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Decarbonisation determinants of the steel industry

Introduction

Steel is one of the most important raw materials for global development and is essentially necessary to meet a range of needs of modern society. About 2 billion tons of steel are used per year in construction, transportation, consumer products, and machinery (IRENA 2023). In the case of steel, its excellent strength, durability, ease of processing, and recyclability ensure its wide application and make its replacement a challenge (de Villafranca Casas et al. 2022). To obtain the desired properties, steel can be modified – to a wide extent – by alloying with various elements, e.g. manganese and nickel (IRENA 2023). Since steel can be recycled without losing its properties, this makes it an important enabler of the transition to a more circular economy (IRENA 2023). Due to its advantages and desirable properties,

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steel production is nearly 20 times greater than the total production of all non-ferrous metals (Pandit et al. 2020).

At the same time, iron and steel production is one of the most energy-intensive industries in the world, accounting for about 7% of global greenhouse gas emissions (GHG) and 11% of global carbon dioxide (CO_2) emissions (Kim et al. 2022; Hasanbeigi et al. 2023). The Intergovernmental Panel on Climate Change (IPCC), the United Nations 2030 Sustainable Development Goals (SDGs), the United Nations Framework Convention on Climate Change (UNFCCC), and the Paris Agreement (UNFCCC 2016) have mandated that necessary measures be taken to limit the global temperature increase to below 2°C by 2050 (Mahat et al. 2023). The purpose of this article is to describe where the steel industry is today and to identify the challenges it will face in the coming years as it strives towards a zero-emission economy.

1. Steelmaking processes

1.1. Production and consumption of steel

Iron and steel have played a significant role in the development of civilization since 3,000 BC metals (Pandit et al. 2020). It is now a global industry and will remain so in the years to come. Steel is produced in 71 countries and consumed worldwide. The G20 countries, representing the world's largest economies, produce about 85% of the world's steel and also consume about 80% (IRENA 2023). It should be emphasised that global steel production is dominated by a few entities: China produces more than half of the world's crude steel production, followed by the European Union, then India, and the United States. They produce about 70% of the world's steel, and a significant part of steel consumption is also concentrated in these regions (IEA 2020; IRENA 2023).

World crude steel production in 2023 amounted to 1892.2 Mt (in 2022 – 1,890 Mt). It was produced in 71 countries by 50 steel companies, including China Baowu Group (130.77 Mt), and Arcelor Mittal (68.52 Mt) (WSA 2024).

Steel is needed in all sectors of the economy, but more than half is used in construction and infrastructure.

The directions of steel use in 2023 and its structure are shown in Figure 1.

The construction and infrastructure sector consumes the most steel, as much as 52% of global consumption. Steel is a construction material in constructing houses, bridges, roads, tunnels, railways, and other infrastructure facilities. Its strength and durability make it an irreplaceable material for construction applications. 16% of global steel consumption is used for the production of industrial machinery and equipment, agricultural machinery, or in the energy sector (e.g. wind turbines), while 12% – in the automotive industry in the production of bodywork, running gear, axle suspension, engine components and many other vehicle components.

Table 1. The countries – largest producers of crude steel of and consumers of finished steel products in 2023

Tabela 1. Kraje – najwięksi producenci stali surowej i konsumenci wyrobów stalowych gotowych w 2023 roku

Country	Producers		Consumers	
	productions (mt)	share in the world (%)	consumption (mt)	share in the world (%)
China	1,019.1	53.9	895.7	50.8
India	140.8	7.4	133.4	7.6
Japan	87.0	4.6	53.3	3.0
United States	81.4	4.3	90.5	5.1
Russia	76.0	4.0	44.6	2.5
South Korea	66.7	3.5	54.7	3.1
Germany	35.4	1.9	28.1	1.6
Türkiye	33.7	1.8	38.1	2.2
Brasil	31.8	1.7	23.9	1.4
Iran	31.0	1.6	19.5	1.1
Italy	21.1	1.1	23.5	1.3
Mexico	16.2	0.9	28.5	1.6
Rest of the world	252.0	13.3	329.2	18,7
World	1,892.2	100.0	1,763.0	100.0

Source: WSA 2024; WiseEuropa 2024a.

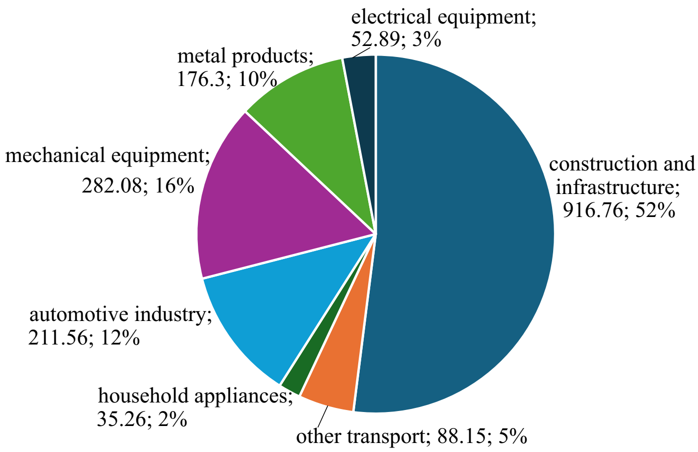

Fig. 1. Steel consumption in individual sectors of the world economy in 2023 (Mt; %)
Source: WSA 2024

Rys. 1. Zużycie stali w poszczególnych sektorach gospodarki świata w 2023 roku (Mt; %)

Metal products in the form of steel pipes, sheets, rods, metal structural elements, many tools as well as elements of military and armament equipment (ammunition, military equipment) account for 10% of global steel consumption.

The following should also be mentioned:

- other transport (3%) such as ship hulls, railway cars, etc;
- electrical equipment (3%) for the production of transformers, electronic housings, and other structural elements in the electrical industry;
- household appliances (2%) such as washing machines, refrigerators, and other appliances. This includes both structural elements and housings of various household appliances

It is hard to imagine a near or distant future without the use of steel. All that remains is to develop innovative technologies that will reduce its carbon footprint and lead to reducing its impact on the environment and climate.

1.2. Steel production technologies

Historically, the breakthrough in steelmaking technology was the introduction of oxygen into molten pig iron, reducing carbon residues. This and subsequent innovations led to the widespread use of Open Heat Furnaces (OHF), utilised worldwide in the first half of the 20th century. Currently, due to high emissions, the OHF technology is in decline. In parallel, the technology of Electric Arc Furnaces (EAF) was developing. EAF allows for the production of various types of steel. The process is less energy-intensive than previous ones and allows the use of scrap. This is particularly important in the context of recycling materials, but it requires a large amount of electrical energy. It is currently one of the two major steelmaking technologies in the world, along with the Blast Furnace – Basic Oxygen Furnace (BF-BOF) process, which uses a stream of pure oxygen (blast) to oxidize impurities in liquid iron to create high-purity steel. Crude steel production by the process was as follows in 2023 (WSA 2024):

- In the world – 1892 Mt:
  - Blast Furnace–Basic Oxygen Furnace (BF-BOF) – 71.1%;
  - Electric Arc Furnace (EAF) – 28.6%;
  - Other processes – 0.3%.
- In the European Union (27) – 126.3 Mt:
  - Blast Furnace–Basic Oxygen Furnace (BF-BOF) – 55.2%;
  - Electric Arc Furnace (EAF) – 44.8%.
- In Poland – 6.4 Mt:
  - Blast Furnace–Basic Oxygen Furnace (BF-BOF) – 48,8%;
  - Electric Arc Furnace (EAF) – 51,2%.

Steel is produced by using one of three main processes (Diez et al. 2023; de Villafranca Casas et al. 2022; Fan, and Friedmann 2021; Pandit et al. 2020; WTO portal):

- Blast Furnace – Basic Oxygen Furnace (BF-BOF);
- Direct Reduction – Electric Arc Furnace (DR-EAF);
- Electric Arc Furnace (EAF).

These three production paths are characterised by large differences in emission intensity, which are related to energy consumption and types of fuel used. Blast Furnace (BF) and Smelting Reduction Furnace (SRF) produce hot, liquid iron, while Direct Reduction (DR) – sponge iron. In contrast, Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) produce liquid steel.

Steel production in Blast Furnaces BF and Basic Oxygen Furnaces accounts for 71.6% of global steel production (Pandit et al. 2020). The top charge to the Blast Furnace is iron ore in the form of lumps (ore pieces) or sintered (granulated) ore fines and coal in the form of coke and powdered coal (pulverised injection) and various fluxes, while the bottom charge is blown air. As a result of the reaction of oxygen contained in the air with carbon, carbon monoxide is formed, which is a reducing agent and provides energy for the reduction processes. The products obtained from the blast furnace are molten iron (pig iron), low-melting slag (impurities), and Blast Furnace Gas (BFG). The iron obtained from the Blast Furnace (BF) is transformed in the Basic Oxygen Furnace (BOF) into steel. In the Oxygen Furnace, pure oxygen – produced in the Air Separation Unit (ASU) – is injected into the molten iron to burn the carbon residues contained within it.

The processes taking place in the Blast Furnace (BF) and Basic Oxygen Furnace (BOF), despite their considerable efficiency in terms of energy consumption, are characterised by high CO_2 emissions (Diez et al. 2023; EUROFER 2019; IEA 2020; Koolen, and Vidovik 2022; Mandova et al. 2019). It should be emphasised that the emission levels vary depending on the country and in most of them these emissions range from 1.8 to 4.0 t CO_2 per ton of crude steel (UK Steel 2022). In the case of China, CO_2 emissions amount to 1.84 t CO_2 per ton of crude steel, and the EU 1.81 t CO_2, and in South Africa and India over 3.8 t CO_2 per ton of steel (Diez et al. 2023; Koolen and Vidovik 2022). In 2023, the average CO_2 emissions from steelmaking processes were (WSA 2024):

- BF-BOF – 2.33 t/t crude steel,
- DRI–EAF – 1.37 t/t crude steel,
- EAF – 0.68 t/t crude steel.

Electric Arc Furnace (EAF) steel production is based on steel scrap. Electrical energy is supplied via graphite electrodes to melt the scrap. Steel production in the EAF is inherently low-emission compared to the integrated BF-BOF process and is the easiest to modify. The carbon footprint per tonne of steel produced from the EAF process, depending on the type of iron (pig or scrap), electricity sources, and efficiency, ranges from 0.23 to 0.46 tonnes of CO_2 (Fan and Friedmann 2021). Every 1,000 kg of steel scrap processed into new steel results in the following raw material savings: over 1,400 kg of iron ore, 740 kg of coal, and 120 kg of limestone (Pandit et al. 2020). Currently, the EAF process accounts for about 20% of Australia's steel production and about 23% of the world's total steel (Pandit et al. 2020). About 30% of world steel production uses scrap as metallic input into the process (IEA 2020; IRENA 2023).

In the direct reduction of iron (DRI) process, sponge iron is obtained, which is usually processed in an Electric Arc Furnace (EAF). The reduction process is carried out based on gas, especially natural gas (NG). The leading countries producing DRI are: India (coal raw material), Venezuela, Iran (gas raw material), and Mexico (Fan, and Friedmann 2021; Pandit et al. 2020).

The International Energy Agency IEA in its proposed baseline scenario predicts that direct and indirect CO_2 emissions from global steel production will increase from 3.7 Gt CO_2/year in 2019 to 3.9 Gt CO_2/year in 2050 (de Villafranca Casas et al. 2022; IEA 2020). However, as a result of increased scrap recovery, the carbon intensity of global steel production seems to decrease, reaching annual emissions of 2 to 3 Gt CO_2 (de Villafranca Casas et al. 2022). Emissions from steel production are generally difficult to reduce because existing efficiency and emission reduction options are limited, and some alternative technologies are expensive. Therefore, it is crucial to accelerate the global scale-up and commercialisation of low-emission steel production technologies, such as technologies that replace coal-based reduction with renewable energy and green hydrogen or the use of carbon capture, storage, and CCS/CCSU (IEA 2022; WTO portal).

A significant reduction of CO_2 emissions from the steel sector is a difficult task without the support of modern technology. There are two main technological paths that lead to the achievement significant CO_2 reductions (Ariyama 2019; EUROFER 2019; Peters et. al. 2019):

- Smart Coal Usage (SCU); SCU focuses on such process modifications that lead to a reduction in coal consumption, including the use of by-product gases for further conversion into valuable products.
- Direct Carbon Avoidance (CDA); CDA consists of the complete replacement of coal with renewable electricity or hydrogen. The use of green hydrogen (produced in the electrolysis of water using renewable energy sources) to reduce iron ore or the direct use of electricity for the electrolysis of iron ore eliminates the formation of CO_2.

These paths aim to significantly reduce carbon usage compared to current steel production methods or avoid CO_2 emissions altogether. Within each of these paths, there are groups of technological approaches.

- Smart Carbon Usage (SCU) includes:
  - Process integration, which concerns the modification of existing iron/steel production processes based on fossil fuels: Pulverised Coal Injection (PCI), Carbon Capture and Storage (CCS), which would help reduce the use of coal and thus CO_2 emissions,
  - Carbon Valorisation or Carbon Capture and Use (CCU), which includes all options for using hydrogen, CO, and CO_2 in steel mill gases or fumes as raw materials for the production or integration with valuable products.
- Carbon Direct Avoidance (CDA) includes:
  - hydrogen-based metallurgy, which uses hydrogen as the main reducing agent in the iron ore reduction stage; this hydrogen can be produced, for example, by elec-

trolysis of water using renewable energy sources; hydrogen plasma smelting reduction or direct hydrogen reduction are process in which carbon-reducing agents are replaced by hydrogen,
- metallurgy based on electricity from renewable or emission-free sources (nuclear energy) for the electrolysis of iron ore (low temperature, high temperature), eliminating the formation of CO_2 and instead producing water or oxygen.

Despite the significant potential of these pathways to reduce CO_2 emissions, these processes have not yet reached commercial maturity, and they are at different stages of development (Conde et al. 2021).

The overall CO_2 footprint resulting from the direct reduction of hydrogen depends on the intensity of CO_2 emissions from the electricity used for its production. This is associated with deep decarbonisation of the electricity sector (Conde et al. 2021), coal storage, and the use of CCS/CCSU (IEA 2022; WTO portal).

In the process of technology modernisation, attention should be paid to waste materials and heat. Currently, the production of one ton of crude steel generates a waste stream of the following sizes: 250–300 kg of blast furnace slag (BFS) at temperatures of 1,500–1,600°C and 100–150 kg of steel slag (SS) at temperatures of 1,550–1,650°C (Barati et al. 2011; Zhang et al. 2013; Sun et al. 2022). These products are characterised by a high level of transferred energy, which constitutes 10–15% of the total energy input in the current iron and steel industry (Sun et al. 2022).

As already mentioned: around 2 billion tonnes of steel are produced each year, accounting for around 7% of global GHG emissions. What is more: steel demand is currently expected to grow to over 2.5 billion tonnes per year by 2050, with the largest increase expected in emerging economies (Yu et al. 2021). As such, transitioning the steel sector to a 1.5°C path will require policy-making in the deployment of technologies and approaches to the circular economy. This will require a concerted effort by a broad range of stakeholders.

It is expected that in the future, more attention will be paid to the energy efficiency of technologies. Climate policy and its impact on the industry (including the steel sector) may drive the steel industry towards more sustainable production practices, i.e. development of EAF technologies, development of hydrogen-based production technologies (DRI), as well as complementary technologies such as carbon capture, storage and utilisation (CCUS).

Decarbonising the steel industry will involve a complex mix of technological innovation, economic change, and sustainable energy sources. Continued progress, concerted efforts, and adaptation strategies are essential to achieve sustainable steel production and to align with global climate goals for a more environmentally responsible future (Diez et al. 2023).

Creating a market for steel produced using less carbon-intensive production processes, which could be named ‘green steel’, has been identified as a way to support the introduction of breakthrough emission reduction technologies in steel production (Muslemani et al. 2021).

2. Impact the climate policy on steel industry

The report by the Intergovernmental Panel on Climate Change (IPCC) is the most comprehensive assessment of climate change undertaken by the IPCC (IPCC 2023). This assessment is depressing for the world community, as it identifies the effects of global warming of 1.5°C above pre-industrial levels.

In the period 2011–2020, the global surface temperature was 1.09°C higher than in the period 1850–1906. The increase in temperature over land was 1.59°C and over the ocean 0.88°C. Global net anthropogenic greenhouse gas emissions in 2019 are estimated at 59 ± 6.6 Gt CO_{2eq}, which is about 12% (6.5 Gt CO_{2eq}) more than in 2010 and 54% (21 Gt CO_{2eq}) more than in 1990. In 2019, about 78% of global greenhouse gas emissions came from the combined energy, industry, transport, and buildings sectors, and 22% from agriculture, forestry, and other land use (IPCC 2023).

It is important to be aware that for every 1000 Gt of CO_2 emitted by human activity, the global surface temperature increases by 0.45°C (likely range 0.27 to 0.63°C). CO_2 emissions estimates for early 2020 are 500 Gt with a 50% probability of limiting global warming to 1.5°C and 1150 Gt with a 67% probability of limiting warming to 2°C. Global net-zero CO_2 emissions for these pathway categories will be achieved in the early 2050s and early 2070s, respectively. This report states that the world will warm by 3.2°C by 2100 under current policies. Much greater efforts are needed to reduce greenhouse gas emissions more rapidly.

According to the European Green Deal (COM 2019), climate change and environmental degradation are key challenges for individual industries in Europe. The goal is to achieve climate neutrality in Europe by 2050. The iron and steel industry is one of the manufacturing industries with high CO_2 emissions in Europe (Gajdzik et al. 2023a; WiseEuropa 2024b). This industry should reduce emissions of several harmful gases, such as ammonia, benzene, carbon monoxide, hydrogen chloride, hydrogen sulphide, hydrogen cyanide, nitrogen oxide, nitrogen dioxide, and sulphur dioxide (Horst and de Andrade Júnior 2023). It should be emphasised that traditional steel production, due to its high dependence on energy and fossil raw materials, is an energy-intensive and emission-intensive process. In 2020, the global steel sector was responsible for 11% of global CO_2 and process-related GHG emissions and 7% of global energy consumption (Swalec and Shearer 2021).

To achieve the 1.5°C target set out in the Paris Agreement (UNFCCC 2016) and avoid catastrophic climate change impacts, CO_2 emissions need to be halved by the end of this decade and reach net zero by 2050. This will involve reducing greenhouse gas emissions across all sectors (IPCC 2022). So, the steel sector faces a difficult decarbonisation challenge (de Villafranca Casas et al. 2022). Fossil carbon is part of the chemical processes used in steel production, which are very emission-intensive even for zero-carbon electricity. Because CO_2 has such a long atmospheric residence time, its concentrations increase and decrease slowly over time, even as annual emissions decrease. This means that CO_2 concentrations in the atmosphere will continue to increase even as annual emissions decrease (Fivel 2019).

Meeting the global challenge of climate change will require transitioning to sustainable energy sources for steel production. Increasing the use of renewable energy in this sector will be key to achieving this goal (IRENA 2023). Developing new, clean technologies takes a long time, and the effects of such solutions will not be visible for the next 10 to 20 years. Therefore, there is a need for action and solutions that reduce emissions today, not in the future (Fivel 2019). Combining "traditional" climate change mitigation strategies, such as zero-emission energy, with demand-side approaches can save time and reduce emissions, regardless of production improvements (Fivel 2019). Technology investments to ensure a drastic reduction in CO_2 emissions to the atmosphere are very capital intensive (Bhaskar et al. 2022). To reduce CO_2 emissions from production processes, production plants must introduce new manufacturing technologies and low-emission energy sources (Gajdzik and Piontek 2023).

European climate policy assumes that deep decarbonisation will be implemented comprehensively in the coming decades of the 21st century. The coming decades will intensify the users' pursuit of zero greenhouse gas emissions. EU climate neutrality is implemented comprehensively and multidimensionally – restructuring changes will cover all areas of the functioning of economies (restructuring of energy-intensive industries will entail changes in dependent industries and markets of product users) (Gajdzik and Kozina 2023).

Promoting decarbonisation in this sector will be a necessity and will require the identification, development, and dissemination of breakthrough technologies for iron and steel production (Skoczkowski et al. 2020; Benson 2022; Estevez et al. 2024).

As already mentioned, steel production is the largest emitter of carbon dioxide among heavy industry branches. The steel sector's emissions result primarily from its dependence on coal. Metallurgical (coking) coal meets 75% of the sector's energy demand, and acts as a reducing agent, energy source, and carbon source (Rocamora 2023). Currently, there are three groups of solutions for steel decarbonisation: reducing steel consumption, increasing the quality and efficiency of processes and increasing the scale of recycling, anddeveloping new technologies and clean energy sources. Financial institutions have a key role to play in the decarbonisation of the steel sector, which should ensure that financial investments are directed toward the right technologies, enabling the sector to move away from metallurgical coal (Rocamora 2023).

3. Decarbonisation of the steel industry

The process of decarbonisation of the iron and steel sector is the subject of a very large number of publications on a global scale. In (Horst and de Andrade Júnior 2023), using the ScienceDirect scientific database, a systematic review of the literature on the sustainability of the iron and steel industry was conducted. The review identifies the main trends, opportunities, and challenges facing this sector regarding climate change mitigation, namely the possibility of achieving CO_2 emission levels in line with climate goals in the period 2030–2040.

The WSD (World Steel Dynamics) report characterises the global decarbonisation of the steel and iron industry, i.e. (WSD 2023):

- global steel production in 2030 will probably reach 1,920 Mt (2019 – 1875 Mt), while CO_2 emissions will decrease from 3,500 Mt (2019) to 3,055 Mt (2030), this will be caused by the reduction of CO_2 emissions in China,
- average global CO_2 emissions in this sector will decrease from 1.87 to 1.59 kg/tcs (kg/tcs = kg CO_2/t crude steel); The EU will achieve the greatest improvement in this indicator,
- the average global CO_2 emission intensity from BF-BOF processes will decrease from 2.24 to 2.05 kg CO_2/tcs (due to reduction of coke rates),
- global steel production from EAF technology will increase from 530 (2019) to 710 Mt, which is an increase of 9 percentage points – from 28 (2019) to 37% of total steel production; the share of EAF steel in developed regions will increase from 41% (2019) to 55%, but decrease in developing regions from 56 (2019) to 47%,
- total ferrous scrap consumption will increase by only 5 Mt in 2030, despite a 45 Mt increase in steel production between 2019 and 2030,
- global steel trade is expected to continue to decline for the rest of the decade, partly due to the effects of industry decarbonisation efforts,
- global overcapacity will increase by at least 220 Mt by 2030, with capacity growth currently outstripping demand in most regions.

The Report (Kiessling et al. 2022) analyses the Bio Steel Cycle (BiSC) and proposes a seven-step strategy to overcome the challenges related to greenhouse gas emissions, especially CO_2, in the iron and steel industry. This industry, as mentioned earlier, generates between 7 and 11% of global CO_2 emissions. The actual level of CO_2 emissions for each ton of steel produced currently generates more than 4.6 t of CO_2 emissions (Kiessling et al. 2022). The seven BiSC steps to achieve net zero carbon steel production seem to be technically feasible and practically possible to implement in the short term, these are (Kiessling et al. 2022):

- change the energy supplier to one generating energy based solely on renewable energy technologies,
- install renewable energy technologies,
- replace coal and coke with biomass, this would quite easily enable a 30% reduction in carbon dioxide emissions,
- install carbon capture and storage (CCS) stack filters,
- use of captured carbon in concrete and food production,
- improve the steel production process,
- biogas from anaerobic digestion – green hydrogen from biogas – used in steel production.

In order to reduce greenhouse gas emissions, much greater action by individual countries is necessary. In this respect, the steel sector can play a key role, although it is considered difficult to reduce emission, on the other hand, it has significant potential for the transformation of steel. The report presents 15 proposals (comments) on the global transformation of steel, these are Agora 2023:

- creating a net-zero iron and steel sector is technically feasible in the coming years,
- an accelerated transformation of the global steel industry can contribute to raising global climate ambitions,
- strategies to achieve an accelerated transformation of steel will include: material efficiency, increased steel production based on scrap and hydrogen, as well as bioenergy and BECCS (Bioenergy and Carbon Capture and Storage),
- a phase-out of coal in the steel sector by the early 2040s is technically feasible,
- international trade in raw iron can help reduce the costs of the global transformation of steel,
- international trade in raw iron can benefit importers and exporters,
- the number and efficiency of Direct Reduction Iron (DRI) plants should be significantly increased, as they currently limit the pace of the global transformation of steel,
- the steel sector can contribute to negative emissions through carbon capture and storage of carbon dioxide from bioenergy BECCS (Bioenergy and Carbon Capture and Storage),
- Carbon Capture and Storage (CCS) in the blast furnace-basic oxygen furnace (BF-BOF) process will not play a major role in the global transformation of steel,
- it is possible that over 90% of blast furnaces will be closed by 2040,
- the construction of coal blast furnaces by 2030 in emerging economies will be burdened with a high risk related to carbon dioxide emissions and stranded assets,
- it should be assumed that in the case of a limited supply of low-emission H_2, but intended for important applications, it should not constitute a bottleneck in the global transformation of steel,
- the availability of DR-class pellets is the main potential bottleneck in the global transformation of steel,
- to eliminate bottlenecks on the way to steel transformation towards achieving a temperature of 1.5°C, joint actions of governments and industry are necessary,
- achieving a net zero steel sector will require governments to adopt comprehensive policy frameworks covering the entire value chain, including international coordination and cooperation.

In the paper (Różański et al. 2022), promising technologies for the decarbonisation of the steel industry were identified, technological paths for processes consisting of these technologies were determined, and scenarios for the decarbonisation process by 2030 and 2050. The European Commission, in preparation for the technological revolution – maximum reduction of CO_2 emissions – in the iron and steel industry, has set two stages of transformation:

- the first – transitional, planned until 2030: modification of current technologies to reduce CO_2 emissions by 50% compared to 1990,
- the second – consists in achieving climate neutrality of the steel industry in Europe by 2050: reduction of CO_2 emissions by about 84% compared to 2015 by: eliminating

hard coal from metallurgical processes, using green hydrogen, implementing direct reduction processes using hydrogen, increasing the share of the electric process in the production of steel from scrap and iron from direct reduction, using CCS and CCU processes, production of iron by electrolysis, using electricity from renewable sources, etc. Achieving these goals will be a long-term process and very expensive, and strategic political decisions made by the governments of individual European Union countries are necessary in this matter.

Another way to reduce emissions is to increase process efficiency. The potential for energy recovery and resource reuse of glassy blast furnace slag and crystalline steel slag and reinvestment of revenues in carbon capture and storage is shown in the work (Sun et al. 2022). If the generated revenues (2030 – 35 ± 16 billion USD; 2050 – 40 ± 18 billion USD) are used for carbon capture and storage processes, CO_2 emissions corresponding to the sectoral 2°C target requirements will likely be achieved without any external investment by 2050.

Technologies enabling industrial decarbonisation exist – from green hydrogen to carbon capture and storage – but they remain expensive and niche (Bhaskar et al. 2022; Ampofo 2023; Estevez et al. 2024). In (Wimmer et al. 2022) an overview of different steel production pathways and their associated CO_2 emissions is presented and transition scenarios are discussed, including hybrid EAF-BOF steelmaking and new green steelmaking methods using hydrogen-based direct reduction (fine ore reduction, final reduction of low-grade iron with DRI (Wimmer et al. 2022).

Without sufficient private sector demand or public sector policy support, these technologies will not be developed to deliver the decarbonisation the world needs. The First Movers Coalition (FMC) was formed to convince the private sector to finance the development and scale-up of the climate technologies needed to deliver near-zero emissions processes that reduce the carbon footprint of these industries by 85–100% (WEForum 2024). Given that global challenges often have local solutions, the Coalition is organising regional workshops in Asia, Africa, and South America to identify existing potential in the regions studied to increase the supply of low-carbon technologies, analyze the challenges and barriers to increasing both demand and supply of near-zero emissions solutions, and recommend further action. The report from the FMC workshop, held October 9–11, 2023 in Sao Paulo, Brazil, focused on three sectors: steel, aluminum, and aviation (WEForum 2024).

The iron and steel industry significantly contributes to global anthropogenic CO_2 emissions, accounting for around 4% of anthropogenic CO_2 emissions in Europe (Kurrer 2020). Replacing coal with hydrogen produced from renewable energy would enable significant decarbonisation of the industry, but would increase the price of a tonne of steel by around one-third (at current prices). The production of hydrogen required to fully decarbonize the steel industry would require an increase in electricity production of around 20% (Kurrer 2020). Investment in renewable energy and the pursuit of a hydrogen economy in Europe could contribute to a long-term competitive advantage for the European steel industry.

Many countries and research groups are involved in the optimisation of steel production processes, trying to achieve decarbonisation without its undesirable effects, such as increased production costs. They include various approaches such as technological changes in processes, utilisation of by-products for waste heat recovery (Wang et al. 2020), political solutions such as the Carbon Border Adjustment Mechanism (CBAM) (Zhao et. al. 2024), acceleration of political decisions related to investment directions (Harpprecht et al. 2022), financial support, and also obtained benefits in the form of energy and carbon savings (Wang et al. 2020), efficiency improvements (Tautorat et al. 2023) financial savings, and other environmental and public health benefits (Kim et al. 2022).

Special interest is put on the shift from primary to secondary steel production with a special focus on insufficient scrap availability and improvement in recycling methodologies for metals and steel (Suer et al. 2022; Colla et al. 2023; Liu et al 2024).

Early research is focused on niche solutions for which the pace of future progress is difficult to predict, including: reducing iron ore with hydrogen plasma (Gajdzik et al. 2023b) or use of biomass with carbon capture and storage/utilisation (Andrade et al. 2024; Lundmark et al. 2024).

Several works concern simulations aimed at determining the economic efficiency of new technologies in the steel industry. They emphasize that the decarbonisation of this industry requires a large availability of cheap energy from non-emission sources. (Lopez et al. 2022; Venkataraman et al. 2022; Zou et al. 2022; Lee 2023). Hydrogen-based steelmaking is a promising technology for industrial decarbonisation. It is only necessary to properly allocate the industry to where there are adequate resources of renewable energy sources and raw materials. The costs may then be significantly lower (Cao et. al. 2024).

4. Discussion

To decarbonize the iron and steel industry it is necessary to change the technology from primary steel production (from iron ore), which uses coke, to direct reduction technology DRI, which uses hydrogen. Such a change will significantly reduce CO_2 emissions. The transition of the steel industry to hydrogen technologies is necessary, but it will be associated with a significant increase in demand for hydrogen and electricity – this means very large investments. Generating the hydrogen needed for steel production will require a huge amount of green electricity to be fed into the electrolysers. Steel produced in low-emission technology – using hydrogen – is currently very expensive, so for the prices of steel from the hydrogen DRI path to be comparable with current methods, the carbon dioxide emission prices in the ETS system should be very high.

There are many barriers and unfavorable circumstances that delay the commercialisation of hydrogen-based steelmaking technology (Ohman et al. 2022). It seems that the basis for success is that there is an overall political framework to support the transformation, that the energy and industrial transformation work together, and that all stakeholders: energy, industrialists, scientists, policymakers and society cooperate with each other.

Summary and conclusions

1. Steel is characterised by specific properties related to excellent strength and durability and ease of processing, as well as the possibility of recycling, and therefore is currently one of the most important raw materials necessary for the development of the world economy. Demand for it is in all sectors of the economy, primarily in construction and infrastructure, which consume more than half of global steel production.
2. Steel is produced by 71 countries and in 2023 the production amounted to 1892.2 Mt, with the G20 countries (the richest countries in the world) producing 85% of the world's production and 80% of its consumption. The largest steel producers are China, then: the EU, India, USA. China's raw steel production accounts for more than half of the world's production.
3. Currently, steel production is carried out using the blast furnace – basic oxygen furnace (BF-BOF) technology, which produced 71.1% of crude steel in 2023, and the electric arc furnace (EAF) technology – production of 28.6%, while 0.3% of steel is obtained in other processes. In the EU, steel production in 2023 using the BF-BOF technology was 55.2% (total steel production was 126.3 Mt), and from the EAF technology – 44.8%.
4. The use of scrap brings tangible material savings. The use of 1 tonne of steel scrap in the production process results in the following raw material savings: over 1.4 tonnes of iron ore, 740 kg of coal, and 120 kg of limestone.
5. Iron and steel production, despite significant improvements in energy efficiency, is an energy-intensive industry. It contributes to about 7% of global greenhouse gas emissions and 11% of global CO_2 emissions. In 2023, the average CO_2 emissions from steel production processes were as follows: BF-BOF – 2.33 t/tcs, DRI-EAF – 1.37 t/tcs, EAF – 0.68 t/tcs.
6. Global net anthropogenic greenhouse gas emissions are estimated at 59 ± 6.6 Gt CO_2 equivalent in 2019, which is about 12% (6.5 Gt CO_{2eq}) more than in 2010 and 54% (21 Gt CO_{2eq}) more than in 1990. To achieve the 1.5°C target set out in the Paris Agreement, CO_2 emissions must be halved by the end of this decade and reach net zero by 2050. Transitioning the steel sector to a 1.5°C path will require effective policies to implement new low-carbon technologies and a circular economy. Coordinated efforts from a broad range of stakeholders will be necessary to develop low-carbon technologies: EAF, hydrogen-based (DRI), supported by CO_2 capture, storage, and utilisation (CCUS) technologies. Improving the energy efficiency of these technologies will also be essential.
7. The topic of decarbonisation of the steel industry on a global scale as well as in individual countries is currently being eagerly taken up by many centers. Several reports, studies, and scientific articles propose strategies to overcome the challenges related to greenhouse gas emissions, especially CO_2. All these publications emphasize that reducing significant CO_2 emissions from the steel sector is a difficult task. It indicates the need to support modern technologies such as smart coal use (SCU), direct CO_2 emission avoidance (CDA), and several other activities related to economic changes and sustainable energy sources.

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DECARBONISATION DETERMINANTS OF THE STEEL INDUSTRY

K e y w o r d s

steel industry, technologies, decarbonisation

A b s t r a c t

The iron and steel industry is a sector with very high energy consumption and also causing high emissions. It is difficult to imagine the development of modern sectors of the economy such as construction, transport or the machinery industry without the use of steel, so forecasts indicate that the demand for steel will increase in the future. Meanwhile, environmental concerns and concerns about climate change are growing, so the iron and steel industry faces a serious challenge related to reducing its emissions in order to achieve the goal set in the Paris Agreement, and this is even more true for this industry in the European Union. Currently, the most popular technology for steel production is the blast furnace process – basic oxygen furnace (BF-BOF). This technology requires the use of coal, which is a source of emissions, so a radical technological change is needed. Decarbonising the steel industry requires changing from coal-based metallurgy to hydrogen-based and electricity-based metallurgy. Changing from primary to secondary steel production (using scrap steel) improves the situation but is not a solution to meet growing demand. There are two main technology paths that can achieve significant CO_2 reduction. The first is Smart Carbon Usage (SCU), which is based on the gradual reduction of coal consumption, including the use of by-product gases for further conversion into valuable products. The second emerging technology path is Carbon Direct Avoidance (CDA). These and other developing methods of low-emission or zero-emission metallurgy are discussed in the article. Unfortunately, some of these methods are not mature and their final commercialisation requires overcoming a number of problems.

DETERMINANTY DEKARBONIZACJI PRZEMYSŁU STALOWEGO

S ł o w a k l u c z o w e

technologie, dekarbonizacja, przemysł stalowy

S t r e s z c z e n i e

Przemysł żelaza i stali jest to sektor o bardzo wysokim zużyciu energii, a także powodujący wysokie emisje. Trudno sobie wyobrazić rozwój współczesnych sektorów gospodarki takich jak budownictwo, transport czy przemysł maszynowy bez wykorzystania stali, zatem prognozy wskazują, że zapotrzebowanie na stali będzie w przyszłości rosło. Tymczasem zyskują na znaczeniu obawy o środowisko i zmiany klimatyczne, zatem przemysł żelazny i stalowy stoi przed poważnym wyzwaniem związanym z redukcją emisji, aby osiągnąć cel wyznaczony w porozumieniu paryskim, a tym bardziej dotyczy to tej branży w Unii Europejskiej. Obecnie najpopularniejszą technologią służącą

produkcji stali jest proces wielkiego pieca – podstawowego pieca tlenowego (BF-BOF). Ta technologia wymaga wykorzystania węgla, stanowiącego źródło emisji, zatem potrzebna jest radykalna zmiana technologiczna. Dekarbonizacja przemysłu stalowego wymaga zmiany metalurgii opartej na węglu na metalurgię opartą na wodorze i energii elektrycznej. Zmiana z produkcji stali pierwotnej na wtórną (wykorzystującą złom stalowy) poprawia sytuację, ale nie jest to rozwiązanie zapewniające zaspokojenie rosnącego popytu. Istnieją dwie główne ścieżki technologiczne, które prowadzą do osiągnięcia znaczącej redukcji CO_2. Pierwsza z nich to *Smart Carbon Usage* (SCU). Druga rozwijająca się aktualnie ścieżka zmian technologicznych to bezpośrednie unikanie emisji dwutlenku węgla (CDA). Te i inne rozwijające się metody niskoemisyjnej lub bezemisyjnej metalurgii zostały omówione w artykule. Niestety niektóre z tych metod nie są na tyle rozwinięte, a ich ostateczna komercjalizacja wymaga pokonania wielu problemów.