass [Anderson, 2022]. However, biochar has a higher proportion of potassium K and phosphorus P, which poses a challenge to steel quality [Anderson, 2022]. Regardless, this method can reduce carbon dioxide emissions by up to 40% [Vogl and Åhman, 2019; Anderson, 2022].

Top gases produced during blast furnace power generation or heating can be recycled by feeding carbon and hydrogen emissions back into the furnace – this is called top gas recycling (TGR). The operation requires less energy and reduces the need for coke. Depending on the flame temperature, injection location and carbon monoxide, expected carbon savings are 21–25% [ULCOS, 2014; Anderson, 2022].

Direct reduced iron (DRI) method

In this alternative method, iron ore is reduced in its solid state using reducing gases like hydrogen or carbon monoxide, producing direct reduced iron (sponge iron). The process runs at temperatures below the melting point of iron and is gaining attention for its potential to reduce CO_2 emissions [Souza Filo et al., 2021]. Together with the next stage of steel production from iron in an electric arc furnace, it is a mature market alternative technological route to the traditional BF method of iron refining.

DRI iron production involves the reduction of iron ore by removing oxygen from the iron through a chemical reaction with a hot reducing gas. The hot DRI iron can be fed directly into an electric arc furnace (EAF) or compacted as Hot Briquetted Iron (HBI), which allows for better storage and transportation. The DRI or HBI iron is then fed into an EAF

to obtain liquid steel from solid iron. This technology is already available on an industrial scale and allows the use of natural gas as a reducing gas in the first step and then switching to hydrogen when it is available in sufficient quantities [Galimberti, 2022].

The main differences between this method and the BF method are [IEA, 2020]: use of high quality DRI pellets, reduction of solid iron ore in a DRI furnace before being sent for melting in an EAF, hydrogen and carbon monoxide are the main reducing agents, use of mainly natural gas to generate the reducing synthesis gas (carbon monoxide and hydrogen). Directly reduced iron DRI and hot-briquetted iron HBI are also increasingly used as raw materials due to their lower content of undesirable metals (e.g. Cu).

Steelmaking

Basic oxygen furnace (BOF)

Basic Oxygen Furnace is the next step after the iron is produced in blast furnace. The process is based on a BF integrated with a basic oxygen furnace (BOF), where iron ore is the main input material, with the addition of usually 15–25% of steel scrap. Inside the BF, the hot temperature melts the iron ore. The products of this process are hot metal and slag. After cleaning, the hot metal is fed to the BOF with limestone and other fluxes and oxygen, as well as steel scrap. The exothermic reactions raise the temperature, and controlled amounts of scrap steel are added to regulate it. The addition of steel scrap contributes to the reduction of CO_2 emissions by about 10–20% [Wimmer et al., 2022]. Moreover, it allows the reuse of already used steel. Increasing the share of scrap in existing BOF installations does not require any changes in infrastructure and could contribute to increase in CO_2 emissions reductions, but the BOF is an autothermal process without the possibility of external (electric) heating. This circumstance is a limitation for increasing the share of steel scrap in the input, which in turn limits the potential for CO_2 reduction [Wimmer et al., 2022]. The result is refined molten steel with desired chemical compositions [Galimberti et al., 2022; Kawabata, 2023]. The process is cheap because it accepts iron ores of different qualities, but it is energy intensive and difficult to decarbonize. This is the main challenge for the steel industry [Carvalho, 2024]. The final production of one ton of steel in the BF-BOF (blast furnace-basic oxygen furnace) requires about 15 GJ of final energy [IEA, 2020].

In the production process of 1 ton of steel in the EU-28, more than 30 kg of dust and 230 kg of slag are generated, which in 2022 constituted more than 5 Mt and almost 40 Mt of secondary raw materials, respectively, for which it is necessary to find ways to completely recycle them [Simoni et al., 2024]. It should be noted that the chemical composition of dust and slag varies depending on the type of feedstock used, the volatility of each of the elements contained in the feedstock, as well as the conditions prevailing in the furnace [Simoni et al., 2024]. SAF or similar open slag bath furnaces (OSBF) can replace iron production in blast furnaces, which will reduce the demand for coke and coal. The advantage of this technology is the possibility of using lower quality iron ore and a significant reduction in carbon dioxide emissions. These technologies are currently under development [Anderson, 2022].

Nowadays, the availability of high-grade iron ores is limited, and the blast furnace process uses low-grade iron ores, which requires novel solutions for final reduction, melting and refining of lower-grade DRI. A two-stage hot metal production process followed by refining in a BOF converter is the most promising solution for low-grade ores [Wimmer et al., 2022].

Electric arc furnace (EAF)

Electric Arc Furnace melts scrap steel or DRI using electric arcs generated between graphite electrodes and the metal charge. The process allows for precise control over the composition and temperature of the steel. EAFs are flexible and can be rapidly started or stopped, making them suitable for recycling scrap and producing various steel grades. The process is often called the secondary steel production as the steel is produced from recycled scrap.

In contrast to the BF integrated with a BOF, in the EAF technology there is no limit on the amount of scrap [Wimmer et al., 2022]. The scrap input to the furnace can consist of the steelworks' own scrap, waste from steel manufacturers, and post-consumer scrap (end-of-life products, obsolete scrap). The EAF is more flexible in terms of the feed mix. The electrical energy supplied to the furnace can maintain a mix of solid feed up to 100% scrap, HBI or DRI [Wimmer et al., 2022]. It means that it is more flexible that BOF in terms of feed mix. Carbon electrode consumption is the main source of direct CO_2 emissions in the EAF [SRIA, 2021].

The energy intensity of steel production in EAFs is about one eighth of that of iron ore production in a blast furnace. The furnace generates 75–80% lower emissions compared to conventional BFs [IEA, 2020]. Like the BF-BOF method, slag is created by introducing limestone and other fluxes into the EAF furnace, which removes unwanted impurities [SRIA, 2021]. Producing one ton of steel using the DRI-EAF method requires 18 to 30 GJ of final energy i.e. A little more than in BF-BOF method [IEA, 2020].

Further steps of final steel materials production

After the steelmaking processing, the molten steel undergoes refining in a ladle. Processes such as vacuum degassing, alloy addition, desulfurization, and inclusion modification are performed to achieve precise chemical compositions and remove impurities. This stage is crucial for producing high-quality steels with specific properties. Then the steel is casted. Here the most common process is continuous casting, during which molten steel is poured into a water-cooled mold, where it solidifies into a semi-finished shape (slab, bloom, or billet). The continuous casting process enhances yield, quality, and productivity compared to traditional ingot casting. The ingot casting is less common today – here molten steel is poured into molds to form ingots. These ingots are later reheated and processed into desired shapes through rolling or forging. At the next step there is the process of rolling and finishing. In hot rolling process semi-finished steel products are heated above their recrystallization temperature and passed through rolling mills to achieve desired dimensions and mechanical properties. In cold rolling process the hot-rolled steel is further processed at room temperature to improve surface finish, dimensional accuracy, and mechanical properties. The final processes like galvanizing (applying a zinc coating), annealing (heat treatment to alter mechanical properties), and other surface treatments enhance corrosion resistance and tailor the steel's properties for specific applications. From raw material extraction to final processing, each stage is crucial in obtaining high-quality steel with properties tailored to customer needs. Thanks to this production process, steel is omnipresent in our environment and is the foundation of many industries.

Advancements in steel production are continually evolving, with research focusing on improving efficiency, reducing environmental impact, and developing new steel grades.

The main emphasis is placed on metallurgical and refining processes. Next stages are also modified to reduce emissions, reduce energy consumption and, above all, improve the quality of the produced steel, considering its various application requirements.

More than half of the steel is produced in a process that focuses on the use of coal in a blast furnace to produce crude steel from iron ore. This causes unavoidable emissions associated with the use of coal in this process. It should be emphasized that steel mills have been trying to optimize this production process for many years to reduce CO_2 emissions. For this reason, further opportunities for reducing emissions are already limited.

The steel sector stays one of the largest industrial emitters of CO_2, as well as a source of many other pollutants [Somers, 2022]. There are many possible ways to decarbonize steel production, but each of them has different requirements that must be met to use a specific technology. A given technology may be preferred over another depending on geographical location, infrastructure construction possibilities, availability of raw materials and their acquisition costs, as well as local regulations and the resulting operating costs or quality of raw materials and process input materials that are ordered on the market [Galimberti et al., 2022].

The fact that steel can be recycled without losing its quality offers an opportunity to partially reduce emissions and is a key factor enabling the transition to a circular economy [IRENA, 2023]. Producing steel from recycled scrap in an electric arc furnace allows for a drastic reduction in CO_2 emissions and is seen as a suitable technology for obtaining steel, especially in countries without their own iron ore resources. Currently, the most popular steel production technologies are primary steel production and secondary steel production [IEA, 2020; Galimberti et al., 2022; Bloomberg, 2024].

GREENHOUSE GAS EMISSIONS FROM THE STEEL INDUSTRY

Emissions from the steel sector contribute to climate change and threaten the chances of stabilizing at 1.5 °C of warming. The steel sector currently accounts for at least 7% of global greenhouse gas emissions, and without decisive action this share will continue to increase [IEA, 2020; IRENA, 2023; SteelWatch, 2023]. It should be emphasized that such a substantial number of emissions is the result of most steel production relying on fossil fuels as energy sources and as reducing agents for iron ore processing.

Methane emissions from metallurgical (coking) coal mining, which largely supplies the steel sector, is estimated at 1 Gt CO_2e per year [Swalec, 2022; Campbell, 2023], then BF-BOF steel production emits 4.2 Gt CO_2e per year and 90% of the emissions for the entire industry. This means emissions of over 3 tons of CO_2e per ton of steel produced in the blast furnace process [WSA, 2022; SteelWatch, 2023]. The transition to a fully sustainable and climate-neutral steel sector will require decisive action to further develop the circular economy [IRENA, 2023].

Steel production involves direct emissions (related to the production process) and indirect emissions (resulting from electricity generation and supplied heat) [Galimberti et al., 2022]. The iron and steel sector are the largest heavy industry sector in terms of CO_2 emissions and the second largest in terms of energy consumption. It is directly responsible for 2.6 Gt CO_2 per year, or 7% of global emissions [IEA, 2020]. Improvements in energy efficiency in recent decades have led to modest reductions in energy use and emissions, but each ton of steel produced today still results in an average of 1.4 t CO_2 in direct emissions [IEA, 2020]. Each ton of crude steel produced by the BF-BOF process accounts for about 1.3 to 1.8 t CO_2.

A ton of crude steel produced by the DRI-EAF method using natural gas results in 1.0 t of direct CO_2 emissions and 0.4 t of indirect CO_2 emissions from electricity generation. In contrast, when coal is used, it generates almost three times more direct emissions and a similar number of indirect emissions [Kawabata, 2023].

The production of 1 ton of raw steel from scrap in an EAF furnace requires about 0.4–0.5 MWh of electricity [SRIA, 2021] and causes about 0.04 t of CO_2 in direct emissions, and an additional 0.3 t of CO_2 in indirect emissions [IEA, 2020]. The industrial sector, of which the steel industry is a part, is responsible for about 45% of sulphur oxides (SOx) and about 25% of nitrogen oxides (NOx) and dust/particulate matter (PM2.5) [IEA, 2019; IEA, 2020].

Electric arc furnace (EAF) technology is recognized for its lower carbon dioxide (CO_2) emissions compared to traditional blast furnace-basic oxygen furnace (BF-BOF) methods. However, CO_2 emissions in EAF steel production still arise from several key sources:

- Electricity consumption: EAFs rely heavily on electricity to melt scrap steel. The CO_2 emissions associated with this process depend significantly on the carbon intensity of the electricity used. In regions where electricity is primarily generated from fossil fuels, the indirect CO_2 emissions can be substantial [Zang et al., 2023].
- Carbonaceous materials: materials such as coal, coke, or natural gas are often used in EAFs to facilitate chemical reactions necessary for steel refining. The combustion of these materials releases CO_2 directly into the atmosphere [DiGiovanni and Echterhof, 2024].
- Electrode consumption: graphite electrodes are consumed during the EAF process, and their oxidation contributes to CO_2 emissions [Richharia et. al. 2020; SRIA, 2021].
- Material handling and transportation: the processes involved in transporting and handling raw materials and finished products can also contribute to CO_2 emissions, though these are relatively minor compared to the primary sources [Gu et. al. 2023].
- The energy intensity of steel production in EAF furnaces is about one eighth of that of iron ore production in a blast furnace. This furnace generates 75–80% lower emissions compared to conventional BF furnaces [IEA, 2020].

Efforts to mitigate CO_2 emissions in EAF steel production include:

- Utilizing renewable energy: employing electricity from renewable sources can significantly reduce the carbon footprint of EAF operations [EIA, 2021].
- Alternative reductants: exploring the use of biocarbon materials as substitutes for traditional carbon sources can help lower direct CO_2 emissions [DiGiovanni and Echterhof, 2024].
- Energy efficiency improvements: implementing advanced technologies and optimizing operational practices can reduce energy consumption, thereby decreasing associated CO_2 emissions.

By addressing these areas, the steel industry aims to further reduce the environmental impact of EAF steel production.

LOW-EMISSION STEEL PRODUCTION TECHNOLOGIES

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) is a testament to the determination to limit the increase in global temperatures to 1.5 °C [UNFCCC, 2016]. To achieve this level, economic sectors should decarbonize, by reducing greenhouse gas emissions by almost half by 2030 and achieving net zero emissions by 2050 [CBI, 2022]. The report of the IPCC Working Group III (Intergovernmental Panel on Climate Change) warns that without rapid and deep emission reductions in all sectors, limiting global warming to 1.5 °C is unachievable [IPCC, 2022; CBI, 2022].

Currently, the term near-zero emissions are used because the current state of technological knowledge predicts that the steel industry's emissions will not be zero in 2050. The IEA has proposed near-zero emission limits for the steel industry, which are: 0.4 t/tcs for steel production from iron ore and 0.05 t/tcs for steel production from steel scrap [IEA, 2022; Kawabata, 2023].

Key technologies for transforming the global steel industry will be commercially available this decade. With over 70% of blast furnaces – major CO_2 emitters – due for reinvestment by 2030, there is an opportunity to replace this emission-intensive process with scrap and hydrogen-based steel production [Agora, 2024]. The most promising technologies in terms of CO_2 mitigation potential are presented in the European Project GREENSTEEL (D1.2). It summarizes iron and steel production technologies, supporting technologies and technological pathways by describing their current maturity (readiness level) and their expected development. The CO_2 mitigation pathways currently being considered in the European steel industry are [Draxler et al., 2021]:

- Carbon direct avoidance (CDA); development of steel production processes using renewable or clean energy sources,
- Process integration (PI); modifications to current steel plants to reduce greenhouse gas emissions supplemented by CCU (Carbon Capture and Usage) and/or Carbon Capture and Storage (CCS),
- Carbon capture and usage (CCU) from steel production process gases to produce further valuable products.

Within these pathways, the most important technologies for iron and steel production for decarbonization of this industry have been proposed [Draxler et al., 2021]:

- Hydrogen-based direct reduction (H2-DR),
- Hydrogen plasma smelting reduction (HPSR),
- Alkaline iron electrolysis (AIE),
- Molten oxide electrolysis (MOE),
- Carbon capture and usage (CCU),
- Iron bath reactor smelting reduction (IBRSR),
- Blast furnace gas injection (BFG),
- Substitution of fossil energy carriers with biomass,
- High-quality steel production with increased scrap use.

The Agora Report [Agora, 2024] analyses and compares eight low-emission technologies for decarbonization of the steel industry, these are:

- direct reduction based on hydrogen – the route with an electric arc furnace H2–DRI–EAF (H2–direct reduced iron–electric arc furnace),
- direct reduction based on hydrogen – the route with an electric furnace H2–DRI–SMELT–BOF (H2–direct reduced iron–smelter–basic oxygen furnace),
- direct reduction with natural gas and CCS – NG–DRI–CCS (natural gas–direct reduced iron–carbon capture and storage),
- electrolysis of molten oxide MOE (molten oxide electrolysis),
- alkaline electrolysis AEL (alkaline electrolysis) + EAF (electric arc furnace),
- blast furnace – the route with an oxygen furnace with CCS – BF–BOF–CCS (blast furnace– basic oxygen furnace– carbon capture and storage),
- HIsarna + BOF process with CCS (HIsarna+ basic oxygen furnace– carbon capture and storage),
- the arc furnace path to near-zero emission scrap NZE–SCRAP–EAF (Near-Zero Emissions–Scrap–Electric Arc Furnace).

The paper of Rolland Berger [RB, 2020] proposes five alternative carbon dioxide emission reduction technologies in addition to CCUS and CCS:

- production of hydrogen-based direct reduced iron in a shaft furnace,
- production of hydrogen-based direct reduced iron in a fluidized bed,
- production of iron in suspension,
- production of plasma steel (directly with plasma),
- production of iron in pyrolytic processes.

The proposed technologies are problematic because they require very large amounts of green electricity for iron pre-processing, hydrogen electrolysers, furnaces and electrolysis to achieve the carbon neutrality goal. The last three technologies mentioned are only in the first stages of development and their feasibility leaves a degree of uncertainty about their industrial implementation.

Hydrogen-based technologies are more developed, although not without challenges. According to the Rolland Berger [RB, 2020], the production of H_2-based direct reduced iron in a shaft furnace as well as in a fluidized bed will be the dominant future technology to produce carbon-neutral steel.

In the work [Branca et al., 2024], based on the document GREENSTEEL Project [Draxler et al., 2021], the impact of technologies and climate goals on the steel industry in the EU was assessed. This work draws attention to the development of both green and digital technologies as key factors of the competitiveness of the European steel industry. New digital technologies, through the optimization of the entire production chain of the steel sector, aim to improve the flexibility and reliability of production processes and maximize efficiency and improve product quality, as well as improve energy efficiency and control the impact of processes on the environment.

DRI steelmaking technologies can now be implemented, being key to decarbonizing primary steel production by gradually increasing the share of hydrogen. It should be emphasized that the flexibility to use any amount of natural gas or low-carbon hydrogen is an important advantage of their implementation. In addition, combining the DRI process with the existing BOF steelmaking process, as well as future iron ore electrolysis technologies, will enable the use of iron ores with lower quality parameters [Agora, 2024]. The International Energy Agency IEA has proposed four key technology groups for the decarbonization of steel production, including carbon capture, utilization and storage (CCUS), hydrogen use, iron ore electrolysis and substituting coke with biomass [IEA, 2020; Kawabata, 2023]. It should be emphasized that to achieve carbon neutrality in the steel industry, the use of biomass with carbon capture and storage/utilization can be an effective strategy, as it can generate negative emissions to compensate for residual emissions. The technology enabling the production of negative emissions by 2050 is the COREX process, which offers a significant potential to replace coal with charcoal [Andrade et al., 2024].

"Green steel" and other terms such as "zero-emission steel", "decarbonized steel" and "low-emission steel" are not always clearly defined; definitions depend on the context [REI, 2023]. Properly formulated steel definitions would be used to develop detailed standards and criteria, thus enabling an international agreement on the decarbonization of steel production. The term "nearly zero emission steel" proposed by the International Energy Agency (IEA) for the conventional BF-BOF process refers to a steel product produced with less than 400 kg CO_2 equivalent per ton (kg CO_2e/tcs) and for the electric arc furnace (EAF) 50 kg CO_2e/tcs, when 100% scrap is used [IEA, 2022; REI, 2023]. According to the German think-tank Agora Energiewende – Global Steel Transformation Tracker, "low-emission steel" is one in which CO_2 emissions are half those of the conventional BF-BOF process [REI, 2023].

Table 1 shows the total energy requirements and estimated crude steel production costs of selected future technologies in 2030 and 2050 compared to conventional BF-BOF technology. It is important to be aware of the considerable uncertainty about future CO_2 emissions, therefore the estimated cost ranges should be considered as probable.

There are diverse options for decarbonizing steel production. If renewable electricity is available, secondary steelmaking using electric arc furnaces can achieve up to 90% emission reductions compared to BF-BOF, provided that sufficient scrap steel of the required quality is available. However, if primary steelmaking is needed, CCS can result in 86% emission savings, but with 17% higher energy consumption of the CCS plant [Gailani et al., 2024; MPP, 2022]. With some modifications to BF and the use of CCS, smelting reduction (HIsarna) and a top gas recycling furnace, it can result in almost 80% emission savings [Keys et al., 2019; Richardson-Barlow et al., 2022].

Table 2 presents the decarbonization potential of selected steel production technologies according to different literature sources compared to CO_2 emissions from BF-BOF. The production of 1 ton of crude steel in a blast furnace and a BF-BOF oxygen furnace includes CO_2 emissions from direct sources (consumption of coke, lime flux for chemical reduction of ore), which is about 1.2 Mg CO_2, and indirect emissions (consumed: reagents, electricity, heat), which is about 1 Mg CO_2 [IEA, 2020]. Thus, the BF-BOF technology causes emissions from 1.8 to 2.2 t CO_2e/tcs (Table 2).

The EAF technology based on steel scrap is characterized by a much lower environmental impact compared to the conventional method (BF-BOF), the reduction of greenhouse gases is lower by about 80–85%. In the case of H2-DRI Green steel technology, the decarbonization potential compared to BF-BOF is the highest and ranges from 97–99%, the unavoidable CO_2 emission is 53 kg (Table 2) [Vogl et al., 2018]. Less mature but developing steelmaking technologies may

Table 1. Energy demand and production costs of selected steel production lines in 2030 and 2050

No.	Technology	Total energy demand GJ/tcs (of which GJ H_2/tcs)	CO_2 emissions, t/tcs	Emission reduction costs in (year) USD/tcs	CO_2 emission reduction costs compared to BF-BOF USD/t CO_2	
					2030	2050
1.	BOF		1.87	472–499 (2022)		
2.	H2-DRI-EAF	10.8 (8.3)	0.01	727–857 (2030)	137–192	99–154
3.	H2-DRI-SMELT-BOF	11.0 (7.6)	0.04	725–871 (2030)	139–203	104–168
4.	NG-DRI-EAF-CCS	13.4 (10.5 natural gas)	0.2	635–766 (2030)	98–161	89–143
5.	MOE	12.4–14.8 (all; electricity)	0	582–766 (2050)	NA	56–146
6.	AEL-EAF	13.7 (all; electricity)	0.01	611–855 (2050)	NA	72–195
7.	BF-BOF-CCS	2,8 (green electricity) 22.8 (19.5 hard coal)	0.51	599–721 (2030)	93–163	83–133
8.	HIsarna-BOF-CCS	15.4 (12.7 hard coal)	0.13	581–704 (2030)	63–117	56–98
9.	NZE-SCRAP-EAF	2.8 (2.5)	0.01	639–837 (2030)	NA	NA

Note: Agora, 2024. BOF – basic oxygen furnace, H2-DRI-EAF – hydrogen-based direct reduction iron-electric arc furnace, H2-DRI-SMELT-BOF – hydrogen-based direct reduction iron-smelter-basic oxygen furnace, NG-DRI-EAF-CCS – natural gas-direct reduction iron- electric arc furnace-carbon capture and storage, MOE – molten oxide electrolysis, AEL-EAF – alkaline electrolysis-electric arc furnace, BF-BOF-CCS – blast furnace-basic oxygen furnace-carbon capture and storage, HIsarna-BOF-CCS – HIsarna-basic oxygen furnace-carbon capture and storage, NZE-SCRAP-EAF – near-zero emissions-scrap-electric arc furnace, NA – not applicable.

Table 2. Decarbonization potential of selected steel production technologies compared to CO_2 emissions from BF-BOF according to different literature sources

No.	Technology	Decarbonization potential compared to BF-BOF, %	Source of literature
1.	BF-BOF	CO_2 emissions per ton of steel 1,8 t CO_{2e}/t_{cs} 2.0 t CO_{2e}/t_{cs} 2.25 t CO_{2e}/t_{cs}	Conde et al., 2021 Ellis and Bao, 2020 Lopez et al., 2023
2.	EAF	85 80	Somers, 2022 IEA, 2020
3.	BF-BOF Blue steel	80 20	Ito, 2021 Pawelec and Fonseca, 2022
4.	NG-DRI Grey steel	50 55 67 40 35	Ito, 2021 Somers, 2022 Somers, 2022 IEA, 2020 Rosner et al., 2023
5.	H2-DRI Blue steel	average 60	Massarweh et al., 2023 Hill et al., 2024
6.	H2-DRI Green steel	98 99 97,2	Ito, 2021 Blank, 2019 Vogl et al., 2018

result in emission savings of up to 89%–94% in the future. Several technological paths can be distinguished here [Gailani et al., 2024]:
- substitution of coal and coke with biomass fuel (currently RTL 7–9), maximum emission saving potential – 40% [Mandova, 2019].
- direct reduced iron based on hydrogen in an electric arc furnace (EAF) using a shaft furnace (currently RTL 6–8), maximum emission saving potential – 89% [Keys et al., 2019; RB, 2020; Draxler et al., 2021].
- direct reduced iron based on hydrogen and a fluidized bed (currently RTL 4–5), maximum emission saving potential – 89% [RB, 2020].
- direct production of steel based on hydrogen without the use of EAF using flash and plasma

reactors (currently RTL 4–5), maximum emission saving potential – 89% [RB, 2020; Sohn et al., 2021; Draxler et al., 2021; Voestalpine, 2022; 2023].
- direct electrification of the steel production process using electrolysis technology in an arc furnace (currently RTL 4–5); maximum emission saving potential – 90% [Keys et al., 2019].

CONCLUSIONS

Currently, BF-BOF is of fundamental importance for steel production. Input products (iron ore, coke and other auxiliary minerals) are directed to BF, where molten iron is created by removing oxygen from iron ore. Next, impurities are removed from pig iron in BOF to obtain steel. The use of gaseous by-products in a cogeneration plant to produce electricity and heat is important for the economic result of the steelworks. However, this has consequences in the form of an increase in the emissions of the steelworks because BF gas is four times more emissive than natural gas. Thus, the production of 1 ton of steel emits about 2 tons of CO_2. The steel production is one of the most emission-intensive industries. At the same time, it is difficult to imagine giving up steel in the current era. Its consumption is expected to increase in the coming years.

Considering the need to eliminate the effects of climate change resulting from greenhouse gas emissions, technological solutions are being looked to reduce the harmful effects of steel production. The widest possible use of scrap for the re-production of steel is of foremost importance. But, the ever-increasing demand for steel in all sectors of the economy means that it is necessary to develop new low-emission technologies for producing steel from iron ores. Despite the ongoing development, innovative technologies are not yet mature enough to effectively replace currently operating production methods. However, it is estimated that the emission reduction potential in currently developed technologies can reach up to 94% compared to the most used BF-BOF method. This means that in the deadline set by the Green Deal (by 2050) it will not be possible to fully decarbonize the steel industry. Given the huge investment required and the struggle to mature a range of new technologies, including electrolysis-based hydrogen technologies, there are doubts as to whether clean steel technologies will be fully competitive within the timeframe envisaged. Great hopes are associated with methods that will use green hydrogen as an energy source in iron and steel production processes.

Acknowledgments

The article was prepared within the statutory works of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences.

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