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An Econometric Analysis of CO₂ Emission Intensity in Poland's Blast Furnace–Basic Oxygen Furnace Steelmaking Process

Bożena Gajdzik ^{1,*} , Radosław Wolniak ^{2,*}  and Wiesław Grebski ³ 

¹ Department of Industrial Informatics, Silesian University of Technology, 44-100 Gliwice, Poland

² Faculty of Organization and Management, Silesian University of Technology, 44-100 Gliwice, Poland

³ Penn State Hazleton, Pennsylvania State University, 76 University Drive, Hazleton, PA 18202, USA; wxg3@psu.edu

* Correspondence: bożena.gajdzik@polsl.pl (B.G.); radoslaw.wolniak@polsl.pl (R.W.)

Abstract: This study examines the carbon and energy intensity of steel production in Poland, with a particular focus on the Blast Furnace–Basic Oxygen Furnace (BF-BOF) process. Given its dominant role in the industry, decarbonizing this process is crucial for achieving the “Net Zero” targets outlined in the Strategy 2050 climate policy. The transition toward deep decarbonization presents significant technological challenges, primarily the shift from high-carbon BF-BOF technology to low-carbon alternatives, such as hydrogen-based direct reduction iron in Electric Arc Furnaces (H₂-DRI-EAF—Hydrogen-Based Direct Reduction Iron in Electric Arc Furnaces). Using time series analysis and econometric modeling, we assess the impact of technological innovation and investment on the emission intensity of BF-BOF technology. The findings highlight the necessity of radical technological transformation for deep decarbonization in the steel industry, reinforcing the urgency of adopting low-carbon solutions. A successful sustainable transition in the steel industry requires a holistic approach, integrating economic incentives, regulatory frameworks, and innovation-driven strategies to foster a competitive, resource-efficient, and environmentally responsible steel sector in the era of deep decarbonization.

Keywords: CO₂ emissions; BF-BOF; steel production; deep decarbonization; Polish steel industry; sustainability



Academic Editors: Eirini Aivazidou and Naoum Tsolakis

Received: 18 March 2025

Revised: 26 April 2025

Accepted: 28 April 2025

Published: 30 April 2025

Citation: Gajdzik, B.; Wolniak, R.; Grebski, W. An Econometric Analysis of CO₂ Emission Intensity in Poland's Blast Furnace–Basic Oxygen Furnace Steelmaking Process. *Sustainability* **2025**, *17*, 4045. <https://doi.org/10.3390/su17094045>

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1. Introduction

Decarbonization can be defined as the orderly reduction of emissions of a greenhouse gas to meet the environmental policy with the ultimate objective of bringing the CO₂ emissions into the atmosphere to a complete halt. The EU has set ambitious goals for reducing harmful greenhouse gas emissions, such as targets of a 55% reduction by 2030 and an even greater decrease of 80–95% by 2050 compared with the levels in 1990 [1,2]. In December 2019, the EU established a strategic course for the green transition with a vision for climate neutrality in 2050 [3]. Over the last four years, concrete policy proposals have been expressed in correspondence with the strategic vision, and subsequently, new tools have been created with respect to the EU's industrial strategy, among them the Carbon Border Adjustment Mechanism (CBAM) [4,5].

Poland, as an EU country, needs to increase the share of RES (renewable energy sources) in overall energy sources, with a strong reduction in coal power generation. In 2022, RES share was 16.9% in energy total [6]. Decarbonization is also included in the Polish Policy [7]. The share of Poland's and the EU's industrial CO₂ (carbon dioxide) emissions is 8% [8]. Energy-intensive industries in Poland mainly consume black energy

(a colloquial or metaphorical expression to denote energy derived from fossil fuels) [9,10]. And although, in the past few years, the share of coal in Poland's energy sources has decreased by seven percentage points [11], Poland does not have a nuclear power plant to power energy-intensive industries, so coal is still an important source of energy.

There are many energy-intensive industries in Poland (steel, aluminum, synthetic fibers, synthetic rubber, soda, chlorine, ferrosilicon, polyvinyl chloride, etc.). The importance of these industries for the Polish economy is evidenced by the fact that, in total, energy-intensive industries account for 5% of GDP and employ more than 400,000 people. According to the Central Statistical Office, Polish industry needs about 50 TWh of electricity (equivalent to one-third of national consumption) [10]. Electricity consumption in kWh per 100 PLN of sold production at current prices in the Polish steel industry was 15.2 (2020 data) [12], including 20.6 for the production of pig iron, steel products, cast iron, and ferroalloys [12]. Compared to other sectors, steel mills are outpaced only by the production of cement (26.3) and paper (23.3) [12].

In the aftermath of the post-pandemic energy crisis, energy prices—particularly for coal-fired power generation and environmental charges—have risen significantly, contributing to an overall energy cost equivalent to approximately 7% of Poland's GDP. This cost burden underscores the economic impact of any potential energy savings, especially in light of growing volatility in global energy markets. Despite a gradual improvement in energy efficiency—evidenced by a reduction in energy consumption from 290 kgoe (kilograms of oil equivalent) per €1000 of GDP in 2008 to 212 kgoe in 2020 (Eurostat)—Polish industry remains markedly energy-intensive, exceeding the EU average by more than 80% [13]. This inefficiency is acutely visible in the steel sector, where coal remains indispensable—not only as the primary energy source but also as a chemical reducer in the Blast Furnace–Basic Oxygen furnace (BF–BOF) steelmaking process. Approximately 50% of Poland's annual steel output—around 4.5 million tons—is produced using this method, which requires between 2 and 2.5 million tons of coke annually and emits an average of 6.94 million tons of CO₂ per year (average for 2005–2022) (World Steel Association, 2022) [14]. The energy intensity of crude steel production in Poland, estimated at 21 GJ per ton (World Steel Association Report) [14], reflects the sector's structural dependence on fossil energy and its substantial environmental footprint.

In this paper, we have formulated the following research questions:

RQ1—What is the impact of technological investments in the Polish steel industry on CO₂ emissions in the Blast Furnace–Basic Oxygen Furnace (BF–BOF) process?

RQ2—Can econometric modeling effectively capture the relationship between investment, energy and coke consumption, and CO₂ emission intensity in the BF–BOF steelmaking process?

For our research, we formulated the following two goals:

RG1—To evaluate the impact of technological investments on the intensity of CO₂ emissions in the Blast Furnace–Basic Oxygen Furnace (BF–BOF) steelmaking process in Poland.

RG2—To develop econometric models that quantify the relationship between CO₂ emissions, energy and coke consumption, and investment levels in the BF–BOF process.

The paper presents econometric models of the impact of both investment and coke and energy consumption on CO₂ emissions in the BF–BOF technology in the Polish steel sector. The following research fields (RFs) were performed:

- RF1: time series analysis of CO₂ emissions and electricity and coke consumption in the BF–BOF steel process from 2005 to 2021.
- RF2: econometric models of the impact of investments realized in the Polish steel industry on the CO₂ emissions in BF–BOF technology.

- RF3: econometric models of the impact of investments and energy and coke consumption on CO₂ emissions in BF-BOF technology.

The final result of this analysis was a set of econometric models presenting the correlation between investments and CO₂ emissions. The research conducted has confirmed the validity and necessity of decarbonizing the Polish steel industry. This process incorporates the Deep Decarbonisation Strategy, which involves replacing the BF-BOF technology with the DRI-EAF technology (where direct reduced iron (DRI) serves as the end product, subsequently converted to steel in an Electric Arc Furnace (EAF)). The presented models will enable a better understanding of the mechanisms of decarbonization of the steel industry, and can be used to forecast the energy intensity of steel production in the transition to net zero carbon.

The paper is organized into six main sections. Following the introduction (Section 1), the paper proceeds with a contextual explanation (Section 2), in which the authors present the context of ongoing changes in the European Union, including those affecting the steel industry. They also identify the main factors—described in the literature—that are driving the sector’s transition towards decarbonization and the adoption of cleaner sources of energy. Secondly, the methodological section provides a logical model of the research process. Depending on the considerations presented in Section 2, the authors determine the specific variables to be researched and provide a detailed description of the model applied in the study. Section 3 is reserved for materials and methodology. Section 4 is the core research section, where empirical evidence from the past is employed to explore patterns and construct models that determine the impact of technological investments on CO₂ emissions during the BF-BOF process.

The following section (Section 5) is a discussion section in which the findings of the analysis are clarified in light of the existing body of literature. The final section (Section 6) is a conclusion that restates the objectives of the study, emphasizes the applied significance of the analysis, and addresses limitations encountered in research.

2. Theoretical Background of Analysis

The transition to sustainable production processes has emerged as an immediate task confronting world economies, particularly in energy-consumption-heavy productions such as steel production. Steel manufacturing is a high-emission industry with an estimated 7% contribution to global CO₂ emissions; hence, its decarbonization is an inherent component of the world’s efforts to confront climate change. In the process, sustainability encompasses more than emissions reduction and now also considers broader environmental, economic, and social dimensions [15–17]. The competitive and sustainable steel industry has to incorporate the circular economy principles with a vision to minimize material losses, reduce waste, and maximize the recycling of materials. Furthermore, the transition to low-carbon technology, i.e., Direct Reduction Ironmaking using Electric Arc Furnaces (DRI-EAFs) on the basis of green hydrogen, is a transformational scale shift necessary to achieve climate neutrality goals in line with the European Green Deal and United Nations Sustainable Development Goals (SDGs), specifically SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action) [18,19].

Steel sustainability transcends technology. The industry must also deal with the socio-economic aspect of deep decarbonization, ensuring a fair transition for the workers and societies that are reliant on conventional steel manufacturing. Investments in renewable energy infrastructure, carbon capture and utilization (CCU), and intelligent manufacturing technology are necessary in order to balance economic competitiveness and environmental sustainability. Additionally, policy interventions such as the EU Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM) are shaping the trajectory of

the steel industry via low-carbon intensification of production without undermining global market competitiveness [20,21]. The success of such endeavors is dependent on a holistic approach beyond environmental footprint, economic resilience, and social prosperity, with sustainability at the center of industrial transition [22–24].

Modernization of the industrial sector in Europe, in this respect, increasingly plays a more vital role in the overall strategy for the EU to make its economy climate-neutral by 2050. The process of such development of European industry can be actively supported by various EU policies, such as climate and energy policy, by establishing clear long-term goals and market incentives under the ETS and newly launched CBAM. Besides these regulatory frameworks, there is an urgent call for industries to adopt principles in the circular economy that focus on maximizing the efficient use of natural resources [25].

Within this context, the industrial sector in Europe contributes to about 20% of value addition within the economy while being responsible for about 80% of the EU's merchandise exports. However, the sector generates about 20% of the EU's total greenhouse gas emissions. Therefore, the proper implementation of the European Green Deal clearly needs a substantial shift from fossil fuel sources to clean, predominantly renewable forms of energy. As a matter of fact, this transition is quite imperative in aligning industrial energy consumption with the ambitious targets stipulated in the wider economy so as to ensure achievements in climate neutrality goals [26,27].

The different legislative measures established by the European Union for advances in its decarbonization initiatives include one of the most important: the EU Emissions Trading System, known as EU ETS, specifically designed to reduce carbon emissions from industrial activities. In recent years, ambitious decarbonization has become a real driving point of European policy—a wide variety of different activities, ranging from the private business sectors to public organizations and agencies. Such collaborations are made with a view to drastically reduce the carbon footprint arising from organizations, as well as from the products thereof [28,29].

This drive toward deep decarbonization reflects a holistic approach from the regulatory frameworks, innovative technological solutions, and collaboration among stakeholders. Acceleration, as one of the hallmarks of the multi-element approach, focuses on targets not just for reductions in emissions but also even for a broader cultural shift toward sustainability along various sectors. It follows, then, that increasingly adopted organizational practices improve energy efficiency by deploying cleaner methods of production and initiating sustainable supply chain practices. This integrated decarbonization commitment is crucial for the attainment of EU climate objectives over the long term and will ensure a resilient, sustainable economic future for the region [30].

Achieving net-zero carbon emissions necessitates replacing carbon-intensive technologies with innovative alternatives. The steel industry is part of the energy- and carbon-intensive sector, playing a crucial role in this transition. Steel producers are active participants in the European dialogue on industrial decarbonization [31]. Investment in new steelmaking technologies (low-carbon or even zero-carbon) in the steel sector needs to be significantly accelerated in order to achieve a net-zero emissions (NZE) scenario by 2050. The steel sector must transition from BF-BOF technology to DRI-EAF technology and incorporate the use of green hydrogen H₂-DRI-EAF [32–39].

Investments that reduce CO₂ emissions from steel production are one of the key criteria for evaluating industry development strategies. Global average CO₂ emissions (was 1.91 tons per ton crude steel in 2022 [Global CO₂ intensity of emissions = (BF-BOF CO₂ intensity 2.33 × BOF share in world production 72%) + (Scrap EAF CO₂ intensity 0.68 × EAF share in world production 21%) + (DRI-EAF CO₂ intensity 1.37 × DRI-EAF share in world production 7%)). According to the formula, CO₂ emissions intensity via production pro-

cesses was BF-BOF 2.33 tons/ton crude steel cast, scrap-EAF 0.68 tons/ton crude steel cast, and DRI-EAF 1.37 tons/ton crude steel cast (world crude steel production with DRI is not yet being reported; the denominator for this calculation was, therefore, estimated by the WorldSteel data management team from data held in the WorldSteel collective databases) [13]. Figure 1 displays the global CO₂ intensity of emissions during the period 2007–2022.

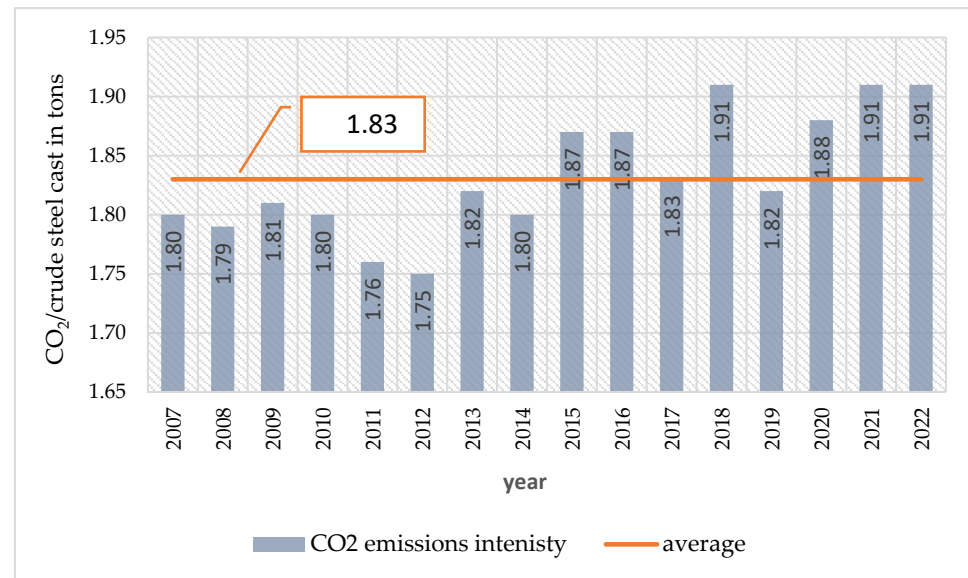


Figure 1. Global CO₂ emissions intensity per ton crude steel. Source: own elaboration based [11].

The Blast Furnace (BF) and Basic Oxygen Furnace (BOF) processes, while notably energy-efficient, are associated with substantial CO₂ emissions [40–44]. It is important to note that emission levels differ across countries, typically ranging from 1.8 to 4.0 tons of CO₂ per ton of crude steel [45]. For instance, China records emissions of 1.84 tons CO₂/tons, the EU 1.81 t CO₂/t, while South Africa and India exceed 3.8 tons CO₂/t [40,44]. According to WorldSteel (2024), the global average CO₂ emissions from steel production in 2023 were as follows [46]:

- BF-BOF: 2.33 t CO₂/ton of crude steel;
- DRI-EAF: 1.37 ton CO₂/t of crude steel;
- EAF: 0.68 t CO₂/ton of crude steel.

For comparison, carbon dioxide emissions from the Polish steel industry are nearly 1 ton lower per ton of steel produced (Figure 2). However, steel production in Poland is almost evenly split between two technological routes, EAF and BF-BOF, each accounting for approximately half of the total annual output. When comparing these two production methods, the BF-BOF process is significantly more carbon-intensive, contributing over 80% of total emissions per ton of steel. Specifically, the BF-BOF route generates an average of 1.35 tons of CO₂ per ton of steel, as illustrated in Figure 3. Therefore, it is this technology that must be replaced by a new, low- or zero-emission alternative [47–49]. Moreover, the technological trends (Industry 4.0/Industry 5.0) toward smart manufacturing in the steel industry are strongly linked with the decarbonization of used technologies [49].

Achieving the deep reductions in CO₂ emissions necessary to meet climate goals will inevitably require a fundamental transformation in the production of iron and steel. In this context, state-of-the-art technologies, such as DRI-EAF, are being actively developed alongside other innovative approaches. Despite the challenges, progress continues, particularly with recent advancements in H₂-DRI applications. However, the portfolio of announced low- and near-zero-emission initiatives remains significantly below what is

required to achieve the NZE Scenario [30–36]. Alarmingly, approximately two-thirds of all global projects announced to date still depend on high-emission practices. This highlights a major shortfall in the decarbonization of steelmaking and underscores the urgent need for greater investment and innovation in cleaner technologies. More than that, there is a need for teamwork among all those involved in the iron and steel industry: policymakers, manufacturers, and researchers. It may involve the promotion of low-emission technologies, increasing research and development, and facilitating knowledge sharing down the value chain. Only in this way can the industry bridge the gap between ongoing initiatives and ambitious reduction targets that will be consistent with a sustainable future.

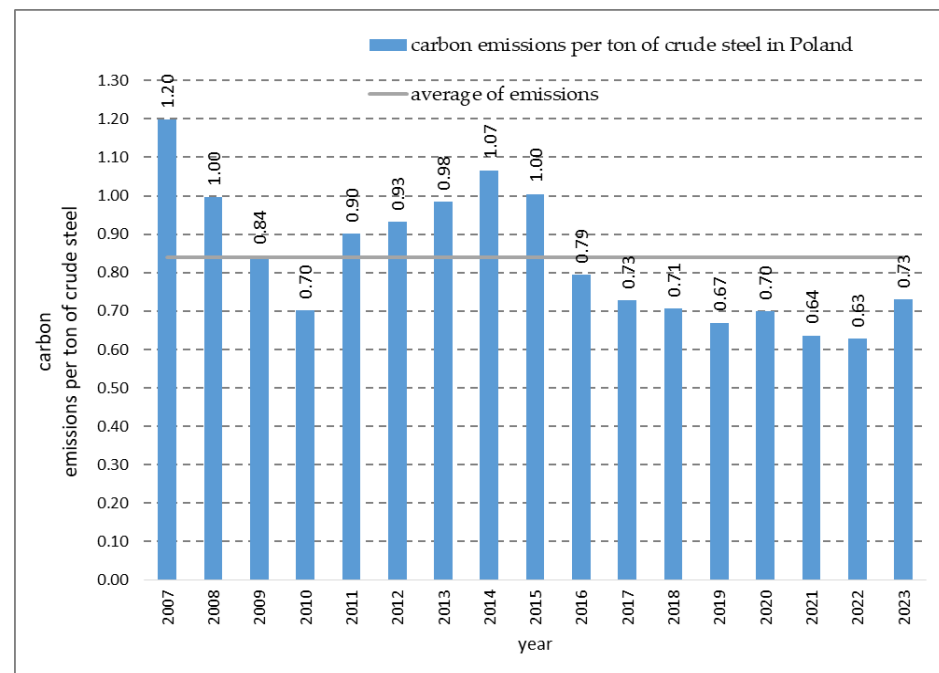


Figure 2. CO₂ emissions intensity per ton of crude steel in Polish steel industry. Source: own elaboration based on data from Polish Steel Association, Poland, Katowice [13].

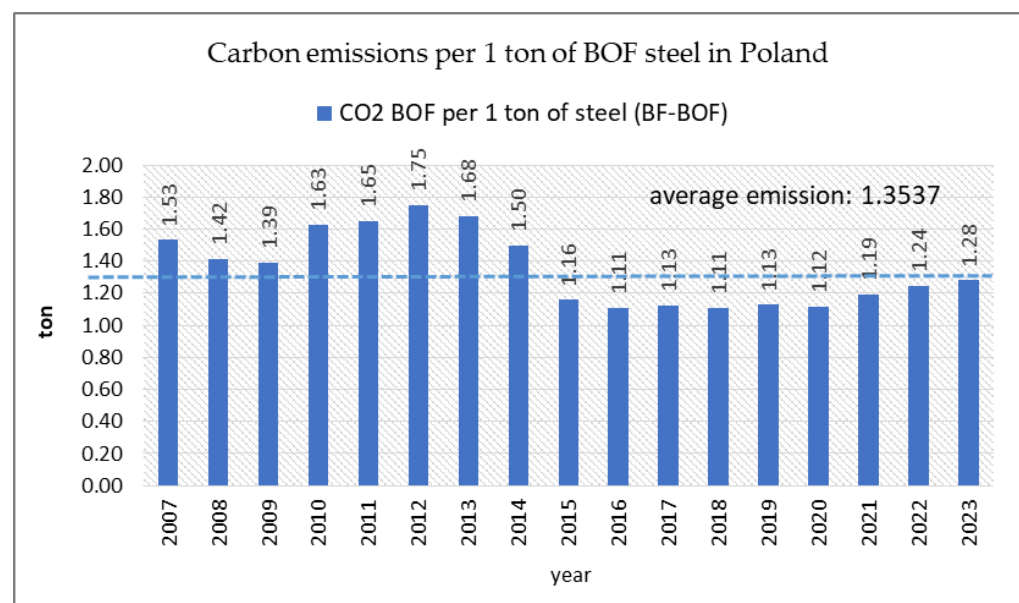


Figure 3. CO₂ emissions intensity per ton of BOF steel of Polish steel industry. Source: own elaboration based on data from Polish Steel Association, Poland, Katowice [13].

Steel production accounts for 2.6 Gtons of CO₂ emissions, equivalent to approximately 7% of anthropogenic greenhouse gas emissions [36]. When considering the CO₂ emissions associated with electricity consumption from the grid, the CO₂ emission factor for primary steel is 4.5 times higher than that for steel produced from scrap. The decarbonization of the steel industry has adopted baseline strategies such as replacing BF-BOF technology with DRI-EAF technology and advancing H₂-DRI. This approach is transformative, as it requires substantial investment in carbon-neutral technologies. However, not all steel mills will be able to implement it immediately. Carbon Capture, Utilization, and Storage (CCUS) technologies are also under development. The choice between these strategies depends on various factors and the broader context of each situation. Additionally, the implementation of carbon capture and storage (CCS) technologies can complement transitions to carbon-neutral solutions.

CCUS means the suite of technologies deployed over the past two decades, which captures, utilizes, and stores carbon emissions produced either from power generation or industrial processes [38]. That is well off the 1.7 billion tons the International Energy Agency estimates will be needed by 2030 if net-zero goals are to be met—a number despite that agency's emphasis on the urgent need for expanded capture. CCUS implementation in the process of industrial decarbonization is a canalization investigation that is very capital-intensive; infrastructure development, for example, may involve pipelines that would transfer captured carbon from production sites to storage sites [50,51].

Deep decarbonization is now real, instead, for most firms in the industry. Companies that extract and process fossil fuels as part of their core business are under strong pressure to begin shifting investments to low-carbon or breakthrough zero-carbon technologies. Companies should not consider such resulting decarbonization policies as a constraint but rather an opportunity for growth. Competitive advantages that will appeal to both ecologically sensitive consumers and business partners come with the identification of green energy solutions and smart usage management. This requires intra-organizational cooperation on various levels of life cycle assessment (LCA) [51–53].

Recently, the attention of enterprises has been paid to sustainable development, adding the requirements, regulations, and standards of environmental protection into the operational policy and strategy. Even today, in the context promoted for more than a decade everywhere in Industry 4.0, the potential is still large in green manufacturing initiatives. The integration of green and smart manufacturing concepts, therefore, is greatly underlined by the coming paradigm of Industry 5.0 as well, emphasizing decarbonization and minimum impact on the environment throughout the value chain. Decarbonization policy is one of pro-activity and a strategy for Industry 4.0 or Industry 5.0 [54]. Adequate financial wherewithal needs to be given to businesses for investment in moving their decarbonization process forward. One notices that, compared to low-carbon manufacturing, these transition pathways differ in some respects, the fact that early movers are usually pioneers and large capital groups seize opportunities opened by European funding programs. Table 1 summarizes the process of steel industry decarbonization.

Table 1. Key challenges of steel industry decarbonization.

Direction	Realization of Decarbonization
DRI [32–38,54–58]	This would be the shift from the traditional processes in a Blast Furnace to DRI processes that use either natural gas or hydrogen as their reducing agents. This is quite a process that involves huge investments in new technologies and equipment, infrastructural development at various levels to build technologies for the production and distribution of hydrogen, dealing with regulatory issues, and finding partnerships for low-carbon hydrogen. This would imply that skill development and training of the workforce in new technologies and practices are intrinsic to successful implementation. A few of the major challenges identified with this pathway are the high initial capital costs, availability and price of renewable hydrogen, and requirements for full-scale risk assessments associated with new technologies.
DRI-EAF [32,35,59–61]	Promotion of EVs, hydrogen-powered vehicles, and other low-emission transport modes. Investment in Charging Infrastructure and Renewable Fuels. Emission standards for vehicles and incentives on cleaner transportation technologies. Improvement in the energy efficiency of the EAFs through renovation by renewable sources of energy, better energy use, and advanced recycling of steel materials. Application of artificial intelligence and machine learning for operational efficiency and energy consumption during EAF processes. Major bottlenecks are intermittent renewable energy supply, huge investments needed in grid infrastructure, and possible disruptions in supplies of raw materials. Development and scaling of hydrogen-based DRI technologies to replace fossil fuels in iron reduction processes. It involves securing low-cost, sustainable hydrogen supply chains, further improvement in electrolyzes for hydrogen production, and stakeholder relations across industries for a seamless transition.
H ₂ -DRI [32–38,62–64]	Research and investment need to be performed to overcome technical hurdles and improve efficiencies in the H ₂ -DRI system. Further, supportive policy frameworks will be matched with government incentives in the nascent phases of hydrogen adoption. The currently very low production capacity of green hydrogen, technological advances in cost, and potential hostility from sectors vested in traditional fossil fuel technologies are some key challenges.
CCS/CCUS [65–68]	Climate Policy to Reduce Industrial Process Emission by CCS (carbon capture and storage) and CCUS (Carbon Capture, Utilization, and Storage). Major infrastructure investments are required for the capture of CO ₂ , development of options for storage, and regulatory compliance. Companies will have to develop economic incentives and public acceptance if CCS/CCUS is to be viable and attract investors. There will certainly be a need to develop an effective monitoring and verification system to track the effectiveness of CCS/CCUS deployments in order to engender trust and confidence. Some of the other challenges include long lead times on project development, the intractability of geological storage solutions, and public skepticism over the safety and efficacy of carbon storage.
Smart steel manufacturing [68–72]	On occasions when cleaner methods of production are introduced, energy efficiency and emission intensity measures are applied. Advanced manufacturing technologies would be deployed with investments in digital twins and IoT sensors to optimize production and reduce waste. It is also very critical that measures to reduce the carbon footprint of these digital technologies themselves are put in place. This will involve incorporating renewable energy into the manufacturing operations and setting emission reduction targets for the wider adoption of sustainable supply chain practices. This will encourage a culture of continuous improvement and innovation that, in turn, will make further adoption of new practices and technologies for reduction in emissions within the organizations. Key challenges here come from initial investment costs for smart enabling technologies, skilled labor to manage and maintain these systems, and integration of digital solutions into existing manufacturing processes without disturbance to productivity.
Recycling and circular economy [73–75]	Improve recycling practices in the steel industry to maximize scrap reutilization, thereby reducing raw material extraction and processing. This will involve developing an efficient collection and sorting system for scraps, investing in advanced technologies for recycling, and deploying full closed-loop systems with minimal generation of waste. The application of the circular economy will support companies in their effort to reduce their carbon footprint and create new business opportunities at the same time. Other major challenges facing the development of recycling activities are the continual quality of recycles, changing market prices for scrap material, and consumer awareness to actively participate in the recycling processes.
Sustainable supply chain management [76–78]	All along the value chain of the steel supply chain, embed sustainable best practices to reduce the carbon footprint emissions resulting from the extraction processes of raw materials down to transportation and processing. This shall be performed through engaging the suppliers to entice them toward low-carbon practices, optimizing all the logistical involvements with a view to reducing carbon emission levels arising from transportation, and deliberately choosing only those materials with the least negative impacts on the environment. This, in turn, will drive sustainability emphasis in procurement decisions down the value chain for decarbonization. The complexities range from the intricate nature of supply chain networks to lack of transparency or traceability in sourcing materials to increasing costs for more sustainable alternatives.

Table 1. *Cont.*

Direction	Realization of Decarbonization
Alternative ironmaking technologies [79,80]	Research into alternative production methods for iron that are not based on carbon-intensive processes. This could include technologies such as molten oxide electrolysis, which replaces carbon with electricity during iron ore reduction. Each of these newer processes requires significant investment in research and development to achieve reduced emissions. Additionally, partnerships with universities and startups create enabling technologies. The major hurdles to be surmounted are the scalability of replacement technologies, the heavy investments required for R&D, and the resistance to changing established operations and habits.
Energy and heat efficiency [81–85]	Decarbonizing the steel industry must be closely aligned with energy conservation and efficiency efforts. As an energy-intensive sector, the steel industry is compelled to invest in energy-saving technologies. The increasing demand for energy and its rising cost is a major challenge for the steel industry. To overcome them, the large amounts of coke oven gas, Blast Furnace gas, and converter gas generated in steel production can be captured and used for efficient energy production.
Resources efficiency and ULCOS [86,87]	Steel production, as a functional element, requires innovative and sustainable solutions. Implementation of an operating permit that not only results in the impact of this machine on the environment but also its competitiveness when using ecological modifications, such as maximizing steel recycling, reducing water consumption in production processes and improving its quality after use, minimizing the amount of waste and effective management of by-products, increasing the share of renewable energy sources in energy sources as an alternative to fossil fuels and implementation of breakthrough technologies—technologies such as ULCOS (Ultra-Low-Carbon Steelmaking) are key to dramatically reducing emissions.
Energy transition [88–92]	Transitioning the use of renewable feedstock in steel manufacturing processes instead of consuming fossil fuel is possible. This would involve using wind, solar, and biomass sources to generate energy in production. Companies have to understand their pattern of energy consumption and identify areas where the renewable share of energy can be increased. Long-term PPA with renewable energy suppliers would be a strategic tool for assuring their stable supply. Some major challenges involve the initial capital investment in renewable energy infrastructure, dependence on meteorological phenomena for its generation of energy, and grid stability in the transition process.
Digital transformation [93–98]	Big data analytics, artificial intelligence, and machine learning might be other facets of digitalization that further optimize areas such as production processes, thereby reducing energy consumption and increasing efficiency. Regarding emissions, a decrease is foreseen from the application of digital tools in decision-making and resource management, among others. Some other important challenges are the assurance of skilled personnel to implement and manage the technology, data security and privacy, and disruption of traditional methods once new technologies are integrated.

Source: own analysis on the basis of [32–38,55–98].

3. Materials and Methods

3.1. Data Used for Analysis

The empirical foundation of this research is built on data from the industrial sector and reports published by institutions responsible for data collection in Poland, including the Central Statistical Office (GUS) and the Polish Steel Association (HIPH). These sets of data were critically evaluated in terms of relevance and adequacy to tackle the core issues of the research. The statistical information, which was primarily drawn from annual reports, provided a general overview of the domestic steel industry. When examining the effect of investment in technology on CO₂ emissions in steel plants along the BF-BOF (Blast Furnace—Basic Oxygen Furnace) production route in Poland—also adjusting for the level of electricity and coke consumed along the route—the analytical methods such as descriptive statistics and econometric models were employed. The latter enabled testing of interdependencies among selected variables. The sequence of methodological steps applied within this study is presented in Figure 4.

The analysis concerns the Polish steel industry. The time scope of the analysis was 2005–2021. Industry data on CO₂ emissions in steel production in the Polish steel industry were used for the analysis. The data were CO₂ emissions intensity by total production and by technological processes, with BF-BOF steel production being important due to its high CO₂ emissions and the inclusion of this technology in the decarbonization policy. Data

on CO₂ emissions intensity were analyzed in a time series arrangement, annually for the period from 2005 to 2021, and then econometric models were developed, the essence of which was to look for a relationship between CO₂ emissions and realized investments. Investments were described by cumulative innovation expenditures from 2005 to 2021 in PLN. Data used for econometric analysis are presented in Table 2.

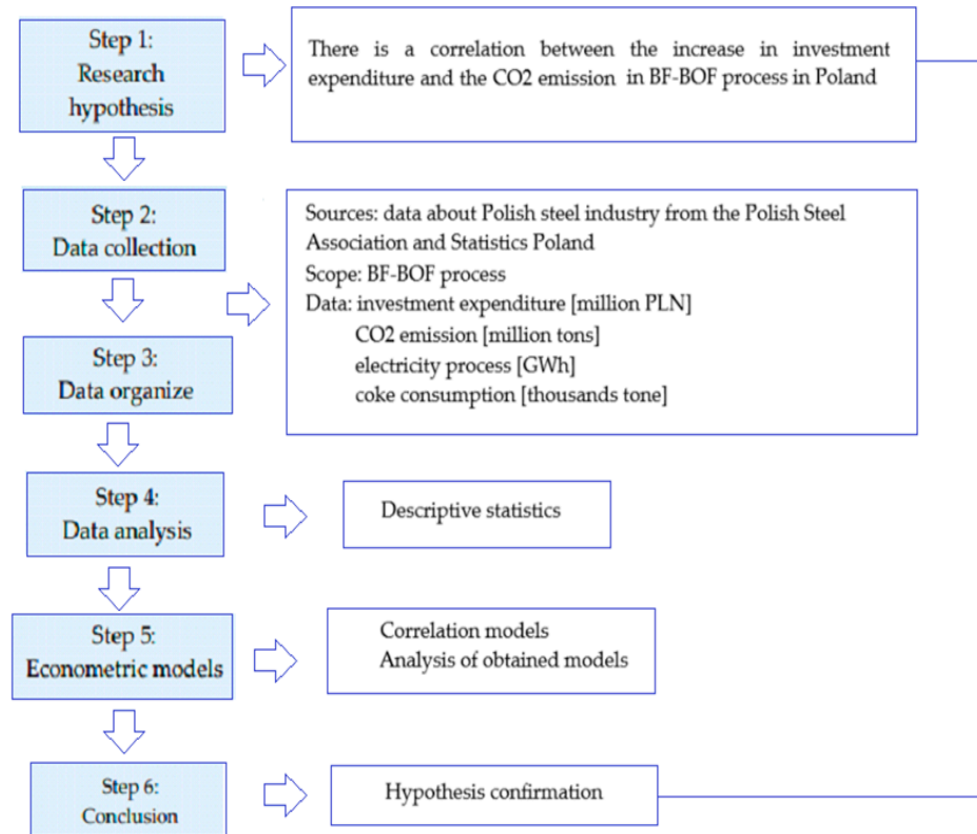


Figure 4. Research methodology. Source: own elaboration.

Table 2. Data used for econometric models.

Year	Investment Total PLN Million	Investment BOF PLN Million	CO ₂ Emissions Total Million Tons	CO ₂ Emissions BOF Million Tons	Coke Consumption BOF Thousand Tons	Energy Intensity BF-BOF GWh
2005	1619 *	809.5	12	10.4	2055.8	423.4424
2006	3130	1716.1	12	10.7	2549.5	685.2082
2007	5152	2828.2	11	9.5	3056.8	682.9585
2008	7146	3924.9	8	7.4	2520.9	563.7123
2009	8840	4856.6	5	4.5	1561.2	441.5064
2010	9324	5098.6	7	6.5	1824.7	546.683
2011	10,023	5448.1	8	7.3	1878	628.7919
2012	10,625	5749.1	8	7.4	1732.7	613.3564
2013	11,200	6036.6	8	7.4	1897.8	585.9563
2014	11,750	6311.6	9	7.6	2539.9	649.4591
2015	12,400	6636.6	7	6.2	2279.9	672.1254
2016	13,230	7051.6	7	5.9	2192.6	655.5415
2017	13,760	7316.6	7	6.4	2190.7	692.7339
2018	14,630	7751.6	7	6.0	2236.3	659.8022
2019	15,426	8237.6	6	5.5	2066.4	671.1065
2020	15,846	8412.6	5	4.4	1637.5	518.0972
2021	16,402	8780.6	6	4.8	1738.6	546.1651

* investment expenditures up to 2005 were accumulated from 2000 and subsequent years (cumulative annually). Source: own elaboration based on [99].

3.2. Overview of Steel Production and Emission Intensity in Poland

The average annual steel production in Poland from 2005 to 2021 was 8.9 million tons of steel. Figure 5 illustrates the trend of steel production in Poland, which is juxtaposed with CO₂ emissions in the Polish steel industry.

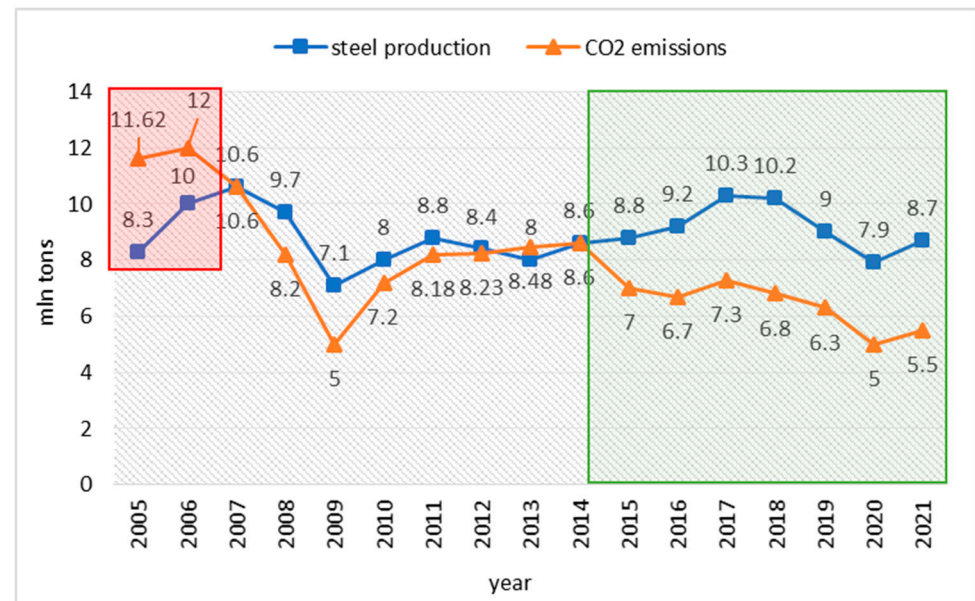


Figure 5. Steel production and CO₂ emissions in Polish steel industry in the period 2005–2021. Source: own elaboration based on [13].

The Polish steel industry uses two steelmaking technologies, namely BF-BOF and EAF. In the analyzed period of 2005–2021, the average annual steel production using BF-BOF technology was 4.8 million tons, while the remaining steel of 4.1 million tons was produced using EAF technology. For every 1 ton of steel produced in Poland in 2005–2021, there were 0.89 million tons of CO₂ emissions. The highest levels of CO₂ emissions were recorded in 2005–2007. It cannot be assumed that the higher the steel production, the higher the CO₂ emissions because in 2017–2018, more than 10 million tons of steel were produced in Poland each year, and CO₂ emissions were lower than in 2006–2007. Since 2014, CO₂ emissions have been declining compared to production volume. Was the downward trend of CO₂ emissions in Poland a result of technological innovation? The answer to this question is the aim of the research (RQ1).

The share of BF-BOF technology in CO₂ emissions was 88.8% (average annual share from 2005 to 2021). Figure 6 illustrates the shares of the two steelmaking technologies in Poland in CO₂ emissions. The BF-BOF technology is carbon-intensive. In the BF-BOF process, the average annual CO₂ emissions amounted to 6.94 million tons. Although, in the second decade of the current century, CO₂ emissions in the BF-BOF process did not exceed the level of 10 million tons, as in 2005–2006, emissions were high. In comparison, the average annual CO₂ emissions in the EAF process do not exceed 1 million tons, amounting to 0.87 million tons per year (average emissions for the period 2005–2021). In contrast, the lowest levels of CO₂ emissions in the BF-BOF process were in 2009 (4.5 million tons) and 2020 (4.4 million tons) [13].

Three environmental aspects describe BF-BOF technology: (i) CO₂ emissions (Figure 7a), (ii) coke consumption (Figure 7b), and (iii) energy intensity (black energy consumption, mainly /63% electricity is produced from coal in Poland [10]) (Figure 7c). The trends are presented in Figure 7a–c.

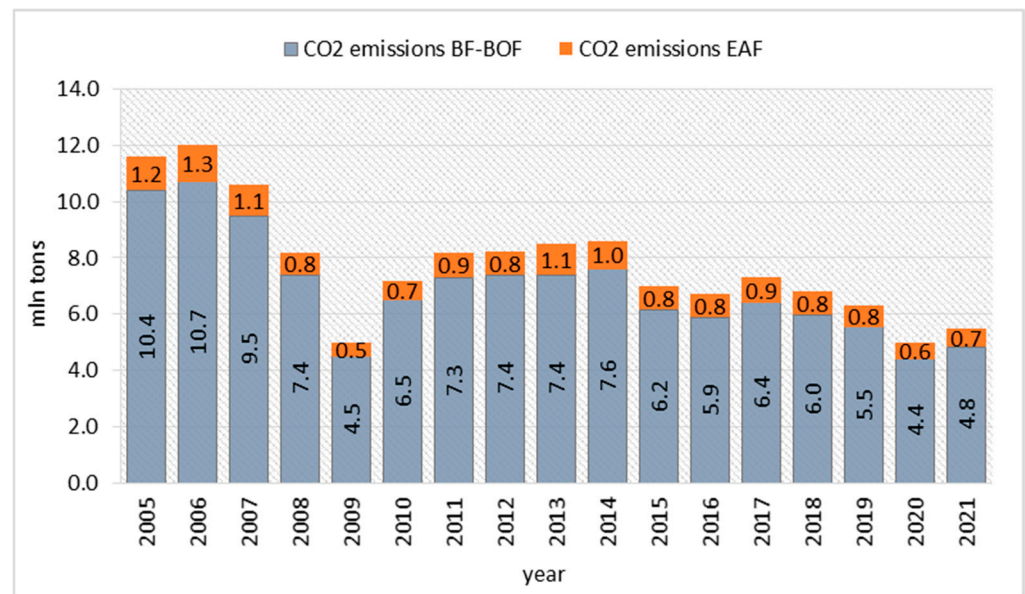


Figure 6. CO₂ emissions intensity in Polish steel industry in the period 2005–2021. Source: own elaboration based on data from Polish Steel Association, Poland, Katowice [13].

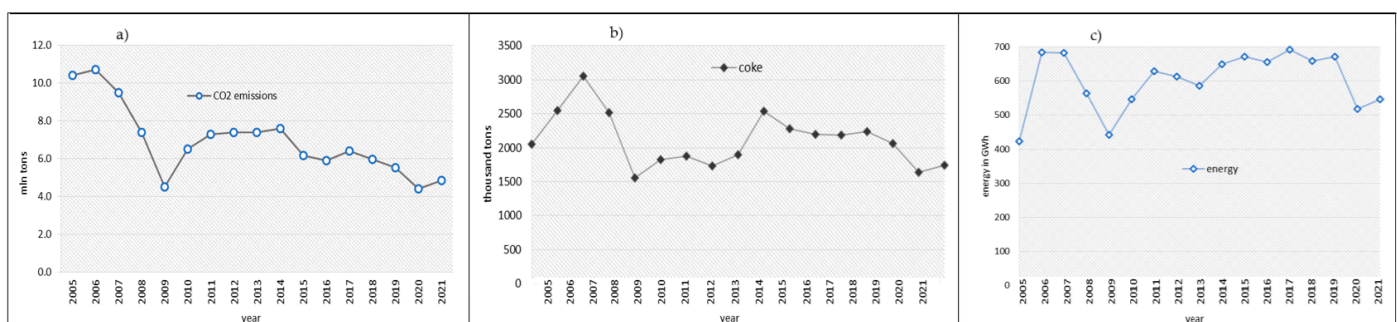


Figure 7. Three environmental aspects in BF-BOF process in Polish steel industry in the period 2005–2021. Source: own elaboration.

After comparing the three trends (Figure 7), it can be concluded that in 2005–2008, both the emissivity of BOF technology, as well as energy consumption and coke consumption, were high. At that time, Poland produced more than 10 million tons of steel per year (Figure 3), of which the BOF technology analyzed accounted for more than 50%. As production declined, the trends of energy intensity, coke intensity, and carbon intensity of the BOF process in Poland flattened. In 2020, then Poland produced 7.8 million tons, including 3.9 million tons with BOF technology, emissivity, and energy, and coke demand was the lowest. The conclusion is, therefore, obvious that the decline in steel production was causing a decline in the negative environmental trends of the steel sector in Poland. However, a research question arises RQ2: whether the decrease in CO₂ emissions was also influenced by technological investments made in the BF-BOF process. To answer this question, econometric modeling was performed on the basis of the data included in Table 2.

Based on the deliberations presented, we formulate the following research hypotheses:

RH1. *In the long term, the increase in investment expenditure (understood as the development of the company's assets) affects the decrease in CO₂ emissions in the steel industry.*

RH2. *The BF-BOF technology is in the declining phase of its life cycle, and further investment will not result in a radical decrease in CO₂ emissions.*

The main theoretical grounds for the formulation of hypotheses are embedded in the general conceptualization of deep decarbonization, or not just incremental efficiency gains but structural, revolutionary industry change. As the paper's literature review discusses, the steel industry—responsible for some 7% of global CO₂ emissions—is required to transition from carbon-intensive technologies such as the BF-BOF process to other low-carbon technologies such as hydrogen-based Direct Reduced Ironmaking with Electric Arc Furnaces (H₂-DRI-EAF) [15,18,19,32–38]. This is necessitated by international agreements such as the Paris Agreement, which place pressure on industries to attain climate neutrality targets. The theoretical fundament in this regard is an appreciation that sustainability should involve environmental, economic, and social pillars and, therefore, needs policy coordination, system-level redesign, and innovation rather than piecemeal technological adaptation.

Another theoretical context for the hypotheses of research is the technological lock-in and path dependency phenomenon through which certain industry technologies, despite their inferior emissions level, remain superior technologies due to investments in historic infrastructure, institution arrangements, and market experience [100–106]. This is seen in the Polish steel industry via sustained dependence upon the BF-BOF route, which, as seen in the article, still produces approximately half of national steel output and more than 80% of associated CO₂ emissions. This lock-in makes additional investment within the BF-BOF process less efficient as technology remains in the mature phase. The presumption that growing investment in BF-BOF will not bring radical emissions cuts (RH2), therefore, receives robust theoretical backing in those models that assume that mature technology possesses an innate resistance to revolution even when boosted by investment in capital [107–111].

Institutionalized policy and economic incentives constitute the third theoretical plane for the hypotheses. European Union decarbonizing instruments, namely CBAM and the ETS, signal the accelerating sunset of the high-carbon industry with internalization of the green cost of carbon and launching sustainability competition [20–22,25,26]. The literature of the paper includes the argument that these mechanisms are not regulative but strategically instrumental in navigating the industry toward climatic goals. Investments based on policy tools such as these will increasingly be channeled into revolutionary innovations as opposed to legacy systems. Therefore, the hypothesis that long-term investment must be in transformation technologies in an effort to significantly curb CO₂ emissions is theoretically sound in policy-led industrial development sustainability. These are the theoretical foundations of the two study hypotheses: investment will curb emissions (RH1), but its effect is curbed by BF-BOF technology (RH2).

The adopted hypotheses were supported by both trends and arguments in the literature and previous research. Reducing CO₂ emissions of the Polish steel industry is included in the country's strategic goals [7]. Steel mills in Poland invest in technologies to reduce the influence on the environment [112,113]. The largest realized investments were in the second half of the first decade of the 21st century, then the average annual investment spending in the Polish steel industry exceeded 1800 million PLN [114]. In the long term (from 2005 to 2021), the average annual investment spending was 900.65 million PLN.

According to Gajdzik et al. [81], realized investments in 2000–2019 contributed to a decrease in the energy intensity of the steel industry in Poland. In the econometric models presented in this publication [81], the following correlations were obtained: an increase in investments by PLN 1 million in eclectic steel mills will reduce electricity consumption in the production of EAF (Y) steel by 60 GWh or—an increase in investment outlays in enterprises producing steel in electric furnaces by PLN 1 million will lead to a decrease in unit electricity consumption by 16.8 kWh/1 ton of crude steel, with other factors remaining

unchanged in analyzed models. Wolniak et al. [82] show that investments in the Polish steel industry improve energy intensity indicators in the Polish steel industry. In the model presented by Wolniak et al. [82], the value of correlation (Pearson) is negative (-0.50963511), so an increase in investment by a unit results in a decrease in the energy intensity of industry by 0.50963511 unit.

3.3. Approach to Econometric Models

The data set presented in Table 2 was used as the foundation for econometric modeling. The process of modeling proceeded in a scientific step-by-step method, beginning with model specification, involved defining explanatory and dependent variables, determining the appropriate form of the model, citing data sources, and providing formal reliability. The statistical information was subsequently analyzed and determined appropriate for constructing robust models. The parameter estimation, presented in Table 3, was carried out with the static sample of Table 2. Validation of the model was carried out by amalgamating coefficient analysis with the application of standard econometric tests. This enabled logical inference as to the effect played by the explanatory variables on the dependent variable(s). The method of parameter estimation chosen was the least squares method. It is a flexible method and one that does not necessitate strong stochastic assumptions. For application purposes, the licensed EXCEL software—and specifically its regression utility—was employed.

Table 3. Structures of the obtained econometric models.

No.	Econometric Model	Components	R ²
1.	$Y = -0.00039X_1 + 11.9999$	Y—CO ₂ emissions (data for Polish steel industry) [million tons] X ₁ —investment expenditure cumulatively (data for Polish steel industry) [PLN million]	R ² = 69.8
2.	$Y = -0.00069X_1 + 10.8747$	Y—CO ₂ emissions from BF-BOF process (data for Polish steel industry) [million tons] X ₁ —investment expenditure on BF-BOF cumulatively (data for Polish steel industry) [PLN million]	R ² = 73.2
3.	$Y = -0.00059X_1 + 0.0015X_2 + 7.2146$	Y—CO ₂ emissions from BF-BOF (data for Polish steel industry) [million tons] X ₁ —investment expenditure on BF-BOF cumulatively (data for Polish steel industry) [PLN million] X ₂ —consumption of coke in BF-BOF (data for Polish steel industry) [thousand tons]	R ² = 81.1
4.	$Y = -0.00076X_1 + 0.00817X_2 + 6.3591$	Y—CO ₂ emissions from BF-BOF (data for Polish steel industry) [million tons] X ₁ —investment expenditure on BF-BOF cumulatively (data for Polish steel industry) [PLN million] X ₂ —electricity consumption in BF-BOF [GWh]	R ² = 86.0

Source: own elaboration.

In order to perform static verification, the following actions were performed: the coefficient of determination (R), the coefficient of fit (R²), the F-statistic in the overall evaluation of the model's fit, the coefficient of expressiveness, and the Student's t-statistic as a measure to check the significance of individual parameters. In addition to that, simple statistical tests were executed. Application of these methods over each of the constructed models ensured their suitability and compliance with the empirical data.

Using econometric modeling methodology, the models defined explanatory variables and explanatory variables for one-parametric and two-parametric models. After evaluating the statistical significance of the models, four were selected from among the models tested and are presented in this publication. The presentations of the models started from one-

parametric (linear) to two-parametric linear models. Table 3 presents the structures of the econometric models.

Table 3 presents four econometric models describing the relationship between CO₂ emissions and explanatory variables in the Polish steel industry, with a special focus on the BF-BOF production path. Each model is based on the same data set for the years 2005–2021, yielding 17 annual observations per model. In Model 1, where the impact of total cumulative investment in the steel industry on overall CO₂ emissions is measured, the 17 observations yielded a relatively modest explanatory power ($R^2 = 69.8\%$), indicating that while investment is linked to emissions decrease, the relationship is not robust if all technology pathways are combined. Model 2, focusing on BF-BOF process investments and the respective emissions, uses the same 17 data points but reaches a higher explanatory power ($R^2 = 73.2\%$). This rise vindicates the analytical focus on the most carbon-intensive path. Model 3 introduces an additional variable—coke consumption—and, using the same 17 observations, explains 81.1% of the variance in emissions, showing that energy-related input factors significantly improve model precision. Lastly, Model 4, which replaces coke consumption with electricity consumption using the full 17-year dataset, has the best explanatory power ($R^2 = 86.0\%$), showing that energy input type and level are of paramount significance in reproducing emission dynamics in BF-BOF production. Throughout the four models, the 17 observations give statistical comparability and consistency, allowing the limits of incremental investment in established technology, as well as the need for revolutionary industrial changes, to be demonstrated clearly and empirically.

4. Results

The subject of our study was to confirm or reject the thesis that investment expenditure decreases CO₂ emissions in the BF-BOF process. The linear models are used in the analysis (Table 3).

Model no. 1 presents the dependence of CO₂ emissions and investment expenditure on process technology for the Polish steel industry. In the model, we analyze all steel plants, both with the EAF and BF-BOF technologies. This model is presented in the Formula (1):

$$Y = -0.00039X_1 + 11.9999 \quad (1)$$

where

Y —CO₂ emissions in total steel production [million tons];

X_1 —investment expenditure cumulatively (total steel plants in Poland) [PLN million].

Figure 8 illustrates the results of research.

The trend in CO₂ emissions (Figure 8) is downward, with no apparent fluctuation, with continued investment. According to the one-factor linear model (1):

increase in investment → decrease in CO₂ emissions.

In accordance with Model 1, an increase in the investment expenditure (X_1) in the Polish steel industry by unite [million PLN] will result in a decrease in CO₂ emissions in steel production (Y) by 0.00039 million tons.

The projected average CO₂ emissions for Model 1 were 7.86 million tons. This forecast is higher than the average emissions, which were 7.81 million tons. Thus, the model is inaccurate (this model obtained the low $R^2 = 0.689$, so the next were analyzed) and useless for explaining the essence of deep decarbonization because it used total investment. Meanwhile, in the Net Zero Strategy, technological innovation in steel mills with the BF-BOF process is key.

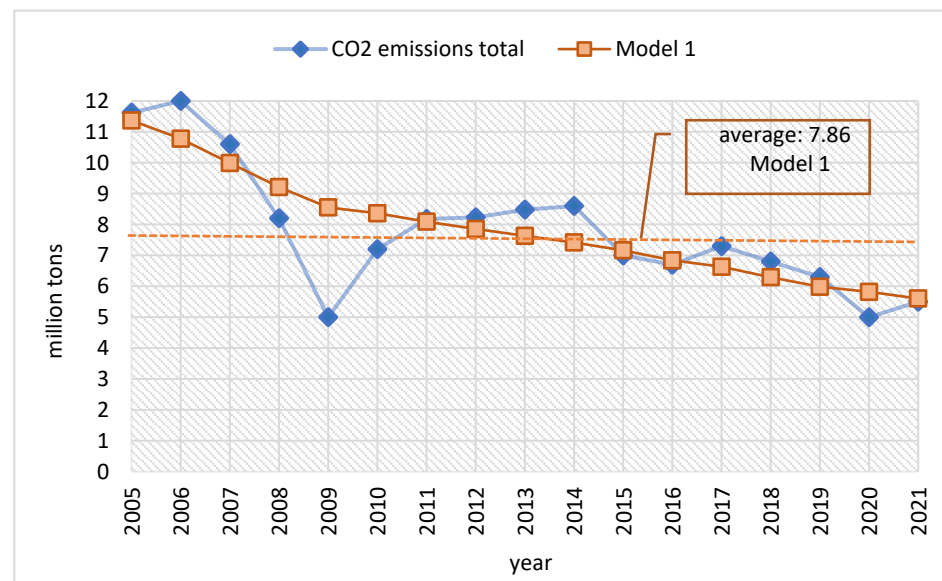


Figure 8. Comparison of total CO₂ emissions with the ex-post forecast based on model with investment expenditure on technology in the Polish steel industry. Source: own analysis.

Parameters in the next model were CO₂ emissions from the BF-BOF process and investment expenditure on the BF-BOF technological process in the Polish steel industry. The next is a one-factor linear model (2):

$$Y = -0.00069X_1 + 10.8747 \quad (2)$$

The model captures the relationship between CO₂ emissions in the BF-BOF process (denoted as Y , measured in million tons) and cumulative investment expenditures in the same process (denoted as X_1 , in million PLN). Compared to model (1), this version demonstrates an improved fit. The coefficient of determination (R^2) stands at 0.732, indicating that 73.2% of the variability in CO₂ emissions is accounted for by the explanatory variable. This suggests a strong model fit, further supported by the values $R = 0.8557$ and adjusted R^2 (R^2_d) = 0.7144. The standard error (Se) is 0.9972. An assessment of parameter significance, conducted using the Student's t -statistic, yielded a result of $t = -6.4$ for the variable X_1 , with a significance level of $p < 0.01$, confirming that X_1 is statistically significant. Figure 9 presents a comparison between the observed empirical trend and the ex-post forecast trend derived from model (2), visually demonstrating the model's predictive capability.

Based on the econometric models (interpretation of model parameters), the following relationships were formulated:

Increase in BOF investment → decrease in CO₂ emissions in BOF.

In accordance with Model (2), an increase in the investment expenditure (X_1) in the BF-BOF process by unite [million PLN] will result in a decrease in CO₂ emissions in the steel production of BF-BOF (Y) by 0.00069 million tones.

The model (Model 2) is better than Model 1 because it focuses on the BF-BOF process, but the decrease in CO₂ emissions is still too small with the current state of investment in the BF-BOF process. Therefore, it can be concluded that the technology has already reached maturity and is in the declining phase of the technology life cycle. The average CO₂ emissions from the model are the same as for the actual data (comparable); the actual emissions were 6.9381 million tons, and in model 2, they were 6.9390 million tons. Subsequent models

were, therefore, investigated, in which further explanatory parameters were expanded, i.e., variables describing the steel production process using BF-BOF technology.

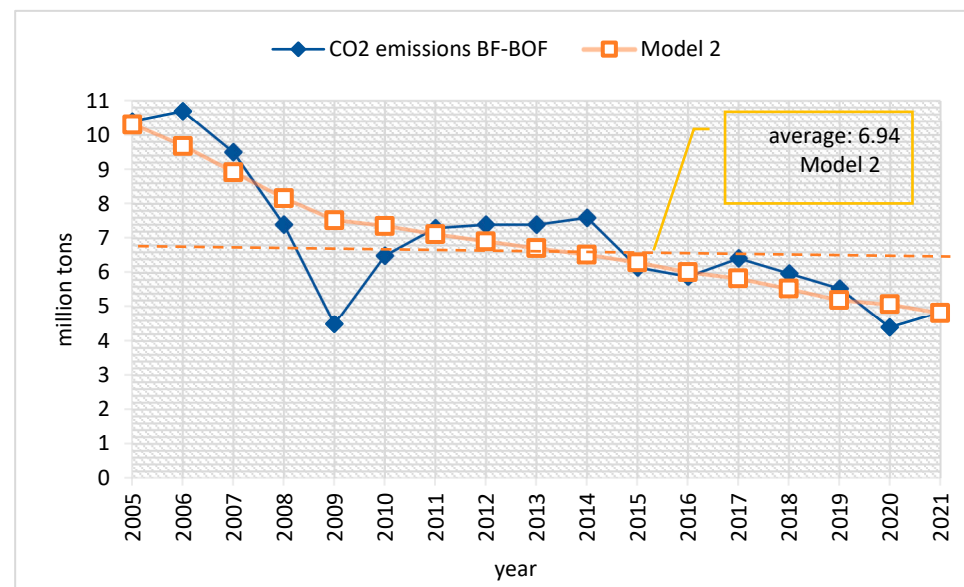


Figure 9. Comparison of actual CO₂ emissions from the BF-BOF process with an ex-post model-based forecast with investment expenditures for BF-BOF technology in the Polish steel industry. Source: own analysis.

The third model (two-factor model) represents the dependence between the CO₂ emission, investment expenditure, and coke consumption in the BF-BOF process in Poland.

$$Y = -0.00059X_1 + 0.0015X_2 + 7.2146 \quad (3)$$

Model (3) demonstrates a high degree of conformity with the empirical data, explaining 81.1% of the variability in the dependent variable Y ($R^2 = 0.81467$). The model's goodness of fit is further affirmed by the adjusted R^2 value of 0.9808 and a low standard error (Se) of 0.017016, indicating a high level of precision in the estimates. Both explanatory variables included in the model are statistically significant: the investment expenditure variable X_1 shows a t-statistic of -5.7 with a significance level above 99% ($p > 0.99$), while coke consumption (X_2) yields a t-statistic of 2.4 at a significance level exceeding 95% ($p > 0.95$). According to model (3), an increase in investment expenditure (X_1) in the BF-BOF process by one unit (i.e., 1 million PLN) while keeping the second variable—coke consumption (X_2)—constant, results in a reduction of CO₂ emissions (Y) from BF-BOF steel production by approximately 0.00059 million tons. This reflects a direct and measurable inverse relationship between capital investment and emission levels within the simplified framework of the model.

Increase in BOF investment → decrease in CO₂ emissions in BOF.

An increase in coke consumption by 1 thousand tons (X_2) in the BF-BOF process will increase CO₂ emissions in the production of BF-BOF (Y) steel by 0.0015 million tons, with the first factor remaining unchanged, which is the investment expenditure in this model (X_1):

Increase in coke consumption in BOF → increase in CO₂ emissions in BOF.

Figure 10 illustrates the trend of empirical data and the trend of the ex-post forecast obtained on the basis of model (3).

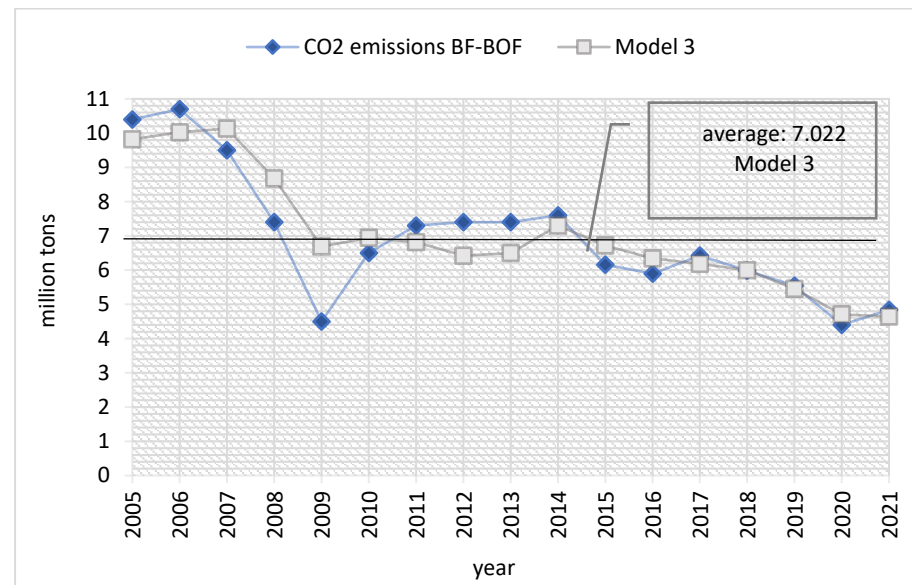


Figure 10. Comparison of the actual CO₂ emissions from BF-BOF process with the ex-post forecast based on model with investment expenditure and coke consumption in the BF-BOF technology in Poland. Source: own analysis.

In this model (Model 3), the average CO₂ emissions are higher than the actual data. The average CO₂ emissions were 7.022 million tons. BF-BOF technology in Poland is based on coke, and it was included in the model. If there were another reductant, for example, hydrogen, which is the reductant in DRI technology (H₂-DRI), then CO₂ emissivity would decrease. So, this confirms the hypothesis (RH2) that this technology is in the declining phase of its life cycle.

Hypothesis 2 (RH2) that “the BF-BOF technology is at the mature stage of its life cycle and additional investment will not result in a spectacular decline in CO₂ emissions” was not directly tested or formally established under the framework of the econometric models presented in the paper. Rather, its examination is predicated on indirect inference derived from the description of the model estimates, i.e., the marginal declining impacts of investment on the abatement of emissions.

The econometric models (Models 1–4) primarily estimate the magnitude of the correlation between investment expenditure (independent variable) and CO₂ emissions (dependent variable), either individually (Models 1 and 2) or in conjunction with other variables such as coke consumption and energy consumption (Models 3 and 4). All models estimate the statistical robustness of these correlations using coefficients, R² values, and t-statistics. The models undoubtedly demonstrate that investment does contribute to emission reduction in the BF-BOF process. However, the rate of reduction is marginal. For instance, in Model 2, each additional 1 million PLN of investment reduces emissions by only 0.00069 million tons—an effect that, while statistically significant, is ecologically too minor in the context of deep decarbonization goals.

- The discovery that BF-BOF technology is in its decline phase and there will be no additional investments which will lead to drastic reductions in emissions is not the outcome of an independent statistical test. Instead, it is inferred from the following:
- The relatively low regression coefficients, especially in later models, suggest marginal environmental returns with high economic investment.
- The flattening of CO₂ reduction progress in the face of continued or even rising investment is exemplified by the time series analysis (Figures 9–11 of the paper).

- Comparison of predicted and actual emissions, and this yields little divergence and thus little scope for further emission improvement through the implementation of identical technology.
- Literature-based claims that BF-BOF, as a carbon-intensive technology on the basis of coke and coal, does not have much technical potential for further decarbonization unless fundamentally replaced (e.g., by DRI-EAF) [32–39].

The last is a two-factor linear model (4), which represents the dependence between CO₂ emission and investment expenditure and energy consumption in the BF-BOF process in Poland.

$$Y = -0.00076X_1 + 0.0081X_2 + 6.3591 \quad (4)$$

The model (4) is well fitted to the actual data, 86.03% of Y variability explained ($R^2 = 0.860271$), the coefficient of fit $R^2_d = 0.9808$, the coefficient of clarity $Se = 0.017016$, the parameter X_1 is significant ($X_1: t = 3.6$ for $p > 0.99$), and the parameter X_2 is significant ($X_2: t = -9.2$ for $p > 0.99$).

In accordance with model (4), an increase in the investment expenditure (X_1) by a unit [1 million PLN] in the BF-BOF process will reduce the CO₂ emissions in the production of BF-BOF (Y) steel by 0.00076 million tons, with the second factor remaining unchanged, which, in this model, are electricity consumption (X_2):

Increase in BOF investment → decrease in CO₂ emissions in BOF.

An increase in electricity consumption by 1 thousand tons (X_2) in the BF-BOF process will increase CO₂ emissions in the production of BF-BOF (Y) steel by 0.00817 million tons, with the first factor remaining unchanged, which is the investment expenditure in this model (X_1):

Increase in energy consumption in the BOF → increase in CO₂ emissions in the BOF.

Figure 11 illustrates the trend of empirical data and the trend of the ex-post forecast obtained on the basis of model (4).

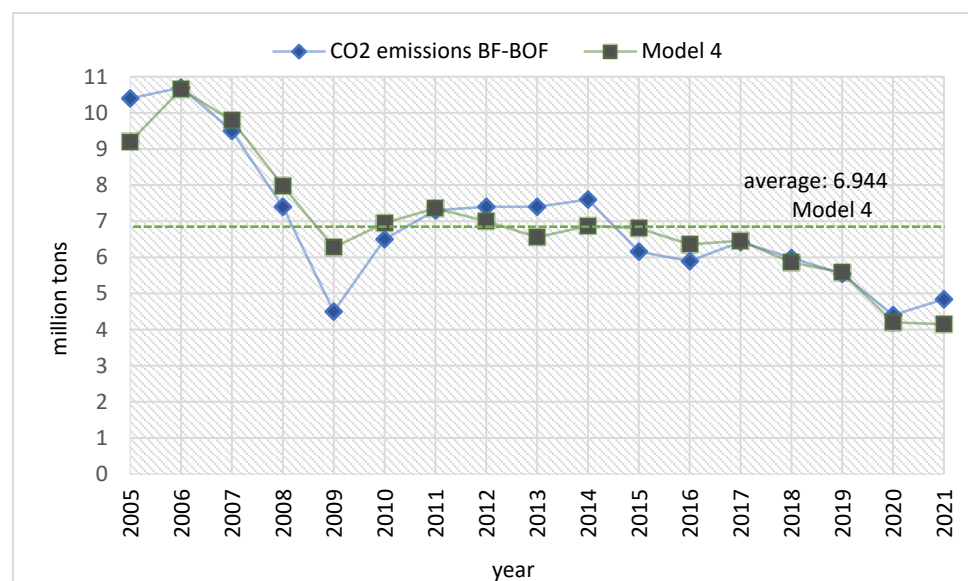


Figure 11. Comparison of the actual CO₂ emissions from BF-BOF process with the ex-post forecast based on model with investment expenditure and energy consumption in the BF-BOF process in Poland. Source: own analysis.

In the latter model, the average CO₂ emissions were 6.944 million tons, and the actual was 6.381 million tons. Electricity, as an explanatory variable in this model, unfortunately, influenced the increase in CO₂ emissions. The situation is caused by the dominance of black energy sources in Poland (63% of electricity was generated from coal in 2023) [10].

The implications of the results of this study are in line with broader trends in the literature, particularly for the modest, long-term scope for additional investment in high-carbon technology such as BF-BOF. Industrial deep decarbonization requires structural transformation rather than gradual innovation, as highlighted by the European Commission [3] and the Energy Roadmap 2050 [1]. The econometric analysis in this study confirms this hypothesis, demonstrating that while BF-BOF investment has yielded measurable reductions in CO₂ emissions, their size still falls short in the context of the EU's net-zero aspirations.

The theoretical argument presented by authors such as those in [15,20] and ref. [22] justifies the argument that industrial transformation must entail more than technical transformation—it must entail policy, economic, and social dimensions if it is to be sustainable. This is reaffirmed by the European Green Deal [3] and policy instruments like the CBAM regulation [4] that not only seek to internalize the environmental externality of carbon-intensive production but also seek to spur a shift to cleaner technologies.

Technologically, the world emission data published by the World Steel Association [14] testifies to the relative inefficiency of the BF-BOF pathway compared to the DRI-EAF and scrap-based EAF pathways. The worldwide average CO₂ intensity of BF-BOF is 2.33 t CO₂ per ton of crude steel, significantly more than scrap-based EAF at 0.68 t. Marginal abatement of 0.00069 million tons CO₂ per million PLN investment in BF-BOF, as shown here, reflects falling returns on investing in aging infrastructure—a motif repeated in [30,35].

Also, the technology path dependency and lock-in effects outlined in references [107–111] put the Polish steel sector's persistent reliance on BF-BOF technology into perspective. These theoretical constructs explain how older systems persist even when more sustainable alternatives exist. The Polish case, with almost half BF-BOF-based steel production, illustrates the institutional and infrastructural momentum that retards technological transition—even amid critical climate necessity.

Following the results in [62,63], the transition to hydrogen-based DRI (H₂-DRI) is considered a key route to zero-carbon steelmaking. Nevertheless, as described in [44,46], such a transition involves enormous capital investments, the establishment of renewable hydrogen infrastructure, and complementary industrial policies—all of which are beyond the scope of BF-BOF modernization. The literature, thus, backs the verdict that BF-BOF investment, although positive in the short term, is inadequate to achieve deep decarbonization. Instead, systematic reinvestment in greenfield technology and infrastructure appears not only preferable but inevitable.

It can be stated that evidence from this research, considered in the context of existing literature, loudly calls for a technological revolution. Gradual upgrading of carbon-based processes cannot serve as a proxy for radical change, particularly in industries such as steel, where emissions are embedded structurally. The Polish empirical record, thus, mirrors European and global expertise: heavy industry decarbonization needs to look beyond efficiency—it needs to be about reinvention.

The longer specification was employed to control for the potential omitted variable bias in the baseline specification and to render the estimated relations more realistic. More specifically, the amount of crude steel production was taken as a control variable, the reasoning that the amount of production is a fundamental determinant of carbon dioxide emissions in steel production. Unless variation in the scale of production is scaled, the effects due to technology investment can be exaggerated or confounded. Adding crude steel production to levels of BOF investment, the model attempts to identify an independent

effect of spending on modernization on emissions to improve the precision of the estimates and also allow the results to better reflect the underlying economic and technological processes involved.

Table 4 contains the data used for the following econometric analysis of carbon dioxide emissions in Poland's steel sector, which speaks of annual observations of total CO₂ emissions (million tons), capital expenditure on Basic Oxygen Furnace (BOF) modernization (million Polish zloty), and volume of crude steel produced (thousand tons) during 2005–2021.

Table 4. Extended econometric analysis of carbon dioxide emissions in Poland's steel industry.

Year	CO ₂ Emissions (Mt)	BOF Investments (M PLN)	Crude Steel Production (kt)
2005	11.62	264.0	8444.0
2006	12.00	906.6	9992.0
2007	10.60	1112.1	10,632.0
2008	8.20	1096.7	9728.0
2009	5.00	931.7	7129.0
2010	7.20	242.0	7993.0
2011	8.18	349.5	8779.0
2012	8.23	301.0	8358.0
2013	8.48	287.5	7950.0
2014	8.60	275.0	8540.0
2015	7.00	325.0	9198.0
2016	6.70	415.0	9001.0
2017	7.30	265.0	10,330.0
2018	6.80	435.0	10,157.0
2019	6.30	486.0	8996.0
2020	5.00	175.0	7856.0
2021	5.50	368.0	8552.0

The model attempts to investigate the impact of investment in the BOF process and the production level of crude steel on total carbon dioxide emissions in Poland's steel sector. Through the inclusion of crude steel production as a control variable, the model takes into account that the industry size (i.e., the production level) is a major determinant of CO₂ emissions. This extension reduces the likelihood of omitted variable bias and allows a more accurate estimation of the effect of technological investments. Including the control variable improved the model's explanatory power, although modestly ($R^2 = 0.196$).

The expanded econometric model is specified as follows:

$$\text{CO}_2\text{emissions}_t = \alpha + \beta_1 \times \text{BOF\_investments}_t + \beta_2 \times \text{crude\_steel\_production}_t + \epsilon_t$$

where

- CO₂_emissions_t represents the total carbon dioxide emissions from the steel industry in year t (in million tons);
- BOF_investments_t refers to the capital expenditures related to the modernization of Basic Oxygen Furnace (BOF) technology in year t (in million PLN);
- crude_steel_production_t denotes the volume of crude steel production in year t (in thousand tons);
- α is the intercept (constant term);
- β_1 and β_2 are the parameters to be estimated, capturing the marginal effects of the explanatory variables;
- ϵ_t is the random error term accounting for unobserved factors.

The augmented econometric model with BOF modernization expenditures and crude steel production as regressors performs somewhat better than the baseline model. The R^2 value of 0.196 shows that the model explains roughly 19.6% of CO₂ emissions' variance.

The positive coefficient sign for crude steel production conforms to theoretical expectations that increased production accompanies increased emissions. Similarly, the positive sign of BOF investment suggests technological advancements along the BF–BOF route may restrain the marginal role of sequential plans for modernization on emission control.

5. Discussion

Time series analysis from 2005 to 2021 and econometric modeling applied in this paper confirmed that the investments in the Polish steelworks, i.e., in BF–BOF, resulted in a measurable but moderate reduction of CO₂ emission and, therefore, confirmed hypothesis RH1. At the same time, the findings validate hypothesis RH2 that BF–BOF technology is at the maturity stage of its lifecycle and further investment brings incremental improvement rather than revolutionary emission saving. Statistical significance of the models supports the relation of investment to emissions reduction but the comparatively modest magnitude of the improvements confirms that deep decarbonization goals cannot be achieved through BF–BOF optimization alone.

Although cumulative investment has caused some environmental improvements, according to the statistics, trend analysis shows diminishing returns in the long term. Structural limitations in the BF–BOF process, i.e., its high carbon-based coke dependence, limit its long-term capacity for deep emissions cutting. As coke usage and energy intensity are interconnected with carbon inputs, deep decarbonization is not possible without a change of technologies. Additionally, while operational efficiency has been boosted by improvement measures such as energy-efficient Blast Furnace operations, digital monitoring systems (i.e., digital twins, IoT sensors), and waste heat recovery systems [115,116], the incremental improvements fall short in the extent of transformational changes necessary to meet EU “Net Zero” aspirations [117–119].

The conclusions thus compellingly suggest going beyond incremental improvements in technology to an overall industrial transformation. The transition to low-carbon steel-making routes, particularly the H₂–DRI–EAF route with green hydrogen, is a feasible avenue to decarbonization depth [32,84,116–118]. Financing for BF–BOF, albeit traditionally justified, cannot achieve emission savings in terms compatible with decarbonization deep policies any longer [120–123]. Hence, the Polish steel industry has to shift its investment attention toward disruption technologies while setting aside a singular focus on incremental improvement in ongoing processes.

The present shift of strategy is synchronized with both the policy directions within the European continent as well as internationally toward in-depth industrial decarbonization [20–22,25,26,115,116]. Even though technological upgrades have been tied up with immediate efficiency gains, the EU Green Deal and SDGs clearly emphasize dramatic change. In this context, policy instruments like the EU ETS and CBAM gain added significance, pushing industries towards cleaner technologies like hydrogen-based DRI–EAF [36–38,62–64]. In the absence of this direction, there is a risk of technological lock-in in the Polish steel sector, where continued investment in incumbent carbon-emitting technologies strangles innovation and the ability to meet future climate targets [107–111].

These findings also vividly illustrate technological lock-in and path dependency [107–111]. BF–BOF process, well entrenched in the Polish steel industry’s infrastructure and investment culture, is a hindrance to technology change. Despite superior options, e.g., H₂–DRI, sunk costs, well-established supply chains, and institutional resistance prevent the transition. Because industries were originally built for coal-based operation, they structurally resist change, except when strategic interventions—technology as well as policy-based—enable a planned transition path [124–126].

The consequences extend beyond the technological and the environmental. Any deep decarbonization policy must adopt social sustainability, ensuring a just transition for workers and communities that rely on carbon-based steelmaking [127–130]. Faced with cumulative industrial restructurings, retraining programs, economic diversification, and public–private collaboration will be needed in order to prevent negative social repercussions. Green infrastructure investments such as renewable energy grids and hydrogen supply chains must occur in parallel with industrial change, offering long-term socio-economic resilience alongside environmental benefits.

In terms of investment strategy, the econometric models indicate that further investment in BF–BOF modernization would yield diminishing environmental returns. Even in the best econometric models, another 1 million PLN investment to BF–BOF only reduces emission by 0.00069 million tons of CO₂—what may be termed a negligible margin. With the energy mix of Poland still remaining coal-based, energy consumption on the BF–BOF route ironically does raise emission intensity, and the transition to renewables is all the more necessary [131,132]. This finding agrees with sustainability concepts on the basis of systemic change rather than marginal efficiency [133–139].

The study concludes that while previous investment in the BF–BOF process has resulted in marginal gains, true sustainability will only be realized if there is a paradigm shift at the industrial level. A transition to low-carbon steelmaking, namely hydrogen-based DRI–EAF technologies, is the only plausible path for positioning Poland’s steel sector on the EU’s net-zero agenda [39,55–64]. Future studies should take into account country-level comparative adoption of green steel technologies and policy systems that effectively steer systemic industrial changes, informing decision-making towards sustainable and resilient steel manufacturing [138–141].

6. Conclusions

This study aimed to explore two research questions for the relationship between technological investment and CO₂ emission in the BF–BOF steelmaking route of Poland. On RQ1, econometric estimation confirmed that total investment in the BF–BOF route over 2005–2021 was associated with a statistically significant, albeit not significant, reduction in CO₂ emission. More specifically, each additional million PLN spent cut CO₂ by 0.00069 million tons on average. However, the modest scale of the reductions implies that while investment improves the environment, it is not sufficient to achieve the radical emissions reductions needed for deep decarbonization. In the RQ2 instance, econometric modeling provided an appropriate way of depicting complex interdependences among investment, energy and coke consumption, and emission intensity. Multi-variable models explained up to 86% of emission variance, with great analytical power, while also depicting structural constraints of BF–BOF technology.

As the European Green Deal, achieving net-zero emissions by 2050 poses a gigantic challenge to industrial sectors, the steel sector being no different. Although technological investments have made the Polish BF–BOF process less emitting, barely profitable and carbon-dependent technology means that greater utilization of BF–BOF only will not be enough to attain climate neutrality goals. The findings confirm that BF–BOF technology is in the maturity phase of its life cycle with little room for CO₂ savings remaining, especially in such a coal-dependent country as Poland, where average emissions remained stable at 6.94 million tons annually over the period under consideration.

Achieving the EU’s “Net Zero” targets will, thus, require a deliberate transition to low-emission routes such as the DRI–EAF route. Most encouraging is the adoption of H₂–DRI technology involving the use of hydrogen as a zero-carbon reductant. Transitioning to DRI–EAF would not only decrease emissions by a significant amount but also position

Poland's steel sector to respond to more ambitious EU climate policies. Incremental BF–BOF modernization investments, as desirable as they may be, are no substitute for the industrial reconfiguration necessary to meet ambitious decarbonization targets.

The research implications for policy are strong for both policymakers and business decision-makers. Public policy must support clean technology creation and scale-up with direct subsidies for low-carbon R&D, regulations like the EU ETS and CBAM, and economic incentives. Policymakers must prioritize green finance, tax credits, and infrastructure investment to incentivize industrial decarbonization with the recognition that investment in incumbent BF–BOF technology yields decreasing carbon abatement returns.

Aside from the regulatory front, the transition also entails formidable social issues. With the reliance of most Polish regions on carbon-intensive steel production, an equitable transition plan is necessary. Re-employment schemes for workers, economic diversification strategies, and public–private partnerships must coincide with technological upgrading initiatives so that the transition becomes socially inclusive and economically feasible.

Last but not least, this research provides empirical validation that sequential investment in traditional steel technologies yields limited environmental returns in the context of net-zero targets. Comparative analyses of competing steelmaking technologies, with specific emphasis on the conditions under which DRI–EAF adoption is efficacious globally, represent a top priority for subsequent research. Lessons from experiences abroad can provide valuable insights into shaping Poland's decarbonization pathway and a sustainable, competitive steel sector in the decades ahead. A limitation of the study is the omission of control variables related to industry scale, such as total steel output or BF–BOF-specific production, which may confound the relationship between investment and CO₂ emissions. Also, the model does not account for the evolving policy landscape, particularly low-carbon transition policies, which likely influence both investment behavior and emission outcomes in the steel sector.

Author Contributions: Conceptualization, B.G.; methodology, B.G.; software B.G. and R.W.; validation, B.G. and R.W.; formal analysis, B.G.; investigation, B.G. and R.W.; resources, B.G. and R.W.; data curation, B.G.; writing—original draft preparation, B.G. and R.W.; writing—review and editing, B.G., R.W. and W.G.; visualization, B.G. and R.W.; supervision, B.G. and R.W.; project administration, B.G. and R.W.; and funding acquisition, B.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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