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Decarbonisation of the steel industry: theoretical and practical approaches with analysis of the situation in the steel sector in Poland

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Abstract

Climate change and environmental degradation are nowadays the key challenges of the industries in Europe (according to the European Green Deal). The primary goal is to achieve a climate-neutral in Europe by 2050. Technologies with carbon dioxide (CO_2) emissions should be completely stopped in the future. The iron and steel industry is among the manufacturing industries with high CO2 emissions in Europe. In Poland, steel mills produce about 9 million tonnes of steel per year (average for 2000-2021). Steel mills in Poland use two steel production technologies, EAF and BOF. The first technology is highly energy intensive, and the second has high emissions of CO_2. There will be no BF technology in zero-emission smelters; this technology will be replaced by DRI (i.e., direct iron reduction) installations, and electric furnaces will be powered by renewable energy. The paper consists of two parts: a theoretical section and a practical section. In the first section, the way the steel industry moves towards climate neutrality was presented. The part of the paper was realized based on European documents and a literature review. The second part was an analysis of the CO_2 emission in the steel industry in Poland. The analysis was realized based on data from the Polish Steel Association.

Keywords

decarbonization, steel industry, Poland, low carbon technologies, CO_2 emissions.

Introduction

With increasing public pressure to limit global warming to 1.5 degrees C, governments are responding with increasingly ambitious decarbonization targets. At the UN climate summit in 2019, 66 countries announced their intention to achieve zero net CO_2 emissions by 2050. This is the target adopted by the EU in its climate policy (European Commission, 2018). The Green Deal policy is also known as the green, energy and hydrogen transition. Using renewable energies and green hydrogen across Europe is essential for achieving the Green Deal goals. Green hydrogen, from the perspective of technological progress and an integrated economic, energy, and industrial transformation, will be a viable power source for district heating installations and networks (natural gas will be replaced by hydrogen). For the energy and green transition in manufacturing industries to be successful, the decarbonization of economies and industries is needed (Deloitte, 2020). Decarbonization is the systematic reduction of carbon dioxide (CO2) emissions into the atmosphere to eventually stop these emissions completely. The manufacturing industry is responsible for 20 % of Europe's emissions. Manufacturing industries with high CO_2 emissions in Europe include iron and steel, cement, chemicals and petrochemicals, pulp and paper, fertilizers, glass, ceramics, oil refineries, and non-ferrous metals (mainly aluminum). Cement, steel, and chemical production processes produce the most CO_2 (CCMI/190, 2022).

European climate policy has set a target of reducing CO_2 emissions by 55% by 2030 ('Fit for 55') while confirming the 2050 target of achieving 'net zero' climate neutrality. In order to meet these targets in the countries of the European Union, there must be integrated action by governments, businesses, organizations, etc. Changes must take place in production technologies, energy, residential heat supply, transport, and many other sectors of the economy. One industry sector that is part of the green transition is the steel industry. Steel mills need to switch from carbon-based energy to zero-emission technologies.

The aim of the paper is to answer the question of how steel producers transform towards carbon-free sustainability. The authors provide answers based on a review of European documents and scientific papers (section no. 1) and analyze the real data about the Polish steel industry (section no. 2). The decarbonization of the steel industry is strongly linked to the mining industry, so this publication falls within the scientific areas presented in "Acta Montanistica Slovaca". BOF steelmaking technology in Poland is based on coke, while EAF technology is based on electricity generated from coal (in Poland, 32% of energy comes from coal) (GUS: Statistics Poland, report: Energy 2022).

Background to the situation in the steel industry in Poland

The key industrial directions in European decarbonisation

The European Green Deal includes such strategic objectives (EU: 2021/1119) (i) increasing energy efficiency, (ii) using new renewable energy sources in decarbonization, (iii) using clean mobility, (iv) building the competitive industry with closed-cycle economy, (v) developing of infrastructure and connections between countries, (vi) developing of bio-economy and CO_2 sinks, (vii) using the systems (technologies) for capture and storage of CO_2. Industrial low-carbon technologies are needed to realize the climate transition (Wesseling et al., 2017a). Industries, including the steel industry, are investing in new technologies. Investments are needed to save energy (Chan et al., 2019). Steel mills are major suppliers of steel and steel products. Many investors involved in the energy transition need steel products. Steel is needed for wind farms, photovoltaics, etc.

In highly developed countries, low-carbon technologies dedicated to various industries are at a high level of technological readiness (TRL). However, the number of innovative technologies, as well as their degree of commercialization, is still too low. A new 'mix' of energy from renewable sources (wind, solar, biomass, etc.) is needed. Hydrogen would be effective in reducing CO_2 emissions in various iron and steel production processes (BF, DRI), as well as in smelting reduction and ancillary processes in steel production. Electrolysis, biomass, and charcoal are also good options for decarbonizing steelmaking processes (Rossetti di Valdalbero, 2017; Kushnir et al., 2020; Suopaj€arvi et al., 2018; IEA, 2017). The European steel industry is on an ambitious path to cut carbon emissions by 55% by 2030 compared to 1990 levels (equivalent to over -30% compared to 2018 levels) and to achieve climate neutrality by 2050.

Climate transformation requires accelerated development of carbon dioxide removal (CDR), carbon capture and storage (CCS), and carbon capture and utilization (CCU) technologies (Kuramochi et al., 2012). Industries will need green hydrogen to replace coal and variable gas to achieve the net zero target. The industry needs to shift from fossil fuel-based energy sources to other non-CO2 and renewable sources (Otto et al., 2017). These sources can include wind energy, photovoltaic and solar energy, hydropower, geothermal energy, biomass, and biofuels. On the path to energy transition, steel mills are both consumers of green energy and energy producers from other sources such as coal or natural gas for industrial purposes. By 2030, the European steel industry will need 150 TWh of renewable grid electricity, half of which will be needed for hydrogen production. The cost of planned investments in the EU is estimated at €86 billion (portal: wgospodarce.pl, 13 May 2022).

Currently, many industries are planning new technological investments (new, low-carbon ones must replace existing, high-carbon technologies). Large suppliers and producers of energy, steel, aluminum, copper, etc., are investing in new technologies that fit firmly into climate policy (Quader et al., 2015; Wiecek et al., 2019). Deep transformation is already underway in capital-intensive industries. The process of transforming the steel industry to low-carbon technologies has started with strong capital groups such as Tata Steel, ArcelorMittal, and ThyssenKrupp. Large companies have adopted ambitious targets to scale up the use of green technologies. Strong equity groups are beneficiaries of innovation and climate programs (Branca et al., 2020). European steelmakers have prepared more than 60 major projects that should reduce CO_2 emissions by 81.5 million tonnes by 2030. This is equivalent to a cut of more than 1/3 of the European steel industry's direct and indirect CO2 emissions in just eight years from now, in line with the EU climate targets. All these projects have a Technology Readiness Level (TRL) of at least 7 out of 9 (Eurofer, 2022: Low CO_2 emissions projects in the EU steel industry). Of these 60 projects, four are in Poland: three in Ostrowiec Swietokrzyski (smelter with EAF furnace production from scrap) and one in Dabrowa Gornicza (smelter with blast furnace). The projects of these investments concern energy efficiency and emission reduction (CDA). The major challenge for steelmakers is to build emission-free steelworks. Steel mills must replace blast furnaces with a DRI plant (i.e., a direct iron reduction plant) and build electric furnaces powered by renewable energy. The transition to DRI technology begins with the abandonment of blast furnace (BF)-based steel production, which will be replaced by DRI-EAF technology (Vogl et al., 2018; Kirschen et al., 2011). The process of technological restructuring in steel mills is being implemented gradually. Currently, 6.39% of steel worldwide is produced using DRI technology. In 2022, global DRI production reached 120 million tonnes (estimate based on Worldsteel's preliminary 12-month data covering about 90% of production), an increase of about 5% compared to the previous year. The largest producers of this technology were India (42 million tonnes), Iran (33 million tonnes), and Russia (8 million tonnes). The largest increases in DRI production were in countries such as Qatar (+106% compared to 2021), Libya (+22%), and Egypt (+13%) (World Steel Association, 2022).

In DRI technology, the iron ore reductant is natural gas or hydrogen. The iron thus obtained can then be fed into electric arc furnaces. The target, least carbon-intensive solution is based on the use of green hydrogen in the reduction process, i.e., produced by electrolysis using electricity from renewable sources. As there is currently no such possibility of producing hydrogen on an industrial scale, in the interim period, other solutions are required, e.g., carbon capture and storage or use of emitted carbon dioxide to reduce the environmental footprint (CCS), increased production of electric steel using steel scrap and hot briquetted iron additive (HBI) and natural gas-based DRI production. However, maintaining steel production in Poland at current levels (about 9 million tonnes of steel) using DRI technology will require about 400 thousand tonnes of hydrogen per year and an additional 22TWh of electricity (for hydrogen electrolysis and new EAF furnaces) (Polish Steel Association, 2022). Steel production in arc furnaces accounts for only 14 % of the GHG emissions from the use of blast furnaces and converter technology (BF+BOF).

The challenge for the EU steel industry is to replace natural gas in furnaces with green hydrogen or induced electricity. The cost of producing hydrogen from natural gas depends mainly on the price of gas, which is low in countries with access to this resource and high in countries that buy natural gas. Hydrogen produced by electrolysis costs between 50 and 55 kW needed to produce 1 kg of hydrogen. Replacing coal with hydrogen produced using renewable energy would enable significant decarbonization of the industry, but at current input price levels, this would raise the price of a tonne of steel by around a third. However, this gap could narrow in future years as, on the one hand, carbon prices may increase as a result of the withdrawal of free allowances and, on the other hand, the declining cost of renewable electricity, efficiency gains from larger-scale hydrogen production and the optimization of hydrogen-based steelmaking processes will reduce the cost of this alternative. The cost of producing green hydrogen has fallen by 60% over the past decade and typically ranges from EUR 3.6 to EUR 5.3/kg (data as of the end of 2020) (Kurrer, 2020).

The technological transformation of metallurgy is currently focused on replacing blast furnaces with arc furnaces, into which iron produced using green hydrogen from direct reduction is fed (Kirschen et al., 2011). European steelmaking has no choice but to decarbonize. In practice, this means that electric furnaces will replace blast furnaces. In the interim, these technologies would operate side by side in parallel, after which the blast furnace would be completely replaced by an electric furnace (a decade perspective). The steel industry in Poland will use DRI-EAF technology in the coming years. Steel mills will see the replacement of current integrated process installations: blast furnace and converter technology (BF+BOF), with direct iron reduction (DRI) installations combined with electric arc furnace (EAF), in short, DRI-EAF. Iron ore electrolysis can emit up to 87% less CO_2 than the current BF+BOF(with full decarbonization of the electricity supply). Hydrogen plasma reduction aims to achieve zero CO_2 emissions. In fact, steel production using hydrogen could emit up to 95% less CO_2 than production (BF+BOF) (Steelonthenet, 2020). CCU technologies (using waste gases from blast furnaces) can reduce emissions by up to 65% if fully implemented (CO_2 reductions also depend on the full life cycle of the resulting chemical products (CCMI/190 – EESC-2022-01057-00-00-AS-TRA (EN) 623/16, 2022).

Along with decarbonization, it is necessary to improve the energy efficiency of industries. In the steel industry, a reduction in steel production using BOF technology will result in an increase in steel production using EAF technology. The current EAF technology is energy-intensive. Therefore, in EAF steel mills, the energy source needs to be changed from coal to renewable energy (electric arc furnaces powered by green 'green' energy). In Poland, 32% of energy comes from coal (CSO, Energy, 2022), and in the EU, only 2.6%. The extent of diversification of energy sources in Poland is still low. This situation concerns not only industries but also households. According to a study by K. Midor (2022), most people (33%) in Poland (case study: Silesia Region) still use hard coal and natural gas (27%) in their households. Household energy awareness in Poland needs to be built up continuously (Jaciow et al., 2022).

In line with EU policy, steel mills must switch from fossil fuels to technologies other than those involving greenhouse gas emissions, mainly renewable energy. Steel mills must invest in emission-free technologies. Hydrogen produced using renewable energy (green hydrogen) appears to be a cross-sectoral response to decarbonization processes (H2 Green Steel, 2021). For example, a project in Sweden aims to eliminate greenhouse gas emissions from steel production by using renewable hydrogen (CCMI/190- EESC-2022-01057-00-00-AS-TRA (EN) 4/11). In Poland, steel mills are highly sensitive to changes in energy prices due to the highest ratio of energy consumption in the value of production sold (2.23ktoe/€ versus 0.21 in manufacturing in 2020). At the same time, the energy intensity of the steel industry in Poland is at a comparable level with the steel industry in the EU. In 2020, the energy intensity of the steel industry was even lower than in the EU and amounted to 0.287 toe/tonne steel for Poland, while the EU average was about 0.33 toe/tonne steel (GUS 2021, Enerdata, www.indicators.odyssee-mure.eu/). Calculations show that for the industry to be zero-carbon and competitive, green hydrogen is needed at a price of about $1.5/kg, which would raise prices by about 15-20% anyway ($100/kg more expensive), but with the introduction of the CBAM mechanism with a CO_2 allowance price of about $120/t would accelerate investments (based on ArcelorMittal, www.argusmedia.com/en/news in June 2022).

For many years, the EU's climate and environmental policy has been aimed at significantly reducing carbon emissions and reducing energy produced from non-renewable sources, including coal. In 2021, the European Commission announced the 'Fit for 55' package. The European Climate Law set a target of a 55% reduction in CO_2 emissions by 2030 while confirming the 2050 target of achieving climate neutrality. The steel industry is to be part of the Fit for 55 program, which aims to reduce emissions by 55% by 2030. With 'Fit for 55', free CO_2 allowances (in the EU ETS) will be phased out, and a carbon border offsetting mechanism (CBAM) will be introduced (The EU plan for a green transformation: consiliumeuropa.eu). European Green Transformation will result in an increase in energy demand by about 50-60%. (ArcelorMittal: www.wnp.pl/hutnictwo).

The decarbonization of the steel industry is based on several innovative technologies at different maturity levels, according to TRL (IEA, 2019). The innovation process in steel mills started with energy efficiency improvements (BAT). The next step was blast furnace gas capture (top gas recovery blast furnace and top gas recovery blast furnace with coke oven gas reforming). In Green Transformation are needed the technologies of new direct reduction based on natural gas, and technologies using hydrogen for iron ore reduction (Wyns et al., 2018). Now, such technologies are testing or using: ULCOS (Tata Steel), DRI, EAF with HBI, HIsarna + CCS (Tata Steel), H2-DRI, Midrex (sponge iron), and HYL, HYBRYT, GrINHy, H2Future, SuSteel, SALCOS. In the future, the technology CCU with the conversion of steel works arising gases to chemical fuels production will be very important. The steel producer will cooperate with the chemical industry. Technology development must accelerate. Economies will need commercial solutions for the electrolytic production of hydrogen and for the use of biomass in steel production (biochar). Innovation in steel plants is needed now because BF+BOF technology is non-ecological and non-economic. New technologies will reduce CO_2 emissions. However, for them to be introduced on a large scale, renewable energy sources with supply infrastructure are needed (Kreutz et al., 2005).

Currently, the EU steel industry consumes around 75TWh of electricity annually, some of which is purchased from the external grid. Producing the amount of hydrogen needed to decarbonize the steel industry fully would require an increase in electricity production of 20% and thus would require an even more ambitious development of renewable energy production in the EU, beyond replacing current fossil fuel electricity production (Eurofer, Nov. 2022). The European steel industry can be innovative in deep CO_2 reductions but needs money (Pers, 2014). Steel mills have planned many technology projects worth around €31 billion until 2030. Overall operating expenditure is estimated at €53 billion (pre-crisis forecast). When these two groups of investment expenditures are added up, the steel industry (the largest steel producer in the world and in the EU) will spend €85 billion on Green Transformation. The planned investments in the biggest capital groups in the world's steel industry are presented in tab. 1.

Tab.1. Planned investments in the world's largest steel industry groups

Company	Country	production capacity (current in Mt)	Project
ArcelorMittal	Germany, Spain, France	47	2030: hydrogen + CCUS 2050: DRI with hydrogen
Thyssenkrupp	Germany	12	2030: hydrogen + CCUS 2050: DRI with hydrogen
Voestalpine	Austria	8	DRI with hydrogen
Tata Steel	Netherlands	8	DRI with hydrogen
SSAB	Sweden, Finland	7	DRI with hydrogen
Salzgitter	Germany	5	DRI with hydrogen
Liberty Steel	Czech Republic, Romania	7	replacement of BOF by EAF

Source: Polish Steel Association, Katowice based on OECD, WorldSteel (Adapted from: Zagórska, M. Presentation, 2022).

Technological strategies of the European steel industry on the road to net zero

The road to the decarbonization of the EU steel industry consists of several steps (Fig. 1). According to EU policy, steel mills have to invest in low-carbon technologies. The implementation of many investments has the support of governmental organizations (key investments for the economy). A source of revenue (investment support) can be the CBAM 'tax'. Without government support, it will be difficult for steel mills to make new investments. With government support, steel mills need to move from smart carbon to hydrogen technologies implementation (DRI-EAF).

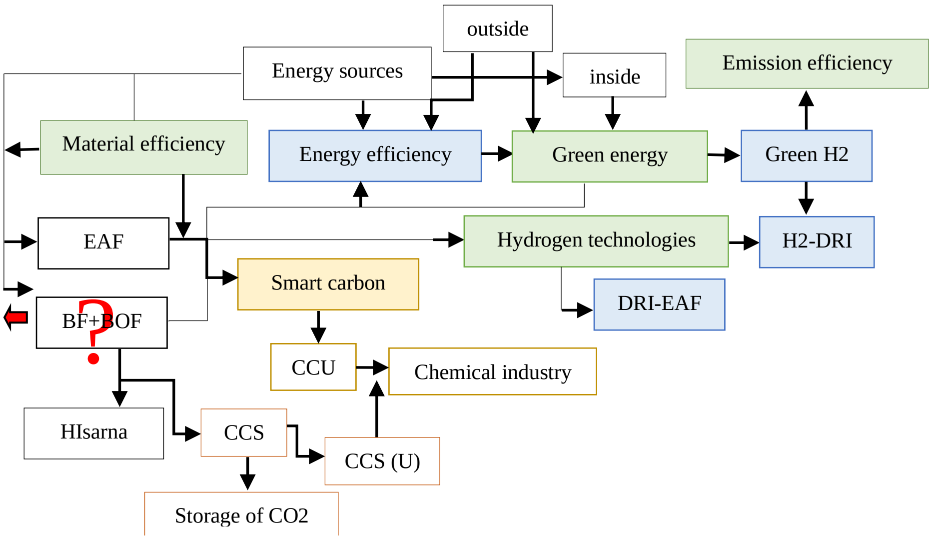

Fig. 1. The way of the steel industry to decarbonization
Source: own elaboration.

One of the technologies of the future, which is called 'smart carbon', is the decarbonization of a fuel feedstock with sequestration of CO_2 converted into a product for the chemical industry. The CO_2 can also be used as a feedstock for chemical or material production (Carbon2Chem, Steelanol). The other option is electrification, i.e., the erection of electric furnaces – replacing blast furnaces – together with a direct iron reduction plant (www.wnp.pl/hutnictwo: Ślęzak). Steel mills owned by large industrial concerns can develop technologies for their own energy sources. Investments in their own energy sources will be large projects and very capital-intensive. For new investments, steel mills need a lot of land. In addition to their own investments, an opportunity for the development of the steel industry is the development of the renewable energy sector and modular reactors.

According to Lechtenböhmer et al. (2016), based on the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC AR5), the three main categories of technical options for reducing carbon dioxide emissions from materials production are (i) improved material efficiency (ii) improved energy efficiency, and (iii) less carbon-intensive energy supply or carbon capture and storage (CCS). For deep decarbonization, material, and energy efficiency will help but will not be able to deliver the reductions needed. In the decarbonization, the processing of feedstock to usable materials, which includes the reduction of process-related emissions (for instance, from calcination of limestone to clinker or reduction of iron ore to iron) is necessary (Nurdiawati et al., 2021). Material efficiency is the key direction of sustainable production (Allwood et al., 2011). Two key strategies for deep decarbonization are (i) modification of existing blast furnace – basic oxygen furnaces (BF+BOF) to use pulverized coal and iron ore (HIsarna technology (Tata Steel) while installing carbon capture technology and storing captured CO_2 in aquifers or inactive oil and gas reservoirs (ii) hydrogen direct iron reduction (H2-DRI) using green hydrogen produced by water electrolysis, together with electric arc furnaces (EAF) (Richardson-Barlow et al., 2022). The HIsarna smelter with CCS is one of several options for integrating CCS into plants that still use coal as the primary reducing agent, and Tata Steel is planning a full-scale HIsarna + CCS plant at IJmuiden in the Netherlands (Tata Steel: Hisarna). Technologies: H2-DRI and EAF, with zero-carbon electricity, are among the no-mine technologies (Vogl et al., 2018; Müller et al., 2021). Major global steel producers have already developed and announced plans for full-scale plants: ArcelorMittal (2021) and Liberty Steel (2021). Other proposed approaches to decarbonize steelmaking include adding peak gas recycling (TGR) and CCS to existing blast furnaces (TNO, 2020). In the process, CO_2 is removed from the blast furnace peak gas, and the remaining stream is heated and reinjected into the blast furnace. A popular technology is the recycling of steel scrap using EAF (Cavaliere, 2019). Still, the variety of steel products that can be produced using this approach is limited by the quality of the scrap. Technological innovation is an effective tool for improving energy efficiency (Arens et al., 2017; Arens and Worrell, 2014; Brunke et al., 2014; Johansson, 2015; Worrell et al.,1997; Hagenbruch and Zeumer, 2017). According to Kim et al. (2022), based on IEA, the sustainable steelmaking technology map consists of four main groups of technologies: (i) carbon capture, utilization and storage (CCUS), (ii) hydrogen production and direct iron reduction (H2-DRI), (iii) direct electrification (DRI-EAF), (iv) bioenergy application.

Steel mills choose technologies that are suitable for them according to their capabilities (Skoczkowski et al., 2022; Karali et al., 2017; Bataille et al., 2018). The entry of innovative technologies as part of the steel industry's decarbonization policy will be between 2020 and 2030 (Pardo and Moya, 2013). The choice of technologies with the right level of energy efficiency can be from off-shelf technologies (melt reduction technologies, direct reduction technologies based on natural gas, direct reduction technologies based on hydrogen, direct use of electricity for iron ore reduction, use of biomass in steel production, increased steel recycling and other pathways of breakthrough solutions for low-carbon steel production) (Kushnir et al., 2020). Technological and economic factors support the steel mill's decision to invest in a particular technology (Fischedick et al., 2014). Smelters select iron reduction options according to their ability to decarbonize processes (Napp et al., 2014). Technologies (BAT) can potentially reduce emissions by 15 to 30% (Tracking IEA, 2017). BAT can contribute to short-term energy and GHG savings in the steel industry, but a transition to low-carbon technologies is needed to reduce CO2 emissions dramatically by 2030 (Griffin and Hammond, 2019). Industrial-scale application of CCS (U) (before or after combustion) can reduce CO_2 emissions by about 90%. (IEAGHG, 2013).

New technologies for low-carbon to net zero (Tagliapietra et al., 2019) will lead to changes in business models. Steel mills will reach low-carbon maturity in the next decades. The new models will be based on three strategies: (i) achieve emission reductions through material and energy efficiency, (ii) emission efficiency, or (iii) a combination of both (Axelson et al., 2021). The transformation of the steel industry to "net zero" is a new path driven by increasingly strong sustainability policies. Political pressure, driven by the need to introduce new technologies (breakthroughs to achieve net zero), will create a completely new steel industry. The innovation process requires research, planning, funds (capital), government programs, investment, commercialization of innovations, etc. Fig. 2 shows an illustrative model of an industry based on the value of low-carbon.

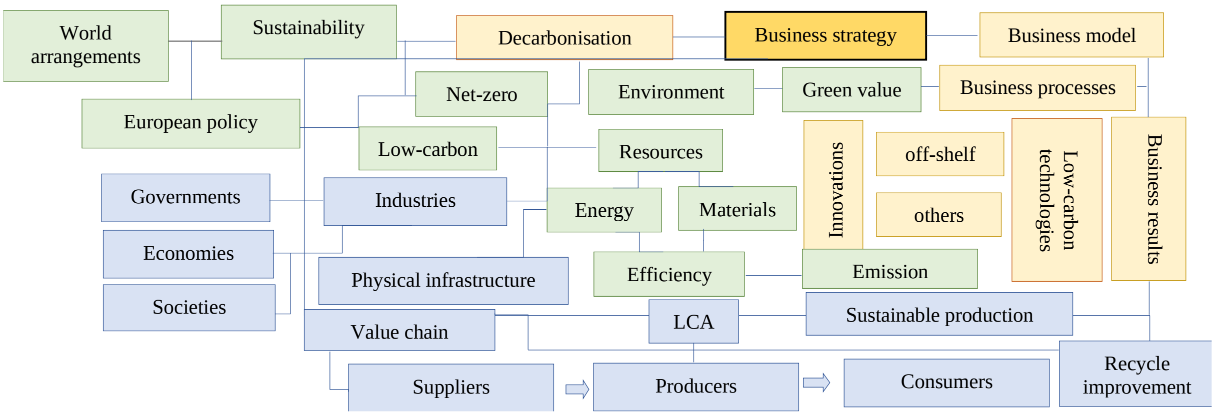

Fig. 2. Components of the business model in the transformation process to net zero production
Source: Own elaboration.

Situation analysis in the Polish steel industry: steel production and CO_2 emission from technological processes

The steel sector in Poland is highly energy-intensive (energy intensity is defined by the ratio of energy to final product costs). Industrial enterprises in Poland consume twice as much energy as households combined. Technological investments in steel mills, which have intensified in Central European countries since the economic reforms of the 1990s, are in line with the policy of sustainability of economies. Environmental aspects in steel mills determine the direction of technological investments (Gajdzik, 2009; Gajdzik, 2012; Kłosok-Bazan et al., 2015). Sustainability in steel mills is strongly linked to economic calculation and requirements (Gajdzik and Burchard-Korol, 2012). In 2002, the steel mills in Poland definitively phased out the technology of open-hearth furnaces (the marten process), which were not efficient and wrong for the environment (in 1990, Polish steel mills with the marten process produced 2 million tonnes of steel) (Gajdzik, 2013). With technological restructuring, the key steel mills in Poland were sold to foreign investors, and they were gradually able to produce competitive steel products (Gajdzik and Sroka, 2012).

In the period 2004- 2020, steel mills in Poland spent 15.5 billion PLN on technological investments (investments in blast furnace technologies, steel mills, and rolling mills). The highest expenditures were in the 2006-2009 period when the mills spent PLN 6 billion as part of restructuring programs for Polish steel mills. Examples of key investments: (i) Project no.1: modernisation of blast furnace no. 2 in Dabrowa Gornicza (October 2006, expenditure: PLN 260 million ($84 million, result: Europe's most modern blast furnace unit, main parameters: (i) working area: increase from 3.200 m3 to 3.600 m3, (ii) production capacity: 2.7 million tonnes per year), (ii) Project no. 2: new COS 3 line in Dabrowa Gornicza (December 2006, expenditure: PLN 488 million ($157 million), record-breaking lead time of 13 months, production capacity: 3 million tonnes/year , result: most modern COS in Europe), (iii) Project no. 3: modernisation of the wire rod mill in Sosnowiec (November 2006, expenditure: PLN 140 million ($45 million), result: provides modern products for the construction industry, capacity: 750 thousand tonnes per year), (iv) Project no. 4: construction of a new hot strip mill in Krakow (June 2007) instead of modernising the old one (expenditure: PLN 1.2 billion ($400 million, results: at start-up, the most modern hot strip mill in the world, largest and most modern rolling mill in Europe, provides products for the automotive and white goods industries, most energy-efficient rolling mill in Europe), (v) Project no. 5: new organic coating line in Swietochlowice (September 2006, expenditure: PLN 107 million ($35 million), result: one of the most modern plants in Europe with capacity: 200 thousand tonnes per year), (vi) project: two-station ladle furnace in Dabrowa Gornicza (June 2009, expenditure: PLN 132 million ($42 million), results: technology for the production of automotive grades, improving the quality and expanding the range of steel grades produced at Dabrowa Gornicza, capacity: 4.5 million tonnes per year, smelting weight: 315 tonnes per vat) (adapted from: Polish Steel Association, 2021).

Technological investments in the Polish steel industry have contributed to lower energy and raw material consumption. According to models proposed by (Gajdzik and Sroka 2021), (Gajdzik et al., 2021) as well as Wolniak et al. (2020), there is a strong correlation between investments and improvements in energy and raw material efficiency in steel mills in Poland. Due to the energy-intensive nature of the iron and steel industry, the pursuit of efficiency and energy savings has become a major priority for the industry.

In the last two decades (since 2000), Poland's annual average steel production has been above 9 million tonnes. In the last decade, steel production in Poland has fallen below 9 million tonnes. Between 2010 and 2021, steel mills in Poland produced about 8.8 million tonnes of steel annually (average volume). This production uses two technologies, EAF and BOF (BOF technology is BF+BOF). Together, the two technologies (EAF +BOF) are the total steel production. Data on steel production in Poland by a technological process are shown in Table 2.

Tab. 2. Statistical data on steel production volumes in Poland between 2010 and 2021

Specification	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	average
steel production (total) thousand tonnes	7993	8779	8358	7950	8540	9198	9001	10330	10157	8996	7856	8454	8801
EAF thousand tonnes	3998	4355	4132	3551	3492	3492	3877	4624	4765	4077	3920	4390	4056
BOF thousand tonnes	3995	4424	4226	4399	5067	5321	5321	5706	5392	4920	3936	4064	4731
pig iron BF thousand tonnes	3638	3975	3941	4011	4637	4821	4674	5151	4853	4386	3470	3587	4262

Source: Polish Steel Association, Katowice.

In September 2022, ArcelorMittal Poland announced its intention to temporarily stop the operation of one of the two blast furnaces at its Dabrowa Gornicza steel plant. The main reasons for the decision were a slowdown in demand for steel, accompanied by rising imports, as well as very high gas and energy prices (AMP press release, 8 September 2022). The blast furnace division in Krakow was closed down early. After the technology was excluded, the production capacity of the Polish steel industry decreased by 2.4 million tonnes (Fig. 3)

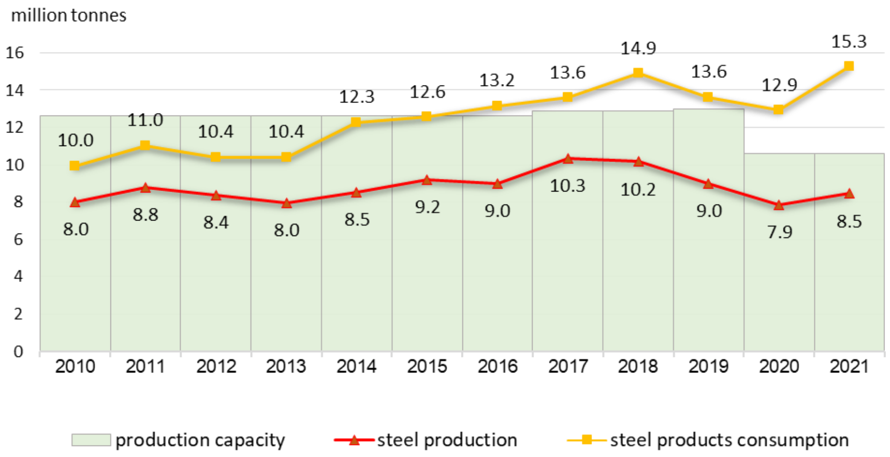

Fig. 3. Steel production, capacity, and consumption in Poland in the period 2010-2021
Source: Polish Steel Association, Katowice.

In Poland, four manufacturing industries (cement, coke, oil production, metallurgy, and fertilizer production) account for 15 percent of total carbon dioxide emissions. In 2019, 56 plants mainly produced cement, metals, fertilizers, coke, and refined petroleum products, generating 46 million tonnes of carbon dioxide (data of Instrat). Among these plants was the largest steelworks in Poland. Therefore, statistical data (data from the Polish Steel Association in Katowice) on the Polish steel industry were analyzed according to CO_2 emissions. The analysis used the rate of CO_2 emissions per 1 tonne of steel. As statistical institutions do not have data on CO_2 emissions per 1 tonne of steel by process, it was assumed (based on metallurgical knowledge) that approximately 88% of CO_2 emissions in steel mills are generated by the BF+BOF process. The share of the BF+BOF process in CO_2 emissions was determined on the basis of data on the overall emissivity of the processes in the steelworks (Fig. 4).

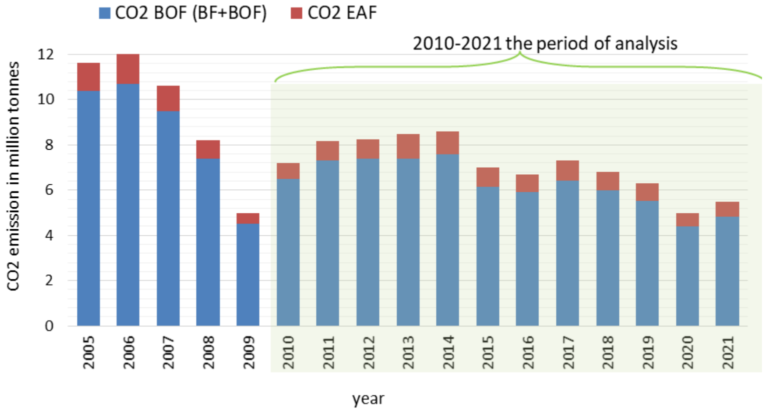

Fig. 4. CO_2 emissions by processes in the Polish steel industry in the period 2005-2021
Source: Polish Steel Association, Katowice.

The use of the index (tonnes of CO_2 emissions per 1 tonne of steel) allowed the technological processes to be compared with each other in terms of CO_2 emissions. The CO_2 emissions indicators determined are shown in Table 3.

Tab. 3. CO_2 emissions indicators in the steel industry in Poland in the period 2010-2021 [in tonnes]

Specification	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	average
CO_2 emission (total) per 1 tonne of steel	0.900	0.930	0.980	1.060	1.060	0.761	0.744	0.709	0.667	0.700	0.633	0.647	0.816
CO_2 emission by processes: per 1 tonne of EAF steel	0.198	0.205	0.216	0.233	0.233	0.167	0.164	0.156	0.147	0.154	0.139	0.142	0.179
CO_2 emission by processes: per 1 tonne of BOF steel	0.792	0.818	0.862	0.933	0.933	0.670	0.655	0.624	0.587	0.616	0.557	0.569	0.995

Source: Polish Steel Association, Katowice.

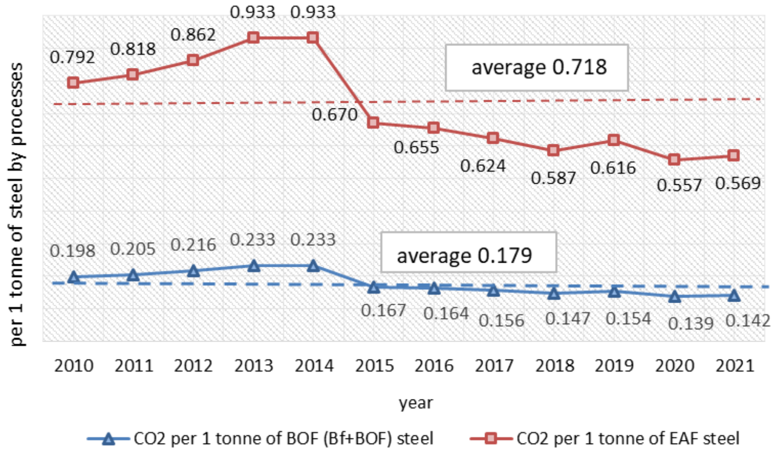

Fig. 5. CO_2 emissions per 1 tonne of steel by processes in the Polish steel industry in the period 2010-2021 [in tonnes]
Source: Polish Steel Association, Katowice.

The analysis of CO_2 emissions carried out was detailed with the coke utilization process in the BF+BOF process (Table 4). Based on coke consumption data (first knowledge), indicators per tonne were determined for the period 2010-2021 (Fig. 6).

Tab. 4. Coke consumption in the steel industry in Poland in the years 2010-2021

Specification	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	average
Coke consumption (total) in BF+BOF thousand tonnes	1825	1878	1733	1898	2540	2280	2193	2191	2236	2117	1638	1739	2022
Coke consumption per unit of BOF (tonne)	0.457	0.425	0.410	0.431	0.501	0.428	0.412	0.384	0.415	0.430	0.416	0.428	0.428
Coke consumption per unit of BF (tonne)	0.502	0.472	0.440	0.473	0.548	0.473	0.469	0.425	0.461	0.483	0.472	0.485	0.475

Source: Polish Steel Association, Katowice.

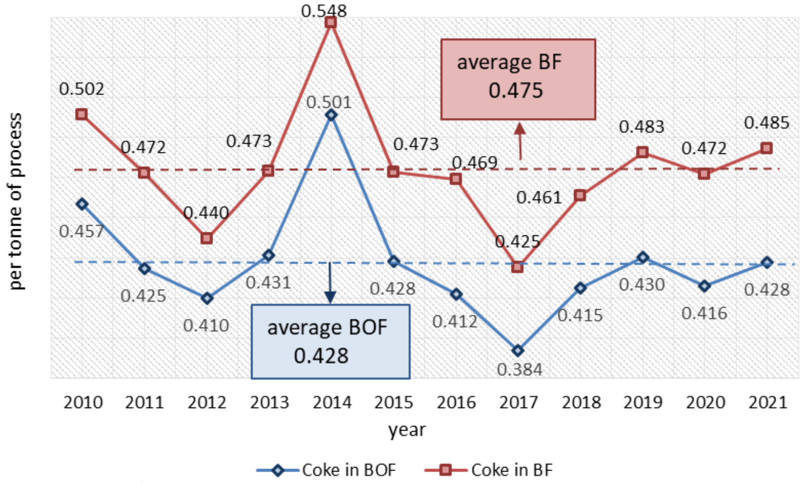

Fig. 6. Coke per 1 tonne of technological processes in the Polish steel industry in the period 2010-2021 [in tonnes]
Source: Polish Steel Association, Katowice.

The analysis carried out based on CO_2 emissions in steel production processes and coke consumption in the BF+BOF process will allow steelworks to determine courses of action for reducing CO_2 emissions in the steel industry in Poland. From 2020 onwards, carbon prices rose rapidly (fig.) High prices can block the development of a coal economy (Fig. 7). Prices for CO_2 emission allowances under the EU ETS have exceeded €90 per tonne. Rising CO_2 emission allowance prices and the changes proposed in the Fit for 55 package are key determinants for investment in new low-carbon technologies in the Polish steel industry. An important impulse for change is also the high price of energy, which in Poland is produced from coal. The prices have also risen sharply in the last two years (Fig. 8). In such a situation on the market, the longer the Polish industry stays with coal, the more devastating the effects of climate change will be. The world market's largest steel company (leader in steel production) exports steel using BF+BOF technology. The capital group, to which the steelworks belong, owns the largest coke. The capital group in Poland has already announced a plan for investment in low-carbon technologies (DRI). Money is needed for new investments. So far, a total of more than PLN 15.5 billion has been spent on innovative EAF and BOF technologies in Poland. Improvements in technology necessitate changes in the human factor. The steel industry in Poland employs 20 thousand people, of which the largest steel producer accounts for about 50%. If the steelworks do not need coke, a reorganization of the human factor must be planned now (coking employs about 2 thousand people, and key steelworks about 10 thousand people).

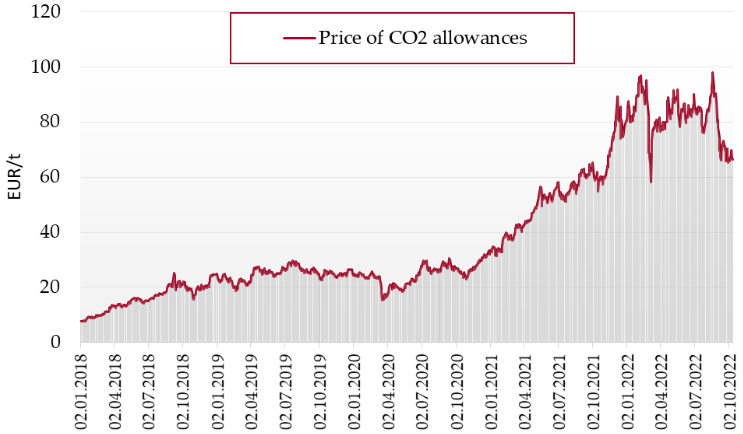

Fig. 7. Prices of CO_2 emissions in the steel industry in the period 2018-2022
Source: Polish Steel Association, Katowice.

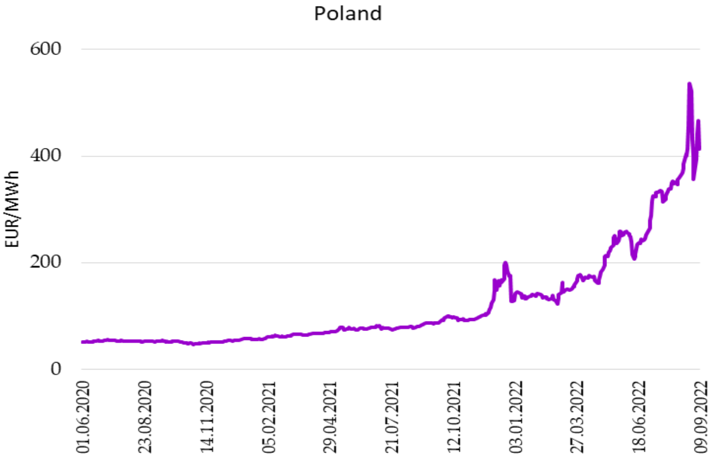

Fig. 8. Prices of industrial energy in Poland in the period 2020-2022
Source: Polish Steel Association, Katowice.

Disussion and Conclusion

Decarbonization is a challenge for the steel sector in Poland. The steel sector in Poland produces almost 9 million tonnes of steel per year, with the demand for steel in Poland being higher and covered by steel from the EU and third countries (Figure 3). Steel products are consumed by key industrial sectors. In addition to steel mills, which are planning radical technological changes, the energy sector in Poland also needs to produce more energy from renewable sources. Combined heat and power plants, wind power plants, photovoltaics, and other planned investments in Poland (nuclear power plant) need steel. Planned technological investments must be cost-effective. CO_2 capture technologies (CCS) must be realized in cooperation between the steel and chemical industries. No one doubts that a new restructuring of the steel industry awaits us. The steel mills will choose from the available technologies on the market (off-the-shelf technologies), those that will be optimal for them (Lie, 2007; IEA, 2013). In the industrial transformation to net zero, barriers to investment that arise in the investment process, which increase the risk of investment, need to be continuously removed. Skoczkowski et al. (2020) looked for risks in the areas of politics, technology, economics, socioeconomics, and climate. Among the risk areas are factors dependent and independent of the smelters, occurring within and outside the smelters themselves and even in the entire supply chains and environment (for instance, lack of diversified energy infrastructure, low energy security of the country, etc.). Barriers to decarbonisation were also presented in publications (Oberthür et al., 2021; Wesseling et al. 2017a; Worrell and Biermans, 2005; de Beer et al., 1998; Wesseling et al., 2017a; Richardson-Barlow et al., 2022; Onarheim et al., 2015) and were: the lack of mature low-CO_2 technologies, High Capex, the long investment cycles, the high technology risk, the high investment costs, the high competitiveness costs, the high costs of global value chains, the lack of policy frameworks, the longtime of projects provide for changing technology in steel industry, the longtime of investments in electricity and others industries important for lo-carbon transformation, the low of cyclical profit margins in CO_2 reduce the availability of investment capital and increase the return on investment times, the high potential loss of market share due to failures in the production process increase the risk perception of innovation, the little opportunity for testing and upscaling of innovations, the incremental improvements to core process technologies over the past decades, the focus on refurbishing existing large-scale plants (so-called brown field investment), particularly in industrialized countries, inhibits more radical innovation. Among the barriers mentioned, in addition to economic and program barriers, the immaturity of the technologies proposed to steel mills in the transition to low carbon is considered a key barrier (Wesseling et al., 2017b). Deep-decarbonisation technologies are either at the R&D stage, undergoing laboratory testing, or pilot investments. Two of the most promising options for deep decarbonization, DRI-EAF and DRI, are also not yet strongly commercialized. Globally, steel production from DRI technology (Worldsteel) is less than 10%.

In decarbonization investments, cooperation is needed with processes that are expected to reduce CO_2 emissions in the supply chain (IEA, 2013 report; Kreutz et al., 2005). Deep decarbonization of electricity, transport, industry, and buildings is an environmental priority for Europe. The system for transforming economies, industries, and societies to low or net zero carbon is formed by policy, infrastructure, knowledge (R&D), finance, and new technologies. The actors in the system are companies (suppliers, producers, consumers), institutions (local, regional, national, global), and policy. The system should be based on networks and interactions of all actors. Many factors need to be taken into account in the transformation of the steel industry to net zero, including regional (nature of the region, importance of the region to the economy) and social (number of employees, number of new jobs) conditions (Xylia et al., 2018). Every country with steel mills needs to develop support programs for steel regions so that the negative effects of the transformation (for instance, redundancies) are not too severe. Technological change is built based on possible scenarios in which decision-makers ('mills') take into account the many factors inhibiting change, for instance, energy prices, scrap supplies, and energy sources (Gajdzik et al., 2023a, 2023b; Gajdzik et al., 2022). In the deep decarbonization of the steel industry, steelworks can be assisted by Industry 4.0 technologies, which already form the structures ('seeds') of smart manufacturing in strong capital groups (Gajdzik and Wolniak, 2021). Strong capital groups, which emerged at the beginning of this century, also have steel mills in Poland (Gajdzik and Sroka, 2012). This strong foreign capital is an opportunity for the steel market in Poland. Despite the barriers, the steel mills (the largest capital groups in the global steel market) began their journey to net zero. In new technologies, however, hydrogen and energy from sources other than coal should be prioritized for iron and steel processes. There are significant potentials for energy savings and CO_2 reduction, and many of the new technologies can even be realized as viable (Johannsen et al., 2023). Although a complete transition to renewable energy may not be feasible until after 2030, steel mills should begin this transition immediately.

List of abbreviations
BAT Best Available Technologies
BF Blast Furnace
BOF Basic Oxygen Furnace
CCS Carbon Capture Storage
CCU Carbon Capture and Usage
CCS(U) Carbon Capture Storage and Usage
CCUS Carbon Capture Usage and Storage
CDR Carbon Direct reduction
CDA Carbon Direct Avoidance
DRI Directed Reduced Iron
EAF Electric Arc Furnace
EC European Commission
EU European Union
EU ETS EU Emission Trading System
H-DR Hydrogen Direct Reduction
ICT Information Communication Technology
IED Industrial Emission Directive
IT Innovative technology
LCA Live Cycle Assessment
R&D Research and Development
TRL Technology Readiness Levels
CO2 carbon dioxide
HBI Hot Briquetted Iron

BF+BOF Blast Furnace and Basic Oxygen Furnace
H2 Hydrogen
DRI-EAF Directed Reduced Iron and Electric Arc Furnace
CBAM Carbon Border Adjustment Mechanism
EU ETS European Union Emissions Trading System
ULCOS Ultra–Low Carbon Dioxide(CO_2) of Steelmaking
TGR Top Gass Recykling
LCA Life Cycle Analysis

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