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Process of Transformation to Net Zero Steelmaking: Decarbonisation Scenarios Based on the Analysis of the Polish Steel Industry

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Abstract: The European steel industry is experiencing new challenges related to the market situation and climate policy. Experience from the period of pandemic restrictions and the effects of Russia's armed invasion of Ukraine has given many countries a basis for including steel along with raw materials (coke, iron ore, electricity) in economic security products (CRMA). Steel is needed for economic infrastructure and construction development as well as a material for other industries (without steel, factories will not produce cars, machinery, ships, washing machines, etc.). In 2022, steelmakers faced a deepening energy crisis and economic slowdown. The market situation prompted steelmakers to impose restrictions on production volumes (worldwide production fell by 4% compared to the previous year). Despite the difficult economic situation of the steel industry (production in EU countries fell by 11% in 2022 compared to the previous year), the EU is strengthening its industrial decarbonisation policy ("Fit for 55"). The decarbonisation of steel production is set to accelerate by 2050. To sharply reduce carbon emissions, steel mills need new steelmaking technologies. The largest global, steelmakers are already investing in new technologies that will use green hydrogen (produced from renewable energy sources). Reducing iron ore with hydrogen plasma will drastically reduce CO_2 emissions (steel production using hydrogen could emit up to 95% less CO_2 than the current BF + BOF blast furnace + basic oxygen furnace integrated method). Investments in new technologies must be tailored to the steel industry. A net zero strategy (deep decarbonisation goal) may have different scenarios in different EU countries. The purpose of this paper was to introduce the conditions for investing in low-carbon steelmaking technologies in the Polish steel market and to develop (based on expert opinion) scenarios for the decarbonisation of the Polish steel industry.

Keywords: decarbonisation; steel industry; Poland; scenarios; net zero steelmaking

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1. Introduction

The economies of many countries, including Poland's economy, must shift from non-renewable energy sources (based on fossil fuels) to low-carbon energy sources and renewable energy sources. These sources can be wind, solar (photovoltaic PV panels), hydro (including geothermal), biomass, and biofuels. New energy sources, while not enough to decarbonise the steel industry, effect better energy efficiency and can significantly reduce CO_2 emissions associated with energy consumption in steel mills. Many industries (energy, steel, and heating) need to shift from fossil fuels to non-GHG technologies, mainly to renewable energy. Decarbonisation of steel production is the process of reducing carbon emissions and improving the energy efficiency of technological processes. The world (highly developed countries) wants to achieve zero CO_2 emissions by 2050 [1]. On the way to net zero, steel mills must reduce their use of fossil fuels (coal is used to produce the coke needed for BF + BOF blast furnace–basic oxygen furnace steelmaking) and invest in carbon-free technologies. Hydrogen produced using renewable energy (green hydrogen) appears to be a cross-sectoral response to decarbonisation processes [2]. Blast furnace–basic oxygen furnace (BF + BOF) technology is trying to be replaced by direct reduced iron (DRI) technology. An alternative to DRI technology is the modernization of EAF steelmaking technology and the construction of furnaces (EAF) in integrated mills (mills with BF + BOF technologies). Electric arc furnace (EAF) steel production accounts for only 14% of the greenhouse gas emissions produced by the integrated method (BF + BOF). The challenge for the steel industry is to replace natural gas in steel furnaces with green hydrogen or induction electricity [2]. In addition to a radical restructuring of technology (replacing BF + BOF technology with DRI and developing electric arc furnace steelmaking technology), an important direction of change is for steel mills and related industries (chemical industry) to invest in carbon dioxide removal (CDR), carbon capture and storage (CCS), and carbon capture and utilization (CCU) technologies [3]. Steel mills must make better use of waste gases from blast furnaces (thereby reducing emissions by up to 65% if fully implemented). Reducing CO_2 emissions is also part of the full life cycle of chemical products [1]. Carbon capture and utilization (CCU) stands for the capture and utilization of carbon dioxide (CO_2) as a carbon source to be used as a feedstock in the production of synthetic fuels, carbonates, chemicals, and polymers [4]. Bringing together stakeholders from across the CCU value chain and industries and sectors can be an opportunity to decarbonise the industry, including the steel sector [5–7].

According to the European "Fit for 55," policy announced on 14 July 2021 (reducing emissions by 55% by 2030, compared to 1990 levels and achieving climate neutrality by 2050) [8], decarbonisation will require a profound transformation of industrial activity (over the next 30 years). Industrial decarbonisation is not a shallow and rapid process but a long and deep one. Industrial decarbonisation is a deep process because it involves fundamental changes in the way we produce and consume energy and because it requires significant technological, economic, and political transformations. Decarbonising industry requires the development and deployment of new, low-carbon technologies. This is a long and complex process that involves extensive research and development, testing, and scaling-up of new technologies. This process takes time, and there may be setbacks and failures along the way. The transformation of carbon-intensive industries to net zero must be well-planned. This is because they are key investments in many industries.

Industrial decarbonisation also requires significant changes in the way we produce and consume energy. This involves shifting away from fossil fuels and towards renewable energy sources, such as solar, wind, and geothermal. This shift will require significant investments in infrastructure and changes in consumer behaviour, which take time to implement. Additionally, industrial decarbonisation also requires significant changes in the way we govern and regulate the energy sector. This involves creating new policies, regulations, and incentives to support the transition to a low-carbon economy. This process can be slow and contentious, as different stakeholders may have competing interests and priorities.

Among the carbon-intensive industries is the steel industry, which—according to the Fit for 55 packages—wants to reduce CO_2 emissions by 35 percent by 2030. To achieve this goal, within a decade, steel mills must also plan investments that will change the way they produce steel. Decarbonising the steel industry is strategic for the economies of many countries. Stakeholders in the transition need to develop long-term tactics aimed at a net zero goal. Deep decarbonisation requires strategic planning, preceded by diagnostic activities that will serve to develop several scenarios for achieving the net zero goal.

The aim of the research was to explore the different approaches that steel mills can take to achieve net zero CO_2 emissions. The study focused specifically on the steel sector in Poland. The work consists of a theoretical part and a research part. The theoretical part was based on a review of policy guidelines, industry studies (industry reports), and scientific publications. The theoretical part focuses on the challenges facing the steel industry on its path to deep decarbonisation and proposals for technological change. The empirical part consists of a diagnostic analysis of the steel industry in Poland and decarbonisation scenarios. The diagnosis was based on industry data (reports of the Polish Steel Association, studies of reporting, and market institutions). The analysis performed gave an accurate picture of the situation of the Polish steel industry and was the basis for the discussion of plans for the transformation of the industry. A group of experts (participants in the discussion) considered various options that the Polish steel industry can adopt and methods of their implementation in the process of transformation to net zero steelmaking.

2. Industrial Decarbonisation: Challenges

The manufacturing industry accounts for 20% of European emissions [9]. Manufacturing industries with high CO_2 emissions in Europe include iron and steel, cement, chemicals and petrochemicals, pulp and paper, fertilizer, glass, ceramics, oil refineries, and non-ferrous metals (mainly aluminium). Greenhouse gas emissions in the industrial sector include carbon dioxide (CO_2) from energy consumption, non-energy use of fossil fuels and non-fossil fuel sources, as well as non-CO_2 gases. Steel production is important for the development of economies. Access to steel and steel products is important to ensuring national security (The Critical Raw Materials Act, CRMA).

In 2022, steel producers faced a deepening energy crisis and economic slowdown. The market situation prompted steelmakers (steel companies) to impose restrictions on production volumes in many countries. In 2022, the world produced 1878.5 million tonnes of steel, including 136.7 million tonnes in the EU (27) [10]. Both world steel production and European steel production showed declines compared to the previous year (world production down 4%, EU27 steel production down 11%). The 2022 recession may also continue into 2023. Due to continued downside factors (war, energy prices, high inflation) and a worsened economic outlook for 2023, apparent steel consumption is also set to drop in 2023, albeit slightly less than previously estimated (−1.6% vs. −1.9%). This would represent the fourth annual recession in the last five years [11]. For decarbonisation to accelerate during the steel market recession, for steel mills to produce steel with low-CO_2 technologies, infrastructure, capital, and support from governing institutions are needed [12].

Internationally, policy options for industrial decarbonisation are largely centred around national targets that will help achieve global emissions reduction targets as outlined in the Paris Agreement. In the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), the 2 °C scenario has been adopted [13]. According to the scenario, limiting global warming to within 2 degrees Celsius above pre-industrial temperatures by the end of this century should be realized. In the scenario, the iron and steel industry is required to reduce CO_2 emissions by 50 Gt cumulatively through 2050, contributing the largest share (35%) of CO_2 emission reductions among all industrial sectors [14]. Currently, the iron and steel industry is responsible for ~8% of annual global CO_2 emissions [15]. In recent years, the CO_2 emissions from the production of 1 tonne of steel amounted to 1.88 t (WorldSteel, average emissions for the period 2019–2021) [16]. CO_2 emissions are the result of BF + BOF coke consumption, as well as energy consumption, which is mainly derived from coal. The steel industry is highly energy-intensive (belonging to the energy-intensive industries). Examples of high energy consumption per produced product (e.g., GJ/t): aluminium (primary: 70 GJ/t; secondary: 10 GJ/t), steel (20–30 GJ/t), cement (3 GJ/t), and glass (4–17 GJ/t) [17]. Currently, the EU's steel industry consumes about 75 TWh of electricity annually, some of which is purchased from the external grid [18]. To produce 1 tonne of steel globally, 20.70 GJ was needed (data for 2019–2021, source WorldSteel) [16].

Internationally, the Climate-Aligned Finance Collective has begun working to build common standards of practice for decarbonising the steel industry and to help carbon-intensive industries achieve decarbonisation goals and monitor progress [19]. The COP26 Glasgow Breakthrough Agenda similarly sets goals targeting clean technology solutions in four different emitting sectors, including steel (COP26, 2021) [20]. The Agenda seeks to promote a steel industry aligned to net zero that leverages existing targets and initiatives but places the steel industry within the broader global fight against climate change and high-emission industrial practices [20]. According to the 26th UN Climate Change Conference of the Parties (COP26), there are many opportunities for industry to exploit post-COVID support, regional "leveling up" [21], and global changes towards more sustainable business practices [22,23]. According to global and European policy, climate innovation is needed in industries [24]. In the period from 2019 to 2021, the world steel industry increased investments in new processes and products by 6.67% [25].

Investments in low-carbon steelmaking technologies can be expected to increase in the coming years, especially in EU countries, where decarbonisation of the steel industry is included in the "Fit for 55". The document announced by the European Commission in 2021, the "Fit for 55" package, which aims to reduce EU emissions by at least 55% by 2030, was in the process of becoming law in 2022, enabling accelerated decarbonisation in the industry by phasing out free emission allowances (in the EU ETS) and introducing the Carbon Border Adjustment Mechanism (CBAM) [26]. In the existing ETS, higher targets are planned in the area of reducing greenhouse gas emissions (including CO_2) by 2030 from the previous −43% compared to 2005 emissions to −62%. The target will be achieved through a faster reduction in free emission allowances for sectors covered by the EU ETS. The allocation reduction rate will increase from the previously planned 2.2% per year to 4.3% per year (in 2024–2027) and 4.4% per year (in 2028–2030). For sectors subject to CBAM (including iron and steel, cement, aluminium, fertilizer, energy, and hydrogen production), it was agreed to abolish free allowances between 2026 and 2034. During this time, CBAM will apply only to the portion of emissions that do not benefit from free allowances under the EU ETS. Eurofer estimated that to maintain production at the level of recent years, the theoretical need to purchase allowances would result in costs of €2.6 billion per year in the first 5-year period, and as much as €9.6 billion in the following period (assuming a fixed allowance price of €60/tonne in the first period and €97/tonne in the second period). With the planned faster withdrawal of allowances, due to CBAM, the costs will rise to as much as EUR 14 billion (the estimate did not take into account technological changes in the sector and the variable level of CO_2 allowance prices in the future) [27].

Transformation 2050 will be radical and revolutionary [28]. In the low-carbon economy, the EU industry needs long-term economic competitiveness and sustainability. The direction set by the EU from low carbon to net zero will transform economies, and the first key changes should be visible in just five years [29]. In the transformation to net zero, radical innovations will include energy-intensive industries and an energy sector that will deliver more and more green energy [30]. Radical innovations in energy-intensive industries could include the development and deployment of new low-carbon technologies, such as carbon capture, utilization, and storage (CCUS), hydrogen production using renewable energy sources, and the use of alternative fuels, such as biomass or waste-to-energy. In addition to technological innovation, energy-intensive industries will also need to undergo significant changes in their operations, business models, and supply chains to reduce their carbon footprint. This could involve adopting circular economy principles to reduce waste and increase resource efficiency, electrifying industrial processes, and transitioning to renewable energy sources, such as solar, wind, and geothermal.

In the case of energy-intensive industries, which include the steel industry (20.70 GJ/tonne crude steel cast) [25], decarbonisation means changing technology and replacing current BF + BOF plants with direct iron reduction (DRI) plants combined with electric arc furnaces (EAF), or DRI-EAF for short. In DRI technology, the iron ore reductant is natural gas or hydrogen. The iron thus obtained can then be fed into electric arc furnaces (EAFs). The existing technology of so-called blast furnaces (BF) and converters (BOF) will be phased out in EU countries. In 2021, the 27 EU countries produced 153 million tonnes of crude steel, including both oxygen (BF + BOF) 56% and electric (EAF) 44% steel [31]. BF + BOF technology is very popular in EU countries. Of the 27 countries, BF + BOF technology is not present in six countries: Bulgaria, Croatia, Greece, Luxembourg, Portugal, and Slovenia [31]. Decarbonisation means a revolution in steelmaking technologies for many EU countries.

The challenge for decarbonising the steel industry is also in ensuring that steel mills have access to green hydrogen, which is hydrogen produced via electrolysis using renewable electricity. The least carbon-intensive technologies will benefit from green hydrogen. Innovative steel mills must have access to green energy. Large steel mills have plants that use waste gases to generate electricity, but larger investments tend to be very forward-looking plans. Building one's renewables is also an option, but for that, large amounts lot of land are required in addition to capital. An opportunity for the development of metallurgy is the development of the renewable energy sector and modular reactors [32].

Since there are currently no technologies for producing green hydrogen on an industrial scale, steel mills are emphasizing improving energy and material efficiency [33–37] as well as increasing the production of electric steel using scrap steel (material efficiency is very high at about 94%) [25].

Already among the new investments are technologies for producing steel with hot-briquetted iron (HBI). The world steel industry has also seen the emergence, for the first time in 2000, of DRI steelmaking using natural gas. Currently, globally, the share of DRI technology in world steel production does not exceed 10% [38]. In 2022, global DRI production reached 120 million tonnes (preliminary data) [38], an increase of about 5% compared to the previous year and an increase of 65% compared to 2000, when the production of steel obtained by DRI technology was first reported in WorldSteel reports. In 2022, the largest producers of steel using this technology were India (42 million tonnes), Iran (33 million tonnes), and Russia (8 million tonnes). The largest increases in DRI production occurred in countries such as Qatar (+106% compared to the previous year), Libya (+22%), and Egypt (+13%) [38]. DRI technology can have an impact on achieving the energy balance of the electric arc furnace (EAF) in the steel industry [39]. The DRI-related challenge is aimed at the traditional steel industry (an integrated method that requires BF + BOF iron ore reduction). Iron ore electrolysis can emit up to 87% less CO_2 than the current integrated method (with full decarbonisation of the electricity supply). Hydrogen plasma reduction aims to achieve zero CO_2 emissions. Steelmaking using hydrogen could emit up to 95 percent less CO_2 than the current integrated method (using electricity generated completely carbon-free), but due to energy losses during hydrogen production, this would ultimately increase energy consumption in the sector [40]. Traditional steel mills have already introduced several new technological approaches currently focused on replacing blast furnaces with arc furnaces, into which iron produced using green hydrogen is fed from direct reduction. Steel production in arc furnaces accounts for only 14% of the greenhouse gas emissions produced by the integrated method, and the main associated challenge is replacing natural gas in blast furnaces with green hydrogen or induction electricity [40].

Other alternatives already being explored are based on CO_2 storage technologies (CCS) or the use (CCU) of emitted carbon dioxide to reduce the carbon footprint. 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) [40]. CCS(U) technologies are being tested at the Steelanol demonstration plant (currently under construction—TRL 9) uses waste gases to produce bioethanol, and the Carbon2Chem project (TRL 7–8) aims to use waste gases as a feedstock for chemicals [40]. Explanation: TRL (technology readiness levels) are various points on a scale used to measure the progress or maturity level of a technology (levels modelled after NASA technologies) [41].

However, many of the new investments in decarbonising the steel industry can only be realized once the appropriate infrastructure is in place, such as transferring the product to the chemical industry, where it will be used. In addition to access to adequate hydrogen infrastructure, steel companies must have future access to large amounts of affordable low-carbon energy (e.g., nuclear) provided by national governments. According to Eurofer's estimates, the industry will need about 400 TWh of renewable electricity annually, of which 250 TWh will be used to produce 5.5 million tonnes of hydrogen by 2050 at the latest [40]. Without cooperation between government and industry, it will be difficult to realize new investments, including direct iron reduction (DRI) combined with electric furnace technology and CCS (U) investments. At the beginning of the road, the share of CCS may be small, but it must grow over time. CCS growth will be accompanied by the development of infrastructure, which the steel industry will need more and more as CO_2 capture (storage) increases [3,5–7]. Transformation of the steel industry towards low-carbon and in the future also towards net zero will be realized without CCS or with CCS. Adoption of carbon capture and storage (CCS): end-of-pipe technology that captures and stores CO_2 from steelmaking operations contributes to emissions efficiency. CCS can be installed through modifications to existing plants or in combination with innovative process technologies but comes with several constraints and challenges [24,42–48].

3. Materials and Methods

The aim of the research is identification of the transformation scenarios of the Polish steel industry. The methodological framework employed for this inquiry is presented in Figure 1.

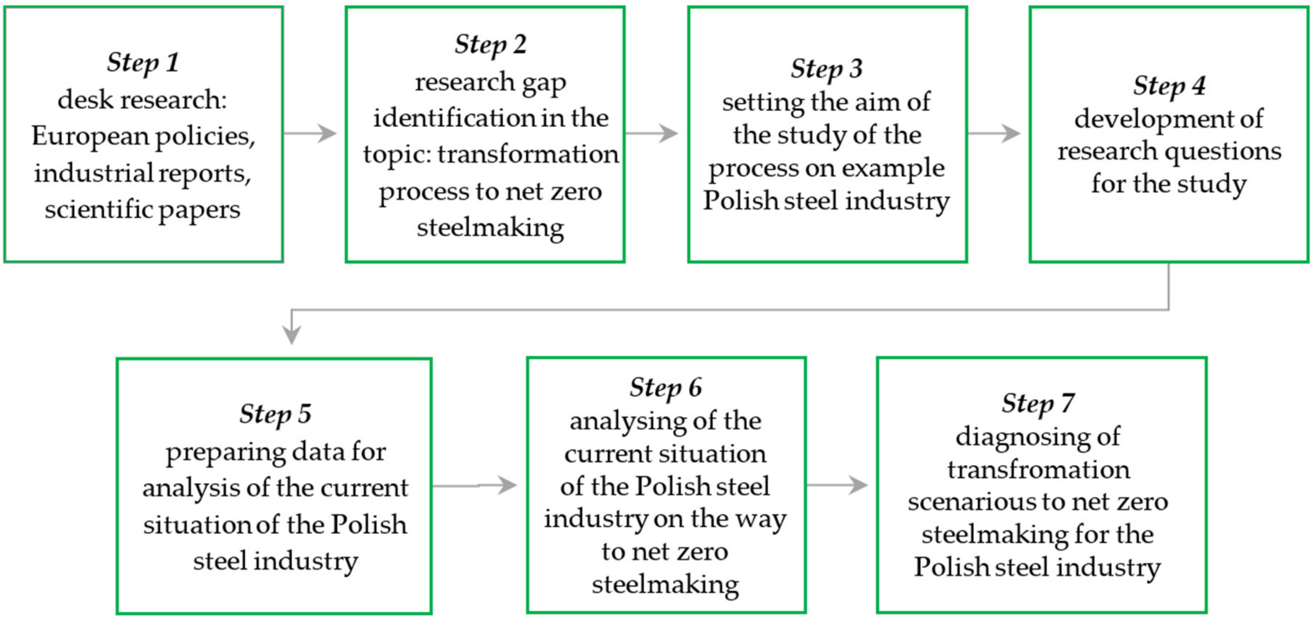

Figure 1. Methodological approach of the study.

Several research questions (RQs) were formulated:

- RQ1: What are the directions (strategies) of technological transformation of the steel industry to net zero steelmaking?
- RQ2: What are the conditions (state diagnosis) for decarbonisation of the Polish steel industry?
- RQ3: What are the possible scenarios for the development of low-carbon steelmaking technologies in the Polish steel market?

To obtain answers to these research questions, the authors performed literature research (assumptions of the European steel industry decarbonisation policy, determinants of steel industry development, and steel industry technological transformation strategies) and gathered expert opinions about the transformation process of the Polish steel industry to net zero steelmaking. Expert opinions were used to develop scenarios for the transformation of the Polish steel industry. The work was concluded with a scientific discussion that addressed the literature and research part of the work.

In conclusion, the authors state that the process of deep transformation of the technology industry to net zero steelmaking will radically change the technologies of steel production in Poland. Steel mills with BF + BOF technologies will introduce DRI + EAF technologies. Plants with arc furnaces (EAF) plan to develop technologies (higher capacity furnaces). Whether steelmakers will also develop CCS(U) technologies depends on infrastructure development and cooperation with industries that will process CO_2 (e.g., the chemical industry). The future source of hydrogen (used in technological processes) will be green hydrogen (a rather distant scenario for the Polish steel industry).

The theoretical part of the paper uses a systematic SLR literature review. The methodology of the literature review is based on the analysis of the topic on decarbonisation of industry, which was considered the main (leading) topic. From this topic, the topic of decarbonisation of the steel industry was further separated in the analysis. The authors reviewed traditional databases (WoS, Scopus), as well as governmental (European) and industry (steel industry) websites, which included documents on decarbonisation of the European steel industry within specific policies. On the websites, statistical steel industry organisations (WorldSteel, Eurofer, Polish Steel Association and others) provided data, which were organised by the authors and presented in the analytical part of the paper. In addition, the authors used the websites of a reporting institution in Poland (Polish Statistics) as well as stock exchange websites (energy prices, gas prices).

The empirical part of the study (expert interviews) was based on the opinions of steel industry experts (the selection of experts was purposeful). The experts were the management of steel companies as well as representatives of industry associations (Chamber of Steel) in Poland. The executives of steel companies represented mills with blast furnaces—i.e., BOF technology—which, in the planned deep decarbonisation, will be changed over DRI + EAF. These steel mills in Poland account for more than 70% of the Polish steel market (market share), and their annual production represents more than 50% of total production. Experts were interviewed on the following topic: the decarbonisation path of the Polish steel industry to net zero and the problems of the Polish steel industry. The interview was freeform (a quantitative limitation was applied). Each expert was asked to express their opinion in a few sentences (approximately 250 words). The experts provided written answers, which were their official positions. Hence, many of them were published on the metallurgical forum.

The methodology and synthesis of the expert survey are presented in Figure 2. The experts' opinions on how to decarbonise the steel industry are in line with existing pathways from energy system modelling in published work on steel decarbonisation. The Polish steel industry, which produces pig iron using BOF technology, is preparing to introduce DRI + EAF technology. In the transition process, steel mills expect financial and commercial support from government institutions (at the national and European steel market level). In addition, a new external energy supply infrastructure is needed. The triad of steel mills, policy, and energy is the key to success as long as there are strong interactions between these elements of the triad.

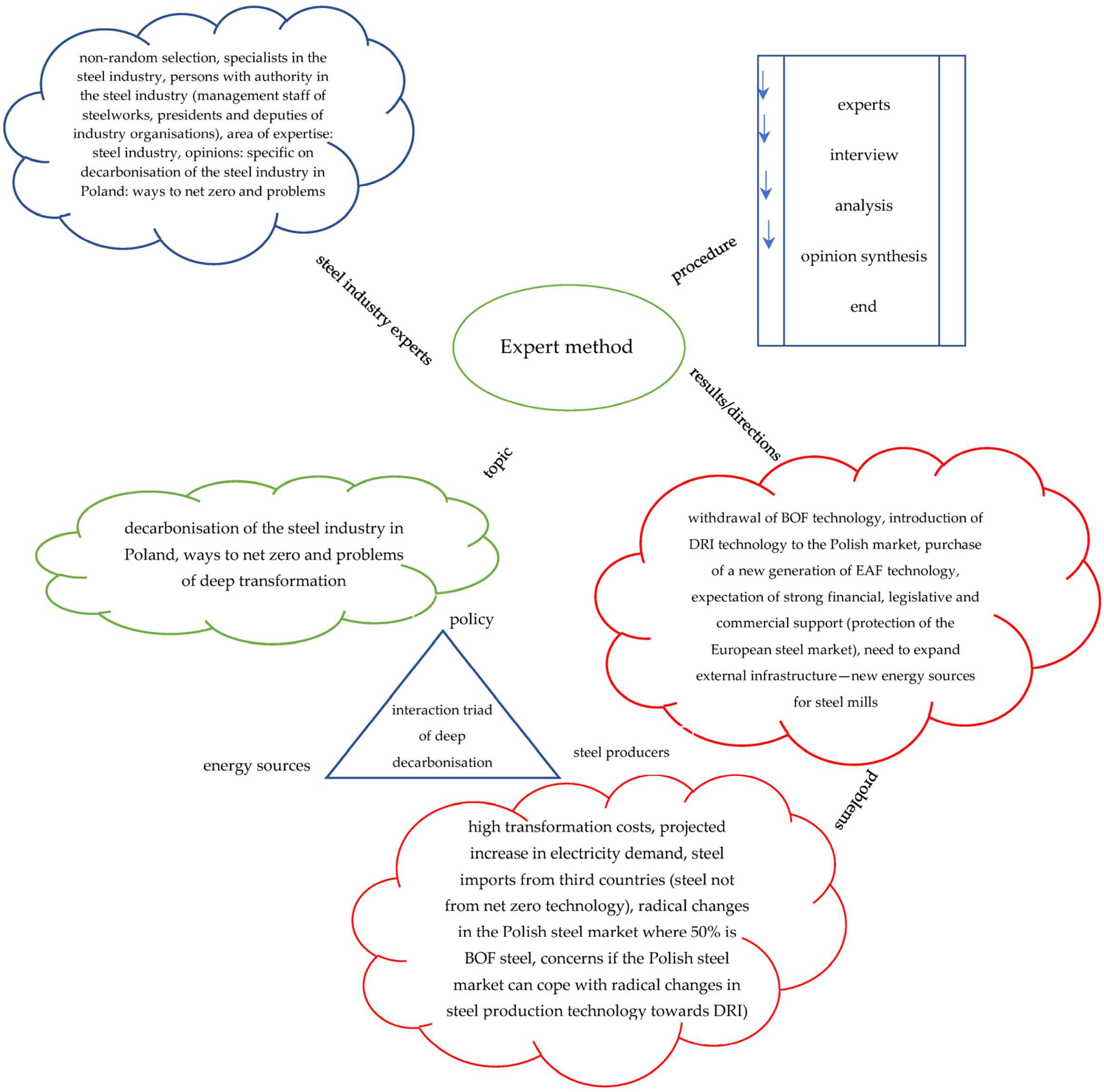

Figure 2. Mind map of expert method. Source: author's own work.

4. Strategic Directions of Changes in Steel Industry Technology

BOF and EAF technologies dominate global steel production [31]. These two key technologies were identified in the Axelson et al. (2021) model [49] as core for the steel business in the process transformation to net zero. In the process of decarbonising the steel industry, these key technologies will change in either an evolutionary or revolutionary manner. According to Wyns and Axelson (2016) [30], the steel plants with BOF technology can adopt benchmark low-carbon steelmaking technologies existing today without significant technological innovation. For example, they can improve energy efficiency and switch to more sustainable feedstock and fuel. This contributes to emission efficiency but has limited emission reduction potential. However, such a direction of change is not sufficient in deep decarbonisation. Steel mills with BF + BOF technologies must therefore plan for radical investments in DRI-EAF technologies. For steel plants with EAF technologies, the scenario is to save energy, eliminate black energy, and use green energy [50]. Steel mills that produce steel using EAF technologies are building new arc furnaces, which in time will become a component of DRI-EAF technologies. Steel mills that rely on BF and BOF, on the other hand, must make more radical changes. BF technology will be phased out, and coke will not be the main reductant in the raw iron production process. The revolutionary direction for steel mills is the use of hydrogen in steel production, with the prospect of green hydrogen. Radical changes in steelmaking technologies will take place with CCS technologies (with CCS and industrial symbiosis meaning resource and energy efficiency through exchanges of, for example, by-products, off gases, or waste heat) [49].

Several technologies are being developed to decarbonise the iron and steel industry. Two of the most promising deep decarbonisation options are [51]: (1) modification of existing blast furnace–basic oxygen furnaces (BF + BOF) to use pulverized coal and iron ore (known as HIsarna technology (Tata Steel, 2020)) [52] while installing carbon capture and storage (CCUS) technology to capture CO_2 in aquifers or inactive oil and gas reservoirs; (2) hydrogen direct iron reduction (H2-DRI) using green hydrogen produced via water electrolysis along with electric arc furnaces (EAF) [51]. Based on these two key strategies (directions of change in steel industry technologies), further sub-strategies (sub-directions) are being developed and are the subject of scientific research. Table 1 shows the possible directions of change according to the base technologies of the steel sector currently in use, BF and EAF.

In Table 1, there is a comparison of two technologies used in steel industry in the green (low-carbon) transformation: BF (blast furnace) + BOF approach and EAF (electric arc furnace) approach.

Table 1. Technologies of steel industry in the green (low-carbon) transformation with estimation of TRL.

BF Blast Furnace + BOF	EAF Electric Arc Furnace
• The blast furnace (BF) is fed with iron ore, limestone, and coke to produce liquid iron. Steel production is realised in the BOF process, but BOF partially reuses BF gas as fuel. Much of the gas is sent to other processes. A feature of this technology evolution is biochars, which can partially replace metallurgical coke. Biochars are expected to reduce the use of metallurgical coke by up to 10%, resulting in less CO_2 going into the air (1.5–2.2 t CO_2/t steel) (TRL 9) [53–55].	• In this process, the heat of electric arcs is used (steel is produced from steel scrap). Energy comes from chemical sources (fossil fuels: natural and coal). Fossil fuels account for the dominant share of total energy. • In the future, the fossil fuels could potentially be replaced by biofuels (TRL 9) ([53] based on: [56,57]). Scenario: black energy will be replaced by green energy. Furnaces (EAF) must be new generation.
• Top-gas-recycling blast furnace without CCS(U) or with CCS(U): carbon capture, utilisation, and storage). BF gas is processed and recycled. Carbon monoxide and hydrogen (H2) work as reducing agents ([53] based on [58,59]). • There are two scenarios here: 1. Top-gas-recycling blast furnace with CCS(U) 2. Top-gas-recycling blast furnace without CCS(U). Examples of technology without CCUS: ULCOS-BF [58], IGAR [59] (TRL7) [59]. This technology without CCUS predicts 25% less CO_2, and with CCS(U), it predicts up to 60% less CO_2 [53]. • According to the program, Tata Steel (ULCOS-BF) modification of the conventional blast furnace reduces emission CO_2 per 1 tonne of steel by 50% [58].	• Direct reduction in EAF process. The reducing agent is natural gas. Iron is not melted but is solid. Solid iron is called sponge iron. The sponge iron is a steelmaking product. Example technologies: Midrex [60], HYL III (third generation, "Energiron") [61]. When these technologies are introduced on a large scale, CO_2 reductions of 40 to 60% can be achieved (TRL 9) ([53] based on [62–64]). Products from direct reduced iron (DRI) are high in iron content and low in copper and other undesirable metal—tramp elements–and nitrogen contents. They are used to make a broad range of steel products. Their physical and chemical characteristics make it desirable for use in the electric arc furnace (EAF), blast furnace (BF), and basic oxygen furnace (BOF) [60]. In Midrex technology, plants can be designed to switch from one DRI form to another with no disruption of product flow—cold DRI (CDRI) to hot-briquetted iron (HBI), CDRI to hot DRI (HDRI), or HDRI to HBI. Products can be produced simultaneously in any combination [60].
• Smelting reduction (without CCUS or with CCUS). Ores are partially reduced in the pre-reduction unit by using the waste gas from the smelting unit. Final reduction and smelting take place in the smelting unit. Steel (raw iron) is produced in the BOF. BOF technology allows the full use of biomass substitutes. Example of technology: HIsarna (Tata Steel) [65]. HIsarna technology is currently being tested without CCS(U). The use of this technology can reduce CO_2 emissions by 35%. However, if CCUS were introduced in addition, CO_2 emissions would fall to 80% (TRL 9). ([53] based on [66,67]). The HIsarna test installation was built on the Tata Steel site in Ijmuiden in 2010. The program consisted of the next period:2010–2014, 2016–2018, 2018–2019 and the actual program is on the period 2020 and further [65]. One test plant is already in operation in India. Another, the second, is being implemented. The technology is not yet commercial.	• Hydrogen direct reduction in EAF process. Instead of natural gas, hydrogen H2 is used in this process (The reducing agent is H2) [53,68–70]. The product for steel production is sponge iron, which is melted and processed [53]. Example technologies (projects): HYBRYT (the Salzgitter AG Group is the initiator of the project, Sweden) [71], GrINHy (the Salzgitter AG Group is the initiator of the project, Sweden) [72,73], H2Future [74], SuSteel (Sustainable Steelmaking) [75], SALCOS [76] (TRL 5–7). In these technologies (projects), hydrogen replaces coke, coal, or natural gas. Hydrogen is an ore-reducing agent. Plasma is used to simultaneously reduce iron ore and melt it into raw steel in a special direct current electric arc furnace [68]. The advantage of using green electricity and hydrogen as a reducing agent is that it almost completely avoids carbon dioxide emissions (95% reduction) [77].

Source: own elaboration based on [53].

Strategies of evolutionary or radical technological innovation (deep decarbonisation) will be pursued in parallel with sub-innovation, the essence of which is to reduce material and energy consumption by increasing material efficiency through structural modifications that—for example—increase product life or enable reuse or the production of high-strength, lightweight steel [33–35,78]. During a "green" transformation, a key block of change and the life cycle of steel enables recycling through end-of-life disassembly and streamlined scrap handling [79–81]. The overriding value of the transformation to net zero is still sustainability. Although sustainability emerged in business as early as the end of the last century, it is still relevant today. New industrial technologies must be strongly linked to sustainable business goals [82]. Innovations in the decarbonisation process of the steel industry increase sustainable product value [83,84]. The value is captured very broadly because it represents products and services for existing markets as well as new markets that will emerge as economies transform to net zero [69]. The market in decarbonisation is challenged by the lack of demand for low-carbon goods today and the resulting need for market creation and diffusion of low-carbon products [85]. Steel mills also take into account the opportunities of Fourth Industrial Revolution technologies in planning investments described as green [86–88]. Steel mills are moving from automation of the production process through electronic information technology to physical and virtual digital technologies to realize the digitization of entire production processes [86–88]. In terms of decarbonisation, modern technologies must contribute to reducing CO_2 emissions.

The determinants of innovative change are the energy and resource conservation policies pursued. For many years now, steel mills have been obliged to use BAT technology, which has systematically reduced the negative environmental impact of steel mills.

5. Decarbonisation Processes in the Polish Steel Industry

5.1. Diagnosis of the Situation of the Polish Steel Sector

In 2021, the Polish steel industry was among the top five European steel producers in the EU, after the German, Italian, French, and Spanish industries. In the global steel market in 2021, the Polish steel industry was ranked 22nd [31]. In 2021, Poland's steel production was 8.5 million tonnes [31]. Steel mills in Poland are needed, as the economy consumes about 13–15 million tonnes of steel products annually and has a crude steel production of 9 million tonnes. In 2022, due to the energy and economic crisis (including the effects of the war in Ukraine), Poland's steel production will fall to 7.5 million tonnes (down 11% from the previous year) [89]. Figure 3 shows steel production and consumption in Poland. Beginning in 2014, there was a significant increase in the consumption of steel products in Poland compared to production. This means that the Polish economy is growing and needs steel. The growing consumption of steel products in Poland is an opportunity for technological innovation of the Polish steel industry on its path to net zero CO_2 emissions. Steel producers in Poland are important for the economy because they produce 3% of the value of industrial output. Income from steel production accounts for 0.3% of the total GDP. In broad terms ("economic footprint"), steel mills in the supply chain produce about 2% of the GDP [90].

Steel producers in Poland use two technologies: BF + BOF and EAF. In the period from 2000–2021, the average shares of steelmaking technologies in total steel production were as follows: EAF 43%, BOF 57%. In 2021, the proportion of the share of these technologies has changed: oxygen 48.1%, electric 51.9% [31]. Figure 4 shows Poland's steel production by technology. The change in the proportion was due to the exclusion of part of the capacity of steel mills with BF + BOF technologies. The structure of steel production by technology seems to be unfavourable for building transformation scenarios for the decarbonisation of the Polish sector. Steel mills with BF + BOF technologies have to invest in new technologies (DRI + EAF), and these investments are highly capital-intensive.

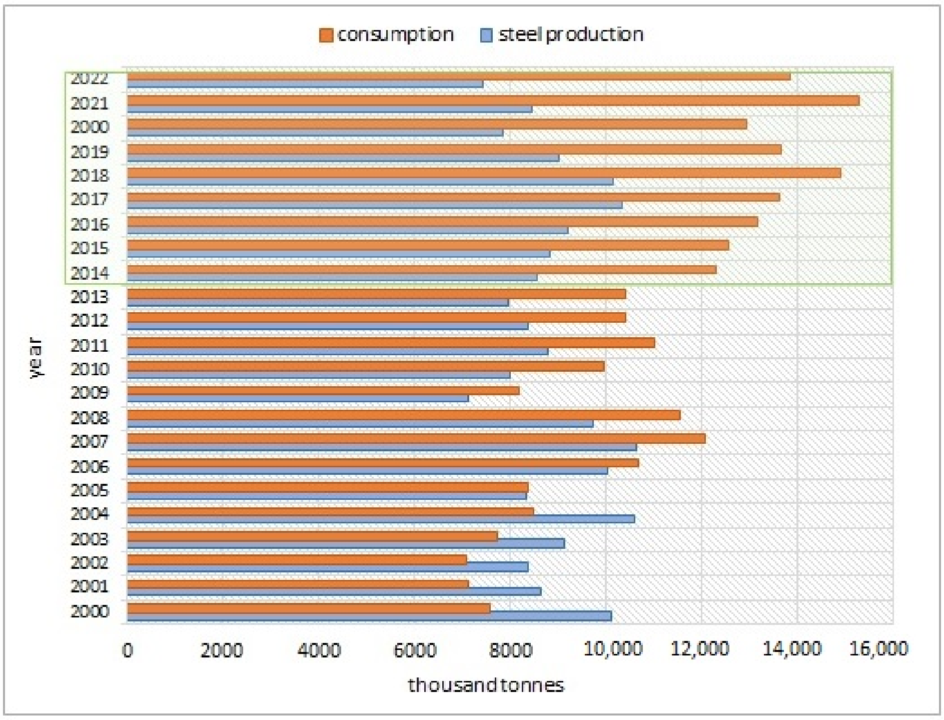

Figure 3. Steel production and consumption in Poland in the period from 2000–2021. Source: own study based on data of the Polish Steel Association in Poland [91].

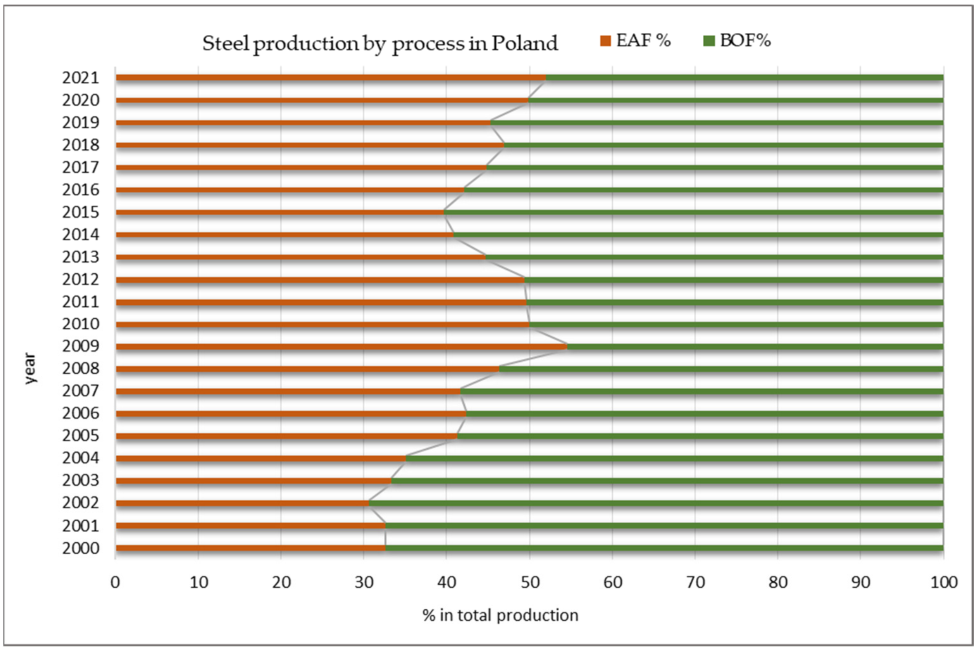

Figure 4. Steel production by technological process in Poland in the period 2000–2021. Source: own study based on data [91].

The steel industry in Poland, along with other industries (cement, metal, chemical) emits the most CO_2 compared to other industries. In terms of CO_2 emissions, by far more is emitted by BF + BOF technologies than EAF technologies. Together, the two technologies that the Polish steel industry uses emit 7.07 million tonnes of CO_2 annually. It can be assumed that for every 1 tonne of steel produced in Poland, there is about 1 tonne of CO_2 emissions.

Having at our disposal (verified) CO_2 emissions data for the period from 2010 to 2021, CO_2 emissions from steel mill production facilities in Poland are presented (Figure 4). In recent years (since 2018), there has been a decrease in CO_2 emissions from steelmaking production installations in Poland (a level below the average annual emission of 7.07 million tonnes). The lowest CO_2 emissions were recorded in 2020, at which time the smelter production installations produced 5.00 million tonnes of CO_2, and the highest emissions of 8.45 million tonnes were recorded in 2014 (Figure 5) [92].

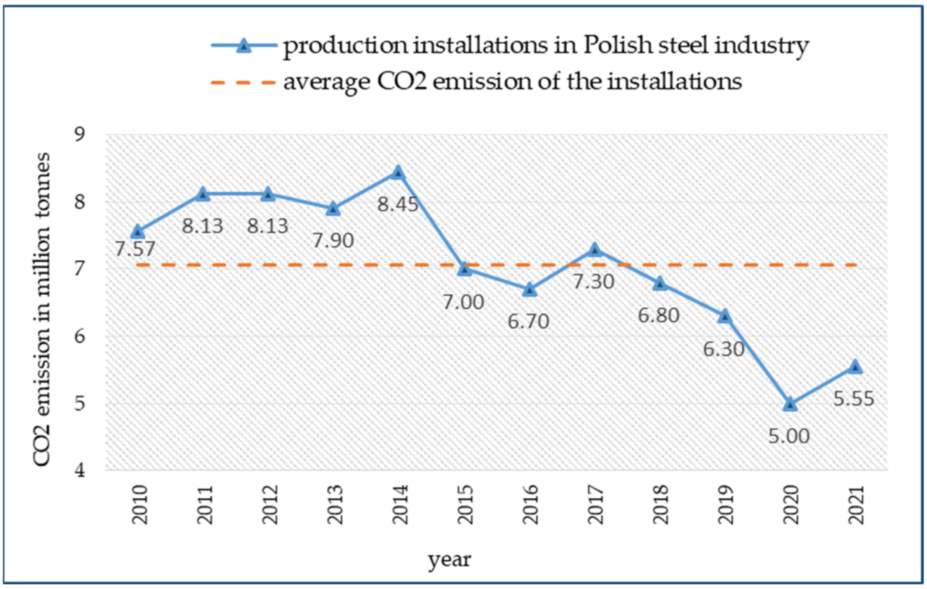

Figure 5. CO_2 emissions from production installations in the steel industry in Poland in the period from 2010–2021. Source: own study based on data from Kobize [92].

In addition to production facilities, energy facilities at steel mills in Poland have high levels of CO_2 emissions (Figure 5). This category of analysis includes steel mill power plants, steel mill heating plants, steel mill boiler plants, etc.). The average volume of CO_2 emissions in 2015–2021 was 4.97 million tonnes. In the latest 2020–2021 period, annual CO_2 emissions from these power generation facilities in the Polish steel industry totalled 4.00 million tonnes. CO_2 emissions of less than 5 million tonnes from power generation facilities were recorded for the first time in 2019 (Figure 6). Comparing CO_2 emissions from these installations with CO_2 emissions from steel mills' production installations (BF + BOF and EAF), it was found that CO_2 emissions from captive power generation in steel mills were about 2 million tonnes lower in technological production installations. The lowest CO_2 emissions were recorded in the Polish steel industry during the use of coking facilities (Figure 6). In recent years (Figure 6), annual CO_2 emissions from coking installations have ranged from 0.50 million tonnes to 0.60 million tonnes. All three installations analysed have seen a decrease in CO_2 emissions in recent years (Figure 6) due to a decline in steel production (Figure 3). Coke is consumed using BF + BOF technology in Polish steel mills. On average, over 2,250,000 tonnes were consumed annually between 2000 and 2021 (Figure 7). There is a coke plant in Poland which is counted among the largest coke producers in the EU. The coke plant is part of a capital group that includes smelters with BF + BOF technologies.

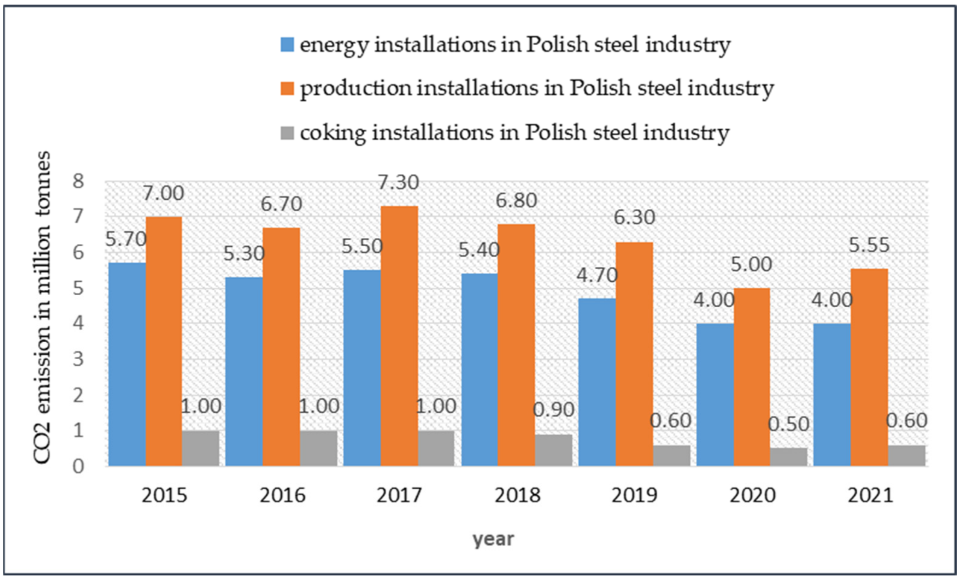

Figure 6. CO_2 emissions from steel industry installations in Poland from 2015–2021. Source: own study based on Kobize [92].

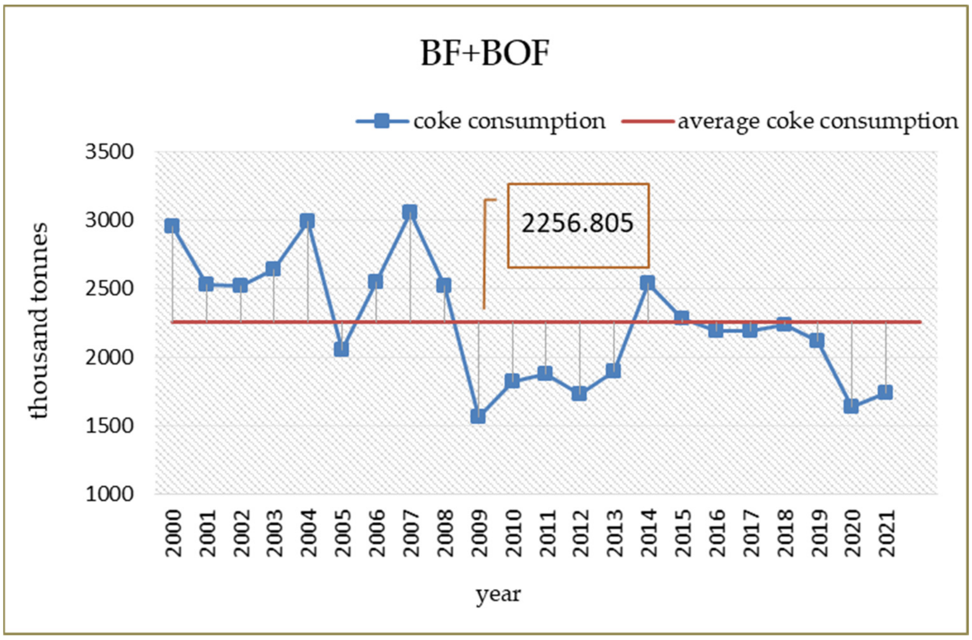

Figure 7. Coke production in Poland in the period from 2000–2021. Source: own study based on data of the Polish Steel Association in Poland [91].

The steel sector in Poland must diversify its energy sources and invest in technologies powered by renewable energy. In Poland, about 50 percent of electricity is generated from hard coal, and just over 20 percent is generated from lignite (together the two energy sources account for more than 70 percent of Poland's electricity generation) [93,94] (Figure 8).

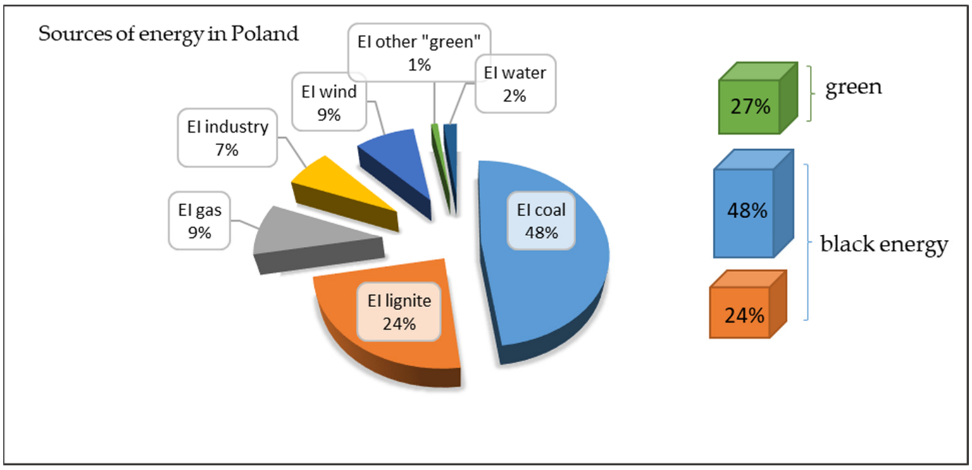

Figure 8. Sources of energy in Poland. EI—energy intensity. Source: own study based on PSE [93].

In the electric process (EAF), unit energy consumption is 3.5 times higher than in the BF + BOF integrated process (blast furnace and converter steel plant), in which the main energy products are coke and process gases [95]. In recent years, the total energy intensity of the steel sector, calculated as tonnes of oil equivalent, has been below 0.200 toe/t. (Figure 9). This is about 0.100 toe lower than the energy intensity of the entire European steel industry (27 countries) [95].

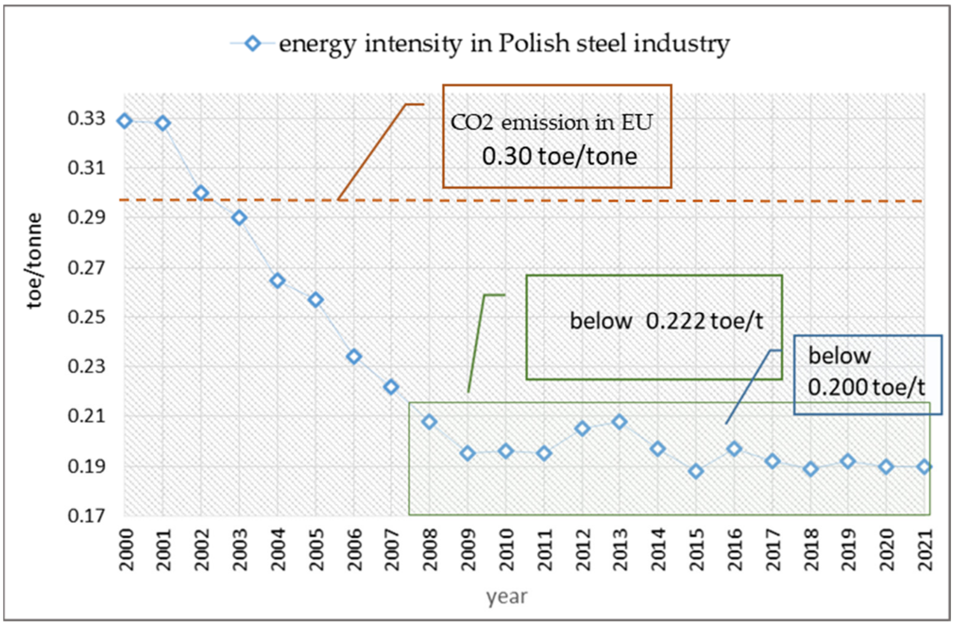

Figure 9. Energy intensity in steel production in Poland in the period from 2000–2021. Source: own elaboration based on data from the Statistics Office in Poland (in Polish: GUS) [96].

The high share, almost 50%, of EAF technology in total steel production, at the current stage of low diversification of energy sources (Figure 9) is unfavourable for the Polish steel industry. Steel production in mills with EAF technologies is more energy-intensive than BF + BOF technology (as of 2009, the ratio of energy intensity of EAF to energy intensity of BF + BOF in Poland was 3.5:1.) (Figure 10).

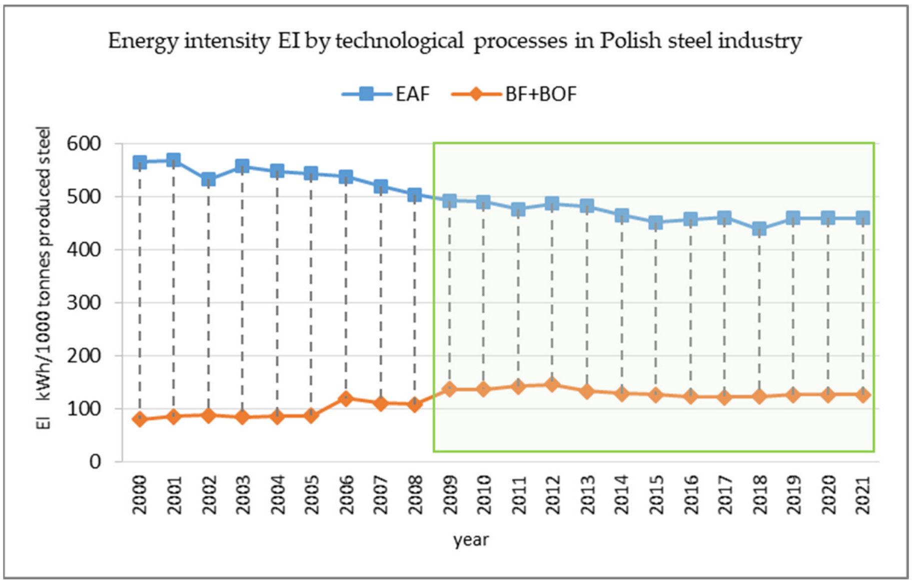

Figure 10. Energy intensity in steel production by technologies in Poland in the period from 2000–2021. Source: own study based on the data of the Polish Steel Association [95].

The decrease in energy intensity of EAF technology in Poland was influenced by investments. According to Model (1) of the authors of the publication [34], a PLN 1 million increase in capital expenditures in enterprises producing steel in electric furnaces will lead to a decrease in specific electricity consumption by 16.5 MWh/1 tonne of crude steel with other factors unchanged.

$$M_1 : \; Y_{jEE\_EAF} = -0.0165x_1 + 549.9 \quad (1)$$

Despite a huge reduction in specific energy consumption (down 0.140 toe/tonne) (Figure 10) and lower CO_2 emissions than the European average (Figure 9), Poland's metallurgy has the highest rate of energy share in sold production among industrial sectors (1.36 kgoe/€ in 2018), i.e., more than eight times higher than the industry average and almost twice as high as the second-ranked chemical industry (Figure 11). This confirms that steel production, in domestic technologically modernized and modern plants, is a very energy-intensive process.

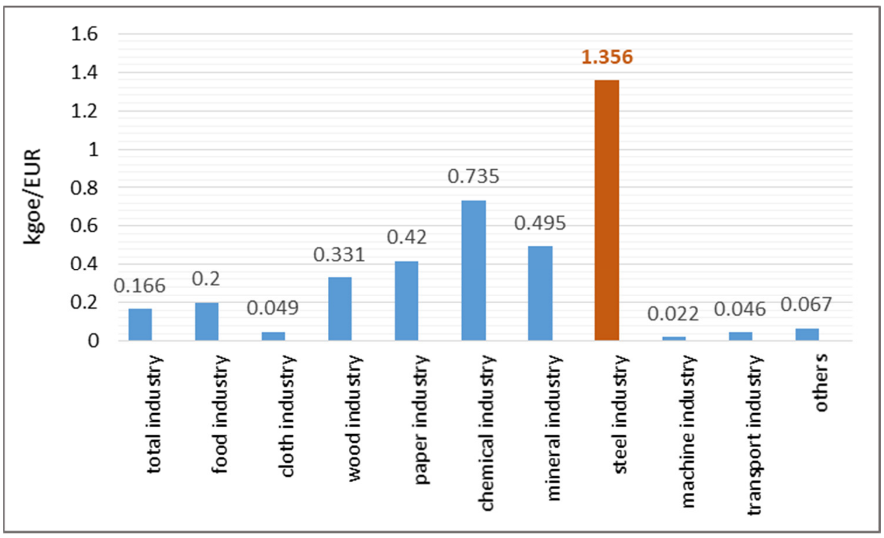

Figure 11. Share of electricity in sold production of industrial sectors in Poland in 2018. Source: own elaboration based on [97].

The energy efficiency of the Polish steel industry is particularly important for new investments in steel mills. When energy prices are rising in the energy market (Figure 12), investments can freeze. The pandemic and energy crisis froze large investments, with the largest steel company shutting down some of its production capacity. In line with the decarbonisation policy, steel in Poland will additionally need to diversify its energy sources. This is because Poland faces huge steel-intensive investments in offshore, wind, and other energy developments. In the last year, the energy prices in Poland grew faster than in previous years (Figure 12). In Tables 2 and 3, resources prices of key resources are presented.

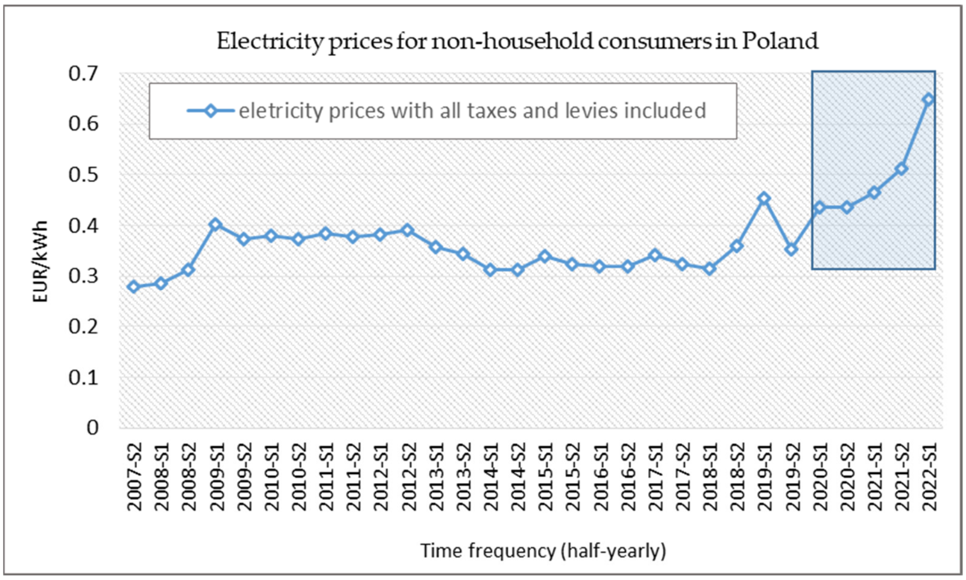

Figure 12. Electricity prices in Poland form industrial users in the period from 2007–2022. Source: [98] electricity prices for non-household consumers—bi-annual data (from 2007 onwards) [NRG_PC_205__custom_4992279] (24/01/2023 23:00).

Table 2. Changes in resource prices (in international comparison for steel industry).

Resources	Electricity/Energy	Natural Gas	Steel Scrap	Coke	Iron Ore
price in 2021	61.74 EUR/MWh	19.48 EUR/MWh	134.60 EUR/t	132.4 USD/t	101 USD/t
price in 2022	400.10 EUR/MWh	205.69 EUR/MWh	420.50 EUR/t	506.0 USD/t	162 USD/t

Source: Based on TGE data, EEX data, (Iron Ore Fe 63.5%, CIF China).

As Poland's steel production declined, steel imports into the country grew. Raw material flowed in from the east, including Asia. Domestic steel accounted for about 26% of the total raw material consumption in Poland—the rest was steel from abroad. Of the EU countries, most is imported from Germany, while foreign steel suppliers also include Russia, Ukraine, Belarus, South Korea, China, India, and Turkey.

In the decarbonisation of the steel industry, the emphasis is on developing EAF technology and phasing out BF + BOF technology. However, for the EAF steelmaking process, a steady supply of scrap must be ensured. The Polish steel industry consumes about 6000 tonnes of scrap metal annually (Figure 13). In the decarbonisation strategy of the steel industry, Polish steel mills need decarbonised scrap. A steady supply of decarbonised scrap must be included in the planned strategies and scenarios for the transformation of the Polish steel industry to net zero.

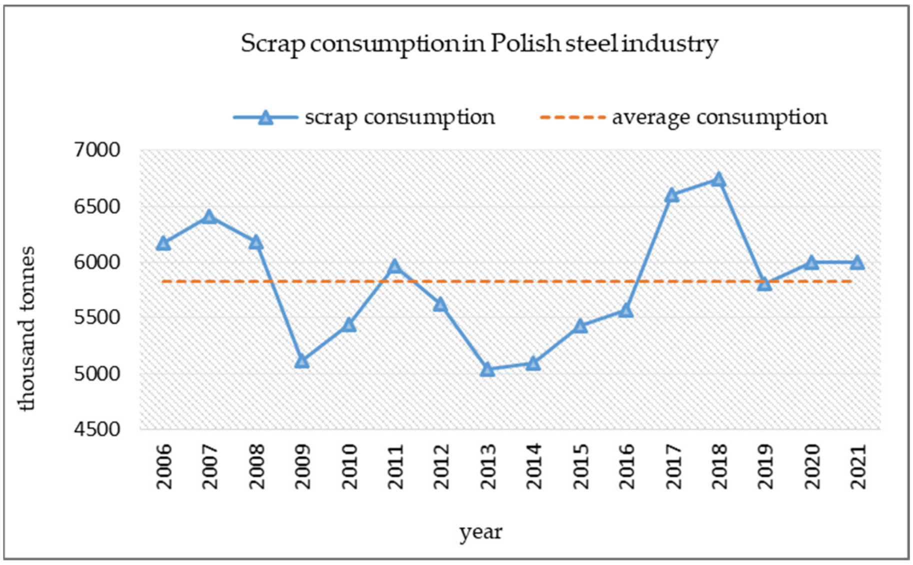

Figure 13. Scrap consumption in the Polish steel industry in the period from 2006–2021. Source: own study based on data from the Polish Steel Association [91].

The Polish steel industry, being part of the EU industry, has made many technological investments as well as embarked on planning new technological investments towards low-carbon technologies. Between 2000 and 2021, the domestic steel industry incurred expenditures of nearly PLN 16 billion related to reducing CO_2 emissions and environmental impacts, which also involved improving production efficiency and energy efficiency [99]. Two companies, Celsa Huta Ostrowiec and ArcelorMittal Poland, are participants in industry decarbonisation projects as of the end of 2022 [100]. Among the 60 announced projects in the EU, four are in Poland: three in Ostrowiec Swietokrzyski (smelter with EAF furnace production from the scrap) and one in Dabrowa Gornicza (smelter with blast furnace). The projects for these investments include energy efficiency and carbon direct avoidance (CDA) [100].

The problems of ecology and energy transition have been the subject of public debate in Poland for many years. Recently, leading think tanks have addressed the topic of identifying the optimal model for the decarbonisation of the Polish economy while estimating the costs and potential gains in both economic and social terms [101]. The decarbonisation process in the Polish steel industry was preceded by BAT investments. The increase in investments served to reduce the energy intensity of the steel sector. The Polish market of steel producers was formed after the restructuring and privatization of steel mills. Comparing capital expenditures by steelmaking technology, the period from 2004 to 2021 was analysed. The beginning of the analysis was taken as the establishment of the capital structure of steel mills in Poland (the largest Polish steel mills are owned by foreign capital) [102]. Figure 13 shows the investment expenditures of the Polish steel industry in 2004–2021 both in total and by technological process. Steel mills spent PLN 15.5 billion on investments in 2004–2011, of which steel mill owners spent PLN 8.3 billion on investments in BOF technologies and PLN 7.1 billion on EAF technologies. Over the past decade, the average annual investment expenditures in the Polish steel sector amounted to PLN 630 million, half of which went to BOF technology improvements and the other half to EAF technology improvements (Figure 14).

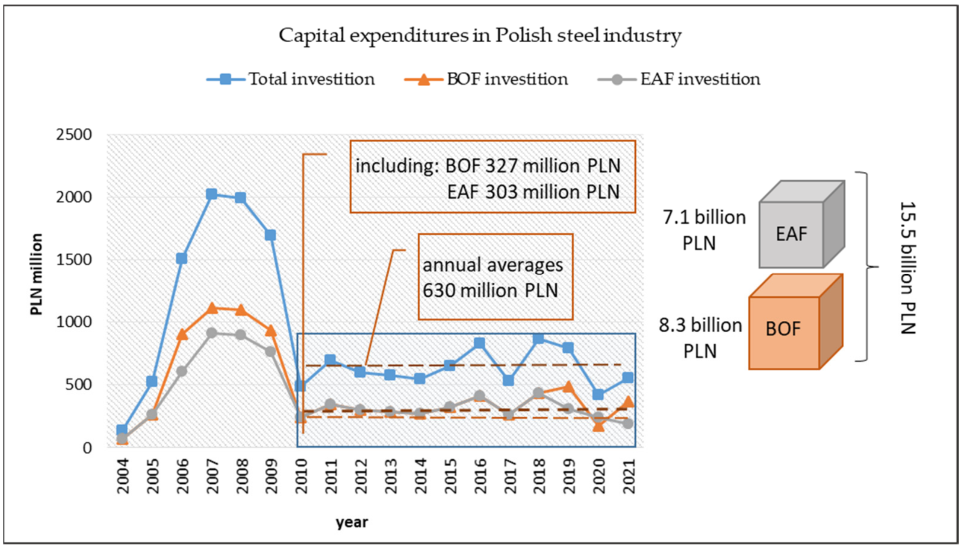

Figure 14. Investment expenditures in the Polish steel industry. Source: own study based on the Polish Steel Association [99].

During the period under review, the value of fixed assets in the Polish steel industry increased (Figure 15), and the average annual increase in the value of fixed assets was about PLN 900 million. After the global economic crisis, which caused a drop in production in 2009 (Figure 2), the value of fixed assets grew at an average annual rate of PLN 762.5 million.

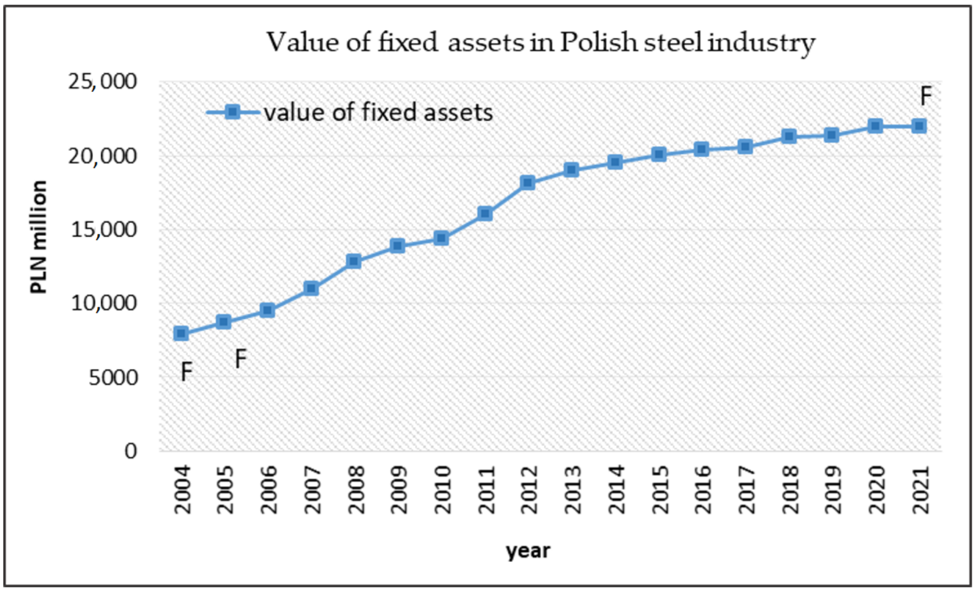

Figure 15. Value of fixed assets in the Polish steel industry. Source: own study based on [103], obtained from the Polish Steel Association. F—Forecast.

The increase in the value of fixed assets was undoubtedly influenced by investments. One of the sources of investment expenditures was profits from operations. Average annual revenues from the sale of steel products in Poland amounted to PLN 22.7 billion (2006–2021 period). Figure 16 shows the revenues of the Polish steel industry. The record year in terms of sales revenue was 2021. The high revenue from the sale of steel products resulted from the rapid increase in prices after the pandemic period for manufactured steel products.

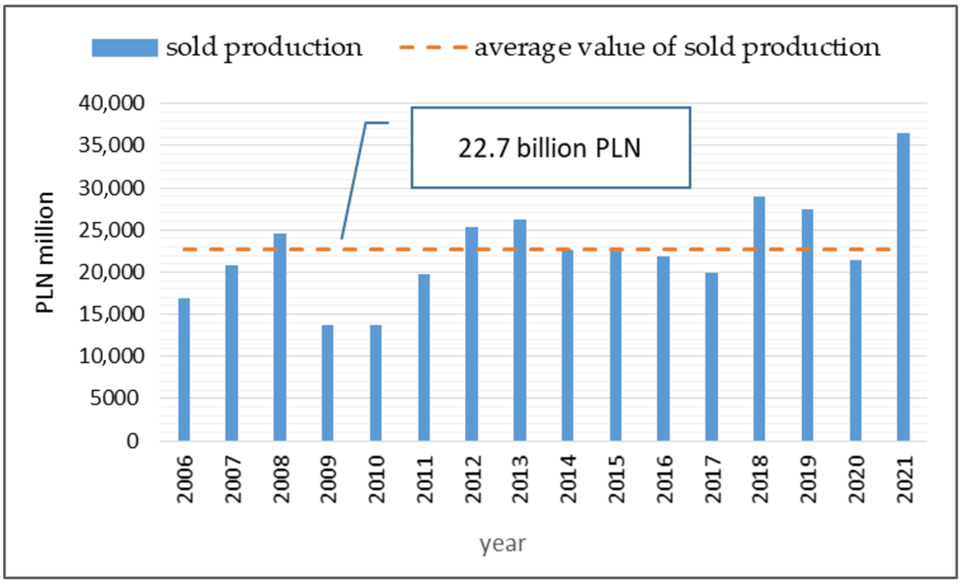

Figure 16. Value of sold production in the Polish steel industry. Source: own study based on [103], obtained from Polish Steel Association.

The analysis performed was used to develop scenarios for the transformation of the Polish steel industry to net zero. The analysed conditions showed that Polish metallurgy can proceed to deep decarbonisation. At the same time, the road to deep decarbonisation will be two-pronged due to the type of technology used (EAF and BF + BOF) and the share of produced steel by process (a ratio of almost 1:1) in the overall volume. The analysis performed did not take into account the social factors of the planned transformation process.

However, the reduction in the employment of workers (staff of steel companies) may be a problem, especially after the shutdown of part of the production capacity in steel mills with BF + BOF technology. The Polish steel sector (total) employs 24,000 people (2021), including almost 10,000 people working in Poland's largest steel mills, which produce steel using BF + BOF technology.

5.2. Transformation Scenarios of the Polish Steel Industry

The transition of European steelmaking to low-carbon, "green" steelmaking requires fundamental changes in the way it is produced, as current technologies are approaching maximum technical and thermodynamic utilization. In line with EU policy, key technologies for decarbonising the steel industry include carbon capture and storage or the use of emitted carbon dioxide (CCS(U)) to reduce the environmental footprint and hydrogen-based steelmaking via direct iron reduction (DRI). Technological change is an extremely complex process, requiring appropriate investment and strategic planning.

The most difficult problem for Poland will be the radical change from BF + BOF to DRI + EAF technologies. The process of decarbonisation of the steel sector, initiated in EU policy, means replacing the currently integrated process installations—blast furnace and converter technology (BF + BOF)—with direct iron reduction (DRI) installations combined with electric arc furnaces (EAF)—in short, DRI + EAF. The largest steel mills in Poland are smelters with BF + BOF technologies. These mills are owned by a global steelmaker which can facilitate new investments (access to capital). The capital group that owns the largest steel mills has already announced investment plans in the direction of DRI. The DRI direction is a strategic direction for high-carbon blast furnace mills in Poland.

According to experts, however, two scenarios of change should be adopted, which are determined by access to sources of iron reduction in Poland. The first scenario (the stage preceding deep decarbonisation) will involve the use of grey hydrogen. The second (long-term scenario) will involve the use of green hydrogen H DRI + EAF. Grey hydrogen comes from the reformation of natural gas, and green hydrogen, produced by electrolysis using "green energy". The iron obtained in both scenarios will be the feedstock for new-generation electric arc furnaces (EAF) (more efficient than current ones).

According to one expert (E1), currently, most of the hydrogen (so-called grey hydrogen) comes from natural gas reforming, which is still associated with sizable CO_2 emissions. Currently, in Poland, 55% of steel (60% of the steel in EU countries) comes from carbon-intensive blast furnace mills, which will have to use hydrogen technologies in the next few years [104]. However, these, for the time being, do not have favourable conditions for development. Therefore (for now) variable gas will be used to produce hydrogen [105]. The cost of producing hydrogen from natural gas depends mainly on the price of gas, which quadrupled in Poland in 2022 compared to prices in 2021 and 2019 [104].

"Green" hydrogen, produced via electrolysis using "green energy," is the only ecologically sound method for the deep decarbonisation of the steel industry. Production of green hydrogen is marginal for the time being because there are still not enough renewable energy sources (in Polish: RES) in Poland. The energy produced from coal in Poland affects the cost of hydrogen production (green hydrogen production is very expensive). According to an expert (E2), from the point of view of steelmaking, the way to manage hydrogen is to produce so-called sponge iron ("direct reduced iron", DRI), which can be used by blast furnace mills, instead of the environmentally burdensome stage of smelting pig iron from iron ore and coke in blast furnaces [106].

Another expert (E3) highlighted the impact of unfavourable political and economic conditions in Central and Eastern Europe on industrial decarbonisation. Furnaces using DRI technology were expected to operate on the gas until Poland's surplus energy from RES increased. Unfortunately, the war in Ukraine and sanctions against Russia halted investment in the Polish steel industry. The energy crisis has reduced gas supplies in Europe and increased gas prices. In addition, producers who make new investments must expect to sell more expensive raw materials for some time after the investment [107]. Investment plans—among other things, due to the prospects of a decrease in the allocation of free CO_2 certificates for industry—can accelerate, but they must be made realistic. Unfortunately, the prices of raw materials in the market are still high (in Poland, wholesale gas and energy prices in 2022, compared to prices at the beginning of 2021, have more than quadrupled) [98,104].

If one takes as a starting scenario (the initial scenario that will precede the relevant scenarios for decarbonisation of the steel industry in Poland) the reduction of steel production in mills with BF + BOF technologies and the increase of production in electric steel plants (EAF), the mills must have a supply of scrap. According to an expert (E4), policies aimed at zero-carbon steel production will also support secondary production, so the struggle to obtain decarbonised steel scrap on the global market will intensify. In recent years, higher ocean freight rates have contributed to the deglobalisation of purchases. At the same time, there has been an increase in demand for scrap in the Middle East and North Africa driven by the drive for decarbonisation, with some plants announcing their intention to double or triple production over the next five years [108].

According to another expert (E5), increasing steel production in electric arc furnaces, and reducing it in BF + BOF, would increase demand for electricity, which is still produced from black coal (48%) in Poland. Regulatory costs borne by smelters, in energy prices, are already a burden on smelters. These costs include the green energy fee, distribution fee, excise tax, cogeneration, transition fee, quality fee, and others, making a total of 16.72 Euro/MWh. Compared, for example, to the price of energy for the steel industry of neighbouring countries, Polish steel mills have higher costs of about 20 Euro/MWh (a reference to Germany) [99]. Due to the low share of energy produced from renewable sources in Poland (green energy), the wholesale price of energy includes not only taxes but also other legislative fees. According to the expert, the decarbonisation of metallurgy in Poland may be inhibited by the lack of a venomous power plant in Poland. The growing demand for energy, which will be with the development of new generation technologies, will require supplies from venom power plants.

The scenario of replacing coal with hydrogen produced using green energy would enable significant decarbonisation of the steel industry, but at the current level of prices for manufacturing factors, this would raise the price of a tonne of steel by about one third (expert opinion E6). However, this gap could narrow in the years to come, as—on one hand—carbon prices may increase as a result of the withdrawal of free allowances. 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 expert cites the cost of producing green hydrogen, which has ranged from €3.6 to €5.3/kg over the past decade (as of the end of 2020). Hydrogen produced by electrolysis costs between 50 and 55 kilowatt-hours (kWh) needed to produce 1 kg of hydrogen [109].

In the opinion of another expert (E7), during the transition period, other solutions are needed—e.g., carbon capture and storage or use of emitted carbon dioxide to reduce the environmental footprint (CCS), increased production of electric steel using scrap steel and/or hot briquetted iron additive (HBI), and DRI production based on natural gas. In his opinion, these scenarios should be considered as a baseline in the transformation of the Polish steel industry to net zero. The steel industry would be changed from DRI + EAF and "smart carbon" into HDRI + EAF [110]. The next expert (E8) explained that the first technology is electrification—simply put, the erection of electric furnaces, replacing blast furnaces, along with a direct iron reduction plant. The second technology is what we call "smart carbon", involving decarbonisation of the fuel input and sequestration of CO_2 with the option of converting it into feedstock for the chemical industry [111].

The Polish steel sector requires access to renewable energy sources to make low-carbon technologies viable. However, according to an expert (E8), it is important to remember that building their own sources is a considerable challenge for steel mills because of the capital intensity. Smelters in Poland have their own plants that use waste gases to generate electricity, but larger investments are rather beyond their means. The scenario of building our own renewable energy sources requires large amounts of land in addition to capital. Undoubtedly, smelters in Poland are waiting for a strong diversification of energy sources, including modular reactors—this could be the technology for the next decade [111].

A number of experts drew attention to the negative scenario of transformation to net zero. The negative scenario, or the so-called passive strategy, is a situation in which steel mills in Poland will not proceed with new investments in the coming years, which will result in a decrease in crude steel production capacity in Poland by about 4 million tonnes. In 2021, there was a record consumption of steel products in Poland (15.3 million tonnes), with a decline in production capacity. In Poland, the consumption of steel products is still higher than the production capacity and volume, hence the import of steel products. If the steel industry in Poland were to put unused capacity into operation as well as invest in new steel plants, it could cover the country's steel consumption. In 2022, Poland's apparent consumption of steel (production + import–export) will fall to 13,815 thousand tonnes (HIPH data). The volume of total explicit consumption in 2022 was the third highest and was 7% higher than the ten-year average, which—according to an expert (E1)—means that steel consumer markets have increased demand. With the growing steel demand, the Polish economy must compensate with imports. The foreign trade balance in the Polish steel market is negative (imports>exports). The first time a negative balance of trade in steel and steel products was recorded in Poland was in 2005. Since that year, steel imports to Poland have been greater than steel exports from Poland. The largest importer of steel products to Poland, among UR countries, is Germany. In 2021, more than 72% of imports from non-EU countries belonged to our eastern neighbours (Ukraine, Russia, and Belarus). In 2022, as a result of the European Commission's imposition of sanctions on imports from Russia and Belarus and the inevitable reduction of imports from Ukraine covered by hostilities, imports from these three countries to Poland halved. During the war period, imports from Japan, India, Turkey, Taiwan, Vietnam, China, and Serbia increased [112].

According to an expert (E9), Polish steelmakers are concerned about importing steel produced using high-carbon technologies. According to the OECD In Asia and Latin America, more than 75% of the capacity planned for 2023–2025 is for steel plants with the blast furnace process. However, these issues are recognized by legislators, who want to protect the market from an influx of cheap raw materials produced using high-carbon methods, such as in China or Turkey. The EU already has a so-called safeguard, a mechanism that provides limits on the import of duty-free steel from outside the Community. The second issue is the so-called carbon tax (CBAM mechanism), which involves adjusting the prices of imported products depending on the CO_2 emissions generated in their production. According to the provisional agreement of EU bodies, this tax is to take effect in October. Interestingly, the government in the US is planning to introduce a similar solution. Experts predict that in such a case the new regulations would hit hard, among others, producers from China, where about 85% of steel is produced using high-carbon blast furnace technology. Technologically, the United States is in a comfortable position; 70% of steel there is produced using the electric method [112].

Opportunities for deep decarbonisation can be seen (E10) in the development of Industry 4.0. Smart steel manufacturing uses the information interaction characteristics of the internet to propose the concept of smart steel, which breaks through the information barrier in the steel supply chain and between equipment in steelmaking [113]. Digitalisation and Industry 4.0 technologies must support sustainability in a world where politics demands it [82,114]. The cooperation of steelmakers with suppliers of raw materials and energy to steel mills and customers of steel products (mainly the automotive and construction industries) as key consumers of steel determines (entices) steel mills to build smart steelmaking and thus invest in low-carbon technologies. Steel mills increasingly use dedicated platforms [115] in their communication systems; cyber–physical models of steel production systems (CPS modelling) in the testing stage of projects; collaborative process systems and solutions such as BIM-enabled platforms (building information modelling [116–120]) and automatic modelling of prefabricated components [121]; and other technologies, such as digital twins, that enable testing of changes (prototyping) in near-real conditions [122]. The market driver of the technological transformation of steel mills is customization, which pulls technological innovation in steel mills [123].

The conclusion of the experts' opinions: the Polish steel industry, which is part of the European steel industry, has no choice but to decarbonise. Steel mills in a net zero strategy must take into account the conditions in which they operate. In Poland, a set of these determinants is presented in this and other publication [124]. Decarbonisation of the Polish steel industry, in practice, means that blast furnaces will be replaced by DRI technologies and new-generation electric furnaces. This baseline scenario will be preceded by a transitional scenario in which there will be a periodic shutdown of blast furnaces (BF) from export and an increase in steel production in electric steel plants (EAF). Taking into account the circumstances of the steel industry in Poland and the expert opinions gathered, additional scenarios were also assumed, including the use of HBI, the development of CCS(U) technology, and a transitional scenario that precedes "green hydrogen" is "grey hydrogen." The scenarios also take into account the impact of the surrounding infrastructure and Industry 4.0 considerations.

In the Figure 17, there is a scenario map for the decarbonisation process of the steel industry. The triangles on this picture symbolise the relations between variables on the map. The sharp ends of the triangles point in the direction of the influence between particular variables. The start-up scenario (planned for the next few years) begins the transformation process to net zero by reducing steel production in BF + BOF technology and investing in EAF technology (increasing production of electric steel using steel scrap and/or hot-briquetted iron additive (HBI)). The Polish steel industry has closed down a blast furnace unit in Krakow, and another blast furnace (in Dabrowa Gornicza) has been temporarily shut down. The largest producers in the Polish steel market (ArcelorMittal Poland, Celsa Ostrowiec) have already announced their investment plans, including in DRI-EAF technologies (ArcelorMittal Poland investment plans). In practice, this means that blast furnaces will be replaced by electric furnaces. During the transition period, these technologies will operate in parallel, after which the blast furnaces will be completely replaced by electric furnaces. This is a decade-long prospect [111].

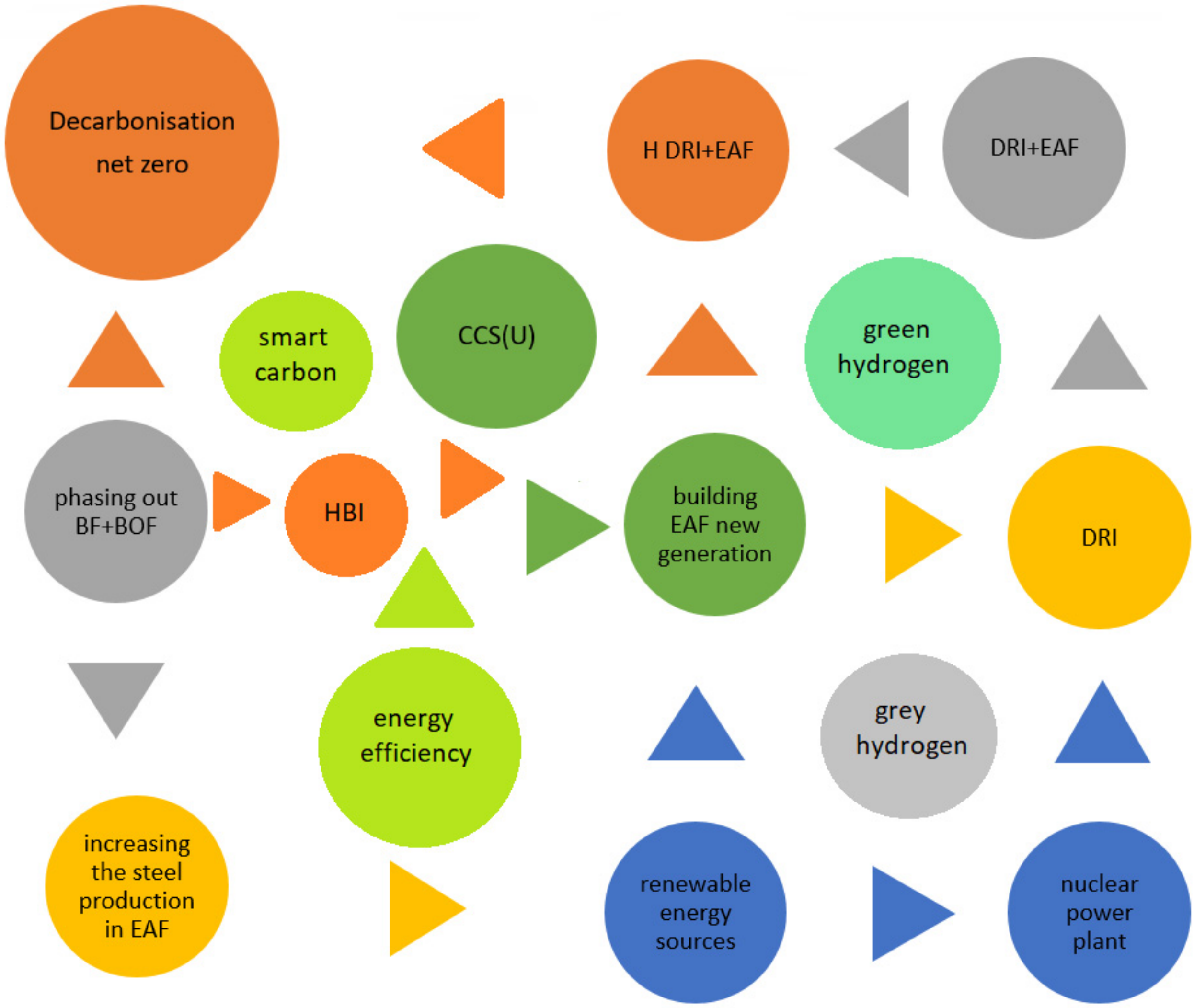

Figure 17. Scenario map for the decarbonisation process of the steel industry.

The direction of investment (DRI + EAF) is the implementation of investments in line with the decarbonisation baseline scenario, which in the paper was also called the key (important) scenario because investments will be very capital-intensive. This scenario will see the development of DRI technology, i.e., innovative direct iron reduction (DRI) combined with electric furnace technology. This base scenario will be supported by the implementation of "smart steel" technology (i.e., Industry 4.0 technology).

Decarbonisation in Poland primarily involves investment in electric furnaces—replacing blast furnaces—together with direct iron reduction plants (DRI + EAF). The baseline scenario calls for the development of hydrogen technologies. In the period preceding deep decarbonisation, Polish steel mills increase demand for natural gas in iron ore reduction processes (in this case, "grey hydrogen"), and in the prospect (target scenario), there will be increased demand for renewable energy sources, which will be used in technological processes at the stage of iron ore reduction with hydrogen, i.e., "green hydrogen". These scenarios are supported by scenarios based on CCS(U). "Smart carbon" technologies reduce the carbon footprint of the fuel input and sequester CO_2 with the option of converting it into feedstock for the chemical industry. In the decarbonisation of the Polish steel industry, there must be a synergy between steel plants and policies (government funds and programs). The symbiosis of politics and business is the beginning of the transformation towards net zero and should intensify as decarbonisation deepens [69]. Symbiosis brings together traditionally separated industries and firms in partnerships [125].

6. Discussion

The steel industry is one of the largest contributors to greenhouse gas emissions, accounting for approximately 7% of global CO_2 emissions. Therefore, the decarbonisation of the steel industry is crucial in the fight against climate change [100]. To achieve decarbonisation in the steel industry, several strategies can be implemented. One of the most promising approaches is to shift from traditional blast furnaces to electric arc furnaces (EAFs) [63,126]. Unlike blast furnaces that rely on coke and coal to produce steel, EAFs utilise electricity to melt scrap steel, reducing emissions of carbon dioxide and other pollutants. Furthermore, EAFs can use renewable energy sources, such as solar or wind, to power their operations, further reducing carbon emissions [127,128].

Another approach to decarbonisation in the steel industry is to implement carbon capture and storage (CCS) technology. This technology involves capturing carbon dioxide emissions from steel production and storing them underground, preventing them from entering the atmosphere [129]. While this approach has shown promising results in laboratory settings, it has yet to be widely implemented on an industrial scale due to high costs and technical challenges. Additionally, there is a need for the steel industry to increase the recycling and reuse of steel products. Recycling steel requires much less energy than producing new steel and therefore reduces emissions significantly. The steel industry can also explore new technologies, such as 3D printing and lighter materials to reduce the amount of steel used in construction and manufacturing [130].

Decarbonising the steel industry is a crucial step towards achieving global climate targets and transitioning towards a low-carbon economy [131,132]. The steel industry must transition from using fossil fuels to low-carbon alternatives, such as hydrogen, carbon capture and storage, and increased recycling and reuse of steel products. Achieving deep decarbonisation requires significant investment and collaboration between governments, businesses, and stakeholders, but the benefits are significant, extending beyond mitigating climate change [133–136].

Based on our research and the literature analysis we can distinguish the following benefits of decarbonisation of the steel industry [133–142]:

- Decarbonising the steel industry can lead to significant reductions in greenhouse gas emissions, particularly carbon dioxide (CO_2), which is one of the main drivers of climate change. By transitioning to low-carbon alternatives, such as hydrogen-based direct reduction or carbon capture and storage, the steel industry can significantly reduce its carbon footprint.
- Decarbonising the steel industry can reduce its dependence on fossil fuels, such as coal and natural gas, which are subject to price volatility and supply chain disruptions. By using renewable energy sources—such as wind or solar power—to produce low-carbon alternatives, the steel industry can increase its energy security and reduce its exposure to price fluctuations.
- The transition towards low-carbon steel production can create new jobs in areas such as renewable energy, hydrogen production, and carbon capture and storage. Moreover, increasing recycling and reuse of steel products can also create new jobs in the circular economy.
- Reducing greenhouse gas emissions from the steel industry can lead to improved public health by reducing air pollution and its associated health impacts. For instance, the use of alternative fuels in steel production can reduce emissions of particulate matter, sulphur dioxide, and nitrogen oxides, which are harmful to human health.

- Decarbonising the steel industry can stimulate economic growth by creating new jobs, promoting innovation, and attracting investments in new technologies and infrastructure. Moreover, the shift towards low-carbon production can also lead to increased competitiveness and market access in a rapidly changing global economy.

Additionally, we should take into account that the process of decarbonisation of an economy and especially the steel industry is not an easy one. We can distinguish some problems which exist when we are moving towards the decarbonisation of this industry [133–142]:

- Decarbonising the steel industry can require significant investment in new technologies and infrastructure. For example, the development of hydrogen-based direct reduction or carbon capture and storage technologies can be costly. This can be a barrier for some companies, particularly small- and medium-sized enterprises, that may not have the resources to invest in these new technologies.
- Decarbonising the steel industry requires the development and implementation of new technologies that can be technically challenging. For example, the production of low-carbon steel using hydrogen-based direct reduction requires significant changes to traditional steelmaking processes. This can require new equipment, materials, and skilled workers.
- The availability of low-carbon alternatives, such as renewable energy, hydrogen, or carbon capture and storage, can be limited in some regions. This can be a barrier to the adoption of low-carbon alternatives by the steel industry, particularly in regions with limited access to renewable energy sources or storage infrastructure.
- The transition towards low-carbon steel production requires new infrastructure, such as pipelines for transporting hydrogen or carbon dioxide and storage facilities for hydrogen and captured CO_2. Developing this infrastructure can be a significant challenge and require investment in new systems and networks.
- The transition towards low-carbon steel production requires supportive policies and regulations that incentivise and support the development and adoption of new technologies. Governments can play a significant role in this transition by providing financial incentives, setting emissions reduction targets, and supporting research and development. However, the lack of supportive policies and regulations can be a barrier to the adoption of low-carbon alternatives.

Overcoming these challenges is essential to mitigating climate change and achieving a sustainable, low-carbon economy [138,139]. The process of overcoming them should be based on collaboration between governments, businesses, and stakeholders, which is essential to addressing the technical and economic challenges of decarbonising the steel industry. This collaboration can lead to the development of new technologies and infrastructure as well as supportive policies and regulations. Innovation is also critical to developing new technologies that can reduce the carbon footprint of the steel industry [140]. Governments, businesses, and research institutions can invest in research and development to develop new low-carbon alternatives, such as hydrogen-based direct reduction or carbon capture and storage [141].

Investment is very important in developing the necessary infrastructure for low-carbon steel production. Governments can provide financial incentives and support to businesses to invest in new technologies and infrastructure, while businesses can collaborate to invest in shared infrastructure, such as pipelines for transporting hydrogen or carbon dioxide. Supportive policies and regulations can incentivise the adoption of low-carbon alternatives by the steel industry [142,143]. Governments can set emissions reduction targets, provide financial incentives for low-carbon production, and implement supportive regulations for the development of new technologies and infrastructure [144]. Education and training are useful in developing the skilled workforce necessary for low-carbon steel production. Governments, businesses, and educational institutions can collaborate to provide training programs and develop curricula that support the development of new skills required for low-carbon steel production [144,145].

The developed scenarios in the research presented in the publication are in line with technologies that are used in the steel industry in other countries. In the case of the first approach—the use of natural gas—natural gas can be used in DRI (direct reduced iron) technology as an alternative to coking coal in the production of reducing iron [146]. The DRI process involves the reduction of iron oxides to produce reducing iron, which can be used as a raw material for steelmaking. The traditional DRI process uses coke carbon as a reducing agent, but natural gas can be used as an alternative reducing agent [147].

The DRI process with natural gas involves feeding natural gas into a reduction furnace, where it reacts with iron oxide to produce hydrogen and carbon monoxide. The hydrogen acts as a reductant, and the carbon monoxide is discharged as waste. This process produces low-carbon reducing iron, which can be used to produce low-carbon steel. For example, Lynn Gorman says [148] that this technology is a very useful method on the road towards green steel making. As indicated by David Wolff, the territory manager at Nel Hydrogen, electric arc furnace (EAF) steelmaking represents a crucial step forward in the mission to reduce CO_2 emissions [149]. The role of this technology in the process of reducing iron in the steelmaking process was also pointed out by Hidetoshi Tanaka [150]. According to him, recently, the gas-based DRI process has undergone significant scaling-up, with units capable of producing over 2 million tonnes per year. In North America, the emergence of shale gas has made electric power and natural gas more readily available at a lower cost. As a result, several projects are currently being pursued to implement upstream ironmaking based on this process.

The use of natural gas in DRI technology has several advantages. First, natural gas is a lower-carbon fuel than coking coal, thereby reducing the greenhouse gas emissions associated with steel production. Second, natural gas is a less expensive fuel than coke coal, reducing steel production costs. Third, natural gas is a fuel with high global availability, allowing access to the raw material in many regions [151–156].

The DRI process uses natural gas or green hydrogen as an energy source, leading to a significant reduction in greenhouse gas emissions compared to traditional steelmaking methods. It has high energy efficiency compared to methods based on high furnaces and oxygen converters, leading to energy and production cost savings [154]. DRI technology makes it possible to produce different types of iron and steel, which makes it possible to adapt production to changing market needs. The use of the technology in question makes it possible to use different energy sources, including green hydrogen, leading to greater energy independence for the steel industry and increasing its sustainable production. The DRI process requires less investment and lower operating costs compared to traditional steelmaking methods, leading to lower production costs and increased competitiveness [155,156].

However, the use of natural gas in DRI technology may require significant investment in new equipment and infrastructure. Changes in production processes are also required, which can be complicated and require high costs. In addition, appropriate supply infrastructure, such as pipelines to transport the gas, also need to be built and can be costly and time-consuming [157]. Despite these challenges, the use of natural gas in DRI technology appears to be a promising solution for the steel industry to reduce greenhouse gas emissions and increase production efficiency [158–160]. Green hydrogen can be used in the steelmaking process to replace traditional fossil fuels, such as coal and natural gas, which are currently used to reduce iron oxides in the blast furnace ironmaking process. Green hydrogen can be used for this purpose through the hydrogen direct reduction (HDR) furnace iron reduction process [161]. In the HDR process, green hydrogen is used as a fuel to reduce iron oxides, leading to the production of iron with lower CO_2 emissions. This process is greener than the traditional steelmaking method and has the potential to reduce greenhouse gas emissions [162]. In addition, green hydrogen can be used as an energy carrier to power steelmaking furnaces and generate the electricity needed for the steelmaking process. Ultimately, the use of green hydrogen in the steelmaking process can help reduce greenhouse gas emissions and reduce the steel industry's dependence on fossil fuels [163]. The processes of using green hydrogen and HDR technology in the world of steel producer are described by Will Hall [164]. According to his concept, it could be predicted that a carbon pricing mechanism of around USD 40/tCO_2 in the steel industry will be required by 2030. This will enable hydrogen direct reduction to compete with conventional BF-BOF plants, provided the cost of hydrogen remains at USD 2/kg. Furthermore, a gradual increase in the carbon price beyond this point will guarantee a progressive replacement of natural gas in the direct reduction process, which will be facilitated by the declining costs associated with green hydrogen production.

The concept of using green hydrogen in the steel industry was also described by Jayson Pike [165]. He thinks that this is a very important and innovative technology that can have a very beneficial impact on the adjusting steel industry's decarbonisation policy [165]. This approach is also seen as important by Kiessling [166]. The use of green hydrogen in the steelmaking process also carries several significant advantages. Green hydrogen does not emit CO_2 during combustion, unlike traditional fossil fuels—such as coal and natural gas—which are currently used in the steelmaking process. Thus, the use of green hydrogen can help reduce greenhouse gas emissions and reduce the negative environmental impact of industry [68,167]. The type of hydrogen in question is a very efficient energy carrier, which means it can be used in the steelmaking process to increase energy efficiency and reduce production costs. Green hydrogen can be produced from renewable energy, such as solar and wind power. This allows the steel industry to become more independent of traditional fossil fuels and increase its sustainable production. Using it in the steel industry requires new technologies and innovative solutions, which contribute to the growth of the industry and the creation of new jobs [168]. In the transformation of steel mills to net zero, the importance of the high technologies heavily popularised in Industry 4.0 will increase [169]. Existing steelmaking professions, e.g., blast furnace worker, steelmaker, are given new name: "process operator."

Reaching zero carbon emissions by 2050 requires rapid actions in both CO_2 emission reductions from the large emitting sources by applying CCSU and switching to sustainable energy systems step by step. In the paper [170] three options to mitigate climate change by minimizing CO_2 emissions are presented: (first option) completely switch to renewable, (section option) completely embrace CCUS, (third option) combination of first and second options. Paper [171] presents decarbonisation models for the glass sector (in our view, these can be adapted to other sectors, including steel.

CCUS, or carbon capture, transport, utilisation and storage technology, is set to become an essential part of realising the decarbonisation of the refining, steel and other industries [172]. It will reach the peak of traditional production around 2030. CCUS is a technology that was already developed about two decades ago, but was not implemented due to implementation costs and reduced plant efficiency. In addition, storing carbon dioxide underground raises public concerns about the physical properties of the gas.

Scientists and practitioners are constantly exploring the topic of radical energy innovation, technologies for the provision of renewable energy are becoming increasingly innovative and accessible to many users [173–175].

Green hydrogen is a low-carbon technology that uses renewable energy to split water into hydrogen and oxygen through electrolysis. This hydrogen can be used as a clean energy source in a variety of applications, including transportation, power generation, and industrial processes. While green hydrogen has several benefits, there are some key differences between green hydrogen and other low-energy technologies, such as carbon capture and storage (CCS) and energy efficiency measures [176].

One major difference is that green hydrogen is a clean and renewable energy source, while CCS and energy efficiency measures are focused on reducing emissions from existing energy sources. CCS involves capturing carbon emissions from fossil fuel power plants or industrial processes and storing them underground, while energy efficiency measures involve reducing the energy consumption of buildings and industrial processes. While these technologies can reduce emissions, they do not produce renewable energy like green hydrogen does [177].

Another important difference is that green hydrogen can be used in a variety of applications, while CCS and energy efficiency measures are more limited in their applications. Green hydrogen can be used in transportation, power generation, and industrial processes, while CCS is primarily used in power generation and industrial applications, and energy efficiency measures are primarily used in buildings and industrial processes [178,179].

We can say that green hydrogen is still a developing technology and faces several challenges, such as high costs and limited infrastructure. CCS and energy efficiency measures are more established and have been implemented on a larger scale. However, with continued investment and innovation, green hydrogen has the potential to become a key component of a low-carbon energy system [180]. The differences between green hydrogen and other low energies technologies were presented in Table 3.

Table 3. The differences between green hydrogen and other low energies technologies.

Technology	Key Characteristics	Applications	Challenges
Green Hydrogen	Renewable energy source, produced through electrolysis of water using renewable energy	Transportation, power generation, industrial processes	High costs, limited infrastructure
CCS	Captures carbon emissions from fossil fuel power plants or industrial processes and stores them underground	Power generation, industrial processes	High costs, limited applicability
Energy Efficiency Measures	Reduces energy consumption in buildings and industrial processes	Buildings, industrial processes	Limited potential for emissions reduction

Source: author's own work on the basis of [176–180].

The stance of steel companies towards energy efficiency varies depending on the company and their individual priorities and strategies. In recent years, many steel companies have recognised the importance of energy efficiency as a means of reducing costs and improving their environmental performance. In addition to energy efficiency measures, many steel companies are also exploring the use of low-carbon technologies such as green hydrogen. While the adoption of green hydrogen is still in its early stages, several steel companies have expressed interest in the potential of green hydrogen as a method of decarbonising their operations [176–178].

For example, in Europe, several steel companies have announced plans to use green hydrogen in their operations, including ArcelorMittal, ThyssenKrupp, and Salzgitter AG. These companies are investing in the development of green hydrogen production facilities and exploring the use of hydrogen as a reducing agent in steelmaking. Additionally, steel companies in other parts of the world, including China and Japan, are also exploring the potential of green hydrogen in the steel industry [179,180].

It can be observed that while the adoption of green hydrogen in the steel industry is still in its early stages, there is growing interest and strategic consideration of the potential of this technology as a way to reduce emissions and improve the environmental performance of steel companies.

7. Conclusions

The developed scenarios for the decarbonisation of the steel industry add value to this research paper. The authors, based first on a literature review and then on discussions with steelmaking experts in Poland, established variants of scenarios for the decarbonisation of the steel industry in Poland. The core of the paper is a diagnosis of the state of the Polish steel industry on the road to net zero steelmaking.

Global steel production is dominated by BOF and EAF technologies. These two technologies are considered core to the steel business in the process of transformation to net zero. In the decarbonisation process of the steel industry, these key technologies will change either in an evolutionary or revolutionary way. Steel plants with BOF technology can adopt low-carbon steelmaking technologies existing today, but such a direction of change is not sufficient for deep decarbonisation. Steel mills with BF + BOF technologies must therefore plan for radical investments in DRI-EAF technologies. For steel plants with EAF technologies, the scenario is to save energy, eliminate black energy and use green energy. The revolutionary direction for steel mills is the use of hydrogen in steel production, with the perspective of green hydrogen. Radical changes in steel production technologies will take place with CCS technologies, which include industrial symbiosis and resource and energy efficiency through exchanges of, for example, by-products, off-gases, or waste heat. Two of the most promising options for deep decarbonisation are the modification of existing blast furnace–basic oxygen furnace (BF + BOF) steel mills to utilise powdered coal and iron ore (known as the HIsarna technology), with simultaneous installation of carbon capture, utilization, and storage (CCUS) technology and the hydrogen direct reduction of iron (H2-DRI) using green hydrogen produced through electrolysis and electric arc furnaces (EAF).

In 2021, Poland was one of the five largest steel producers in Europe and ranked 22nd globally. Steel production was 8.5 million tonnes, but in 2022, it fell by 11% due to the energy and economic crisis and the effects of the war in Ukraine. Consumption of steel products in Poland is higher than production, which means that the Polish economy needs steel. The growing consumption of steel in Poland represents an opportunity for technological innovation and the development of the steel industry towards net zero CO_2 emissions. Poland’s steel industry is important to the economy, producing 3% of industrial output value and 0.3% of total GDP, and in broad terms, steel mills in the supply chain produce about 2% of GDP.

As part of the EU industry, the Polish steel industry is investing in low-carbon technologies and reducing CO_2 emissions. Between 2000 and 2021, investments in emissions reduction amounted to nearly PLN 16 billion, which improved productivity and energy efficiency. Two companies, Celsa Huta Ostrowiec and ArcelorMittal Poland, are participating in industrial decarbonisation projects. There are four industrial decarbonisation projects in Poland, including three in Ostrowiec Swietokrzyski and one in Dabrowa Gornicza. By analysing capital expenditures in the period from 2004 to 2021, it can be seen that steel mills spent PLN 8.3 billion on BOF technologies and PLN 7.1 billion on EAF technologies. In the last decade, the average annual investment expenditures in the Polish steel sector amounted to PLN 630 million, half of which was spent on improving BOF technologies; the other half was spent on improving EAF technologies. The problems of ecology and energy transition are the subject of public debate in Poland, with analysts addressing the decarbonisation of the Polish economy.

The transition of European steel production to low-carbon, “green” methods requires fundamental changes in the way it is produced, as current technologies are approaching maximum technical and thermodynamic utilization. In line with EU policy, key decarbonisation technologies for the steel industry include carbon capture and storage or utilization (CCS(U)) to reduce the environmental footprint and hydrogen-based direct reduction iron (DRI) steelmaking. Technological change is an extremely complex process that requires adequate investment and strategic planning.

The most difficult problem for Poland will be the radical change from BF + BOF technology to DRI + EAF technology. The initiated process of decarbonisation of the steel sector in the EU means replacing the current integrated process plants—i.e., blast furnace and converter technology (BF + BOF)—with direct iron reduction (DRI) plants combined with electric arc furnace (EAF), i.e., DRI + EAF. The largest steel mills in Poland use BF + BOF technologies. These mills are owned by a global steelmaker which can facilitate new investments (access to capital). The capital group that owns the largest steel mills has already announced investment plans in the DRI direction. The DRI direction is a strategic direction for high-carbon blast furnaces in Poland.

However, according to experts, two scenarios of change should be adopted, which are conditioned by access to sources of iron reduction in Poland. The first scenario (preceding the stage of deep decarbonisation) will involve the use of natural gas in DRI technology as a reductant of iron ore with hydrogen (grey hydrogen). The second scenario (long-term scenario) will involve the use of renewable energy (green hydrogen). The iron obtained in both scenarios will be used as feedstock for new-generation electric arc furnaces (more efficient than current ones).

According to experts, most hydrogen (so-called grey hydrogen) currently comes from natural gas reforming, which is still associated with significant CO_2 emissions. Currently, in Poland, 55% of steel (60% in EU countries) comes from high-emissions blast furnaces that will have to use hydrogen technologies in the coming years. These, however, do not yet have favourable conditions for development. Therefore, for the time being, variable gas, which is a by-product of the extraction of natural gas, will be used for hydrogen production. The cost of producing hydrogen from natural gas depends mainly on the price of gas, which in Poland in 2022 increased fourfold compared to prices in 2021 and 2019. Green hydrogen, produced by electrolysis using renewable energy, is the only ecologically justified method in the deep decarbonisation of the steel industry. The production of green hydrogen is still marginal because there are still too few renewable energy sources in Poland. The energy produced from coal in Poland affects the cost of producing green hydrogen, which is very expensive. From the perspective of steel production, the way to utilise hydrogen is the production of so-called sponge iron (DRI), which can be used by blast furnaces instead of the burdening coking coal.

The main limitation of this paper is connected with the fact that it is based on data from Poland. Technological processes in all countries are similar, but the economic effects of their implementation can vary according to the various prices of energy sources and raw materials. Additionally, predictions are not 100% confident because the European Union's policy towards decarbonisation can change, and new innovative technologies can be invented.

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