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An Econometric Model of the Operation of the Steel Industry in POLAND in the Context of Process Heat and Energy Consumption

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Abstract: The analyses presented in the publication allowed, on the basis of the data collected, development of an econometric model for the Polish steel industry from the point of view of the relationship between heat and energy management in the steel production process. The developed model is the main novelty of the paper. The main objective of the study was to develop an econometric model of Poland's heat and energy economy. The following research questions were raised: Is there an econometric model describing heat consumption (intensity) in the steel industry in Poland in relation to steel production and the energy economy? What are the relations between heat intensity and energy prices and steel production in Poland? How might the current energy crisis affect steel production? In the analysis we used data of energy and heat management in the Polish steel industry. An econometric model was developed of the dependence of heat consumption (Yt) on electricity prices (X1t) and steel production (X2t) in Poland. The authors took advantage of open access to data. Annual volumes of heat consumption in steel production processes in Poland were analysed as a function of the annual volume of steel production and the prices of electricity, which are consumed in technological processes in steel mills. We analyzed data for years 2004–2020. The analyses carried out showed that there is an inversely proportional relationship between electricity prices and the intensity of heat consumption by the steel industry. Research shows that rising energy prices lead to lower steel production. This is a dangerous phenomenon for the steel industry in the context of the current energy crisis caused by the pandemic and war in Ukraine. We think that the significance of our results is connected with the fact that the developed model is a useful analytical tool, as it not only allows the analysis of historical data, but can also be used to predict how steel industry parameters will change in the future under the influence of changes in external factors, such as energy prices. This gives a wide range of analytical possibilities for the use of the model.

Keywords: heat intensity; energy price; steel production; Polish steel industry; econometric model; statistical analyses; Industry 4.0

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1. Introduction

Industry's approach to the environment changed over the years. As recently as the last decade of the last century, economic entities did not take radical measures to protect the environment. Industrial activities based on uncontrolled exploitation of nature's resources and excessive emission of greenhouse gases into the environment could be noted [1]. The application of selective environmental measures in companies did not change quickly. State governments had to introduce tough environmental laws. High penalties and emission limits forced industry to reduce the amount of emissions, as well as contribute to investment in new sources of energy and heat. For many years, coal was the primary source of heat. European Union countries favour renewable energy sources (Directive RED II and RED III) [2]. The world highlighted the need for major sustainability reforms in industry. Active sustainable environmental policies were identified as an opportunity for global industrial development. The actions of highly developed countries are based on the assumptions of the green growth path, abbreviated as the green economy. "Green growth is the means by which the current economy can make the transition to a sustainable economy. It involves promoting growth and development while reducing pollution and greenhouse gas emissions, minimising waste and inefficient use of natural resources, maintaining biodiversity, and strengthening energy security. It requires further "decoupling" of environmental impacts from economic growth, and greening of consumption and production patters, while reducing poverty and improving health and jobs prospects. Green growth means making investment in the environment a new source of economic growth" [3]. A prerequisite for industrial development is environmental sustainability in line with the concept of sustainable development, which dates back to the 1970s [4]. Sustainable development is seen as the reconciliation of traditional economic growth with environmental considerations [5].

Rapid technological progress drew the attention of politicians to redefining sustainability and the positioning of the human factor in technological change. Based on the technology of Industry 4.0, the concept of Industry 5.0 was proposed by the European Commission. The pillars (paradigms) of the new industrial development concept are sustainable, human-centric, and resilient European industry [6]. The introduction of these key areas into technological progress means that EU Member States are striving to maintain a balance between rapid technological change based on intelligent process technologies and the development of the human factor and environmental protection. In Industry 4.0, technologies based on IoT, AI, cloud computing, etc. were strongly promoted. In Industry 5.0, attention was paid to the issue of sustainability, which, although respected in Industry 4.0, was not strongly emphasised [7].

In parallel with technical progress, a reorganisation of the human factor is being implemented in companies. In the fourth industrial revolution, human beings tightened their collaboration with computer and internet technologies [8,9]. In the industrial environment, human beings (H-CPPS) are introduced into cyber-physical manufacturing systems (CPPS) under construction [10–13]. Steel companies building smart manufacturing rely on advanced technologies that will increase productivity and human skill development on the one hand, and reduce resource (raw material) consumption and greenhouse gas emissions on the other. The fuel and energy economy is crucial to the development of the steel industry. The consumption of resources and energy in the steel industry impacts process productivity. Process productivity in the context of energy and carbon consumption in the steel industry was written about by Marshall [14], Wang and Tang [15], Panigrahi [16], Maddalena [17], Saha [18], Aha [19], Serebrennikova [20] and Kuriakose and Kuriakose [21], among others.

The importance of heat and energy management in steel mills was the basis for the authors to make an econometric model based on data describing heat and energy management in the Polish steel industry in the period 2004–2020. The following research hypothesis was adopted in the study: H: there is a strong statistical relationship between the energy and heat economy and steel production over time.

This paper consists of a literature part and a research part, created on the basis of empirical data describing the heat and energy economy of the Polish steel industry, which were used by the authors to develop an econometric model in the form of the dependence of the examined factors. The literature part presents the results of other authors' research in the area of the productivity of heat and energy consumption in the steel industry, cited in the previous paragraph of the paper.

The aim of the study is to develop an econometric model of Poland's heat and energy economy. The following research questions were raised:

- Is there an econometric model describing heat consumption (intensity) in the steel industry in Poland in relation to steel production and the energy economy?

- What are the relations between heat intensity and energy prices and steel production in Poland?
- How might the current energy crisis affect steel production?

In our paper we try to find the answer for those research questions. We also try to analyse and discuss achieved result according to other results described in the literature.

2. Literature Review

2.1. Productivity of Processes in the Context of Energy and Heat (Carbon) Consumption in the Steel Industry

Problematical energy efficiency in iron steelmaking is very important from a productivity of steel production point of view. A very important problem is connected with the goal towards the reduction in energy consumption, costs, and various types of emissions in the process of steel production. It is in accordance with the EU decarbonisation policy to meet the global climate and energy goals. To achieve those goals and decrease the carbon dioxide emission of this industry, we should concentrate on energy usage and heat usage in the production of iron and steel [22]. Steel production is very energy intensive. However, some sophisticated energy management systems can ensure efficient usage and recovery of this energy through steelmaking processes. This very big amount of energy consumption in the steel industry leads to the situation of energy constituting a very significant amount of the cost of steel production (20% to 40%) [23]. Because of that, every improvement in energy efficiency results in significant reduction in production costs and can lead to improvement in the competitiveness of a steel plant.

Diversification of heat sources and energy generation is a key direction for industry development. European Union policies apply strict CO_2 emission standards and there is an obligation to produce green energy [2]. The EU virtually phased out 'dirty' technologies from many industries, including steel mills. The steel mills that survived rely on innovation, modernity, and competitiveness. The European Commission requires the steel industry to use innovative steelmaking technologies (DIR) and a sustainable supply chain. The sustainability strategy of the steel mills is continuously pursued and adapted to new legal, economic, and technological requirements [24]. Rapid technological advances forced companies to introduce the pillars of Industry 4.0 [25]. In the steel industry, changes were made to steelmaking processes, which became more flexible and autonomous through digitalisation [26–28].

Steel mills invested heavily in the automation and robotisation of production operations, installing equipment with artificial intelligence algorithms and augmented reality functions. Smart steel production, or actually, smarter a terms more commonly used in steel companies, consist of: big data analysis systems and techniques, real-time process control systems, data generated by sensors and machine sensors and RFID tags, technologies with machine learning algorithms and digital twin models, use of the Industrial Internet of Things (IIoT) and access to cloud services, incremental manufacturing technologies (steel products obtained from 3D printers), predictive maintenance systems, and decision-making systems with computer models and simulations of processes and products (prototyping, production line balancing) [26–31].

The technological and process changes introduced in the steel industry are in line with the vision of technological development of the European steel industry, which is formed by the following priority action lines (EC, March 2004) [32]: moving towards the integration of successive technological processes into a single line in order to: (i) reduce the amount of equipment and capital costs, reduce manufacturing time and production costs, achieve cost-effective production with reduced capacity, (ii) pursue the automation of production operations and invest in advanced technologies that reduce the physical effort of workers (steelworkers), (iii) increase the flexibility of manufacturing processes to enable the production in a cost-effective manner of many differentiated product ranges in a single production line, (iv) implement widespread introduction of process computerisation as applied to the control of technological parameters and the control of steelmaking and logistic processes, (v) apply statistical control of the quality of semi-finished products and products, and increase the productivity and efficiency of equipment by IT-computer maintenance systems, (vi) strive to reduce the unit consumption of energy and raw materials used in the manufacture of steel products, (vii) reduce to a minimum the harmful environmental impact of steelmaking technology, in particular, reducing CO_2 emissions at all stages of production, (viii) aim to reduce to zero the amount of unusable waste, i.e., waste that cannot be recycled or transformed into materials or products, (ix) aim to increase material yields at all stages of steelmaking, (x) aim to eliminate defective production, (xi) aim to minimise process waste and reduce production losses, and (xii) continue the improvement of steelmaking technologies.

The reduction in energy usage is a significant industry challenge. Due to the reduction in energy usage, the industry as a whole can go towards better efficiency of all processes. The activities that are very useful in this process of improving the energy efficiency of the steelmaking industry consist of the improvement of current steelmaking processes based on new technologies, developing new, better technologies, and improving material efficiency. Very important in this process is renewable energy used in steelmaking [33,34]. One of the very important methods of saving energy in this industry is connected with the production of steel, not from iron ore but recycled steel saves. This approach gives significant benefits in the case of energy consumption decrease. The technology gives the possibility of decreasing the amount of CO_2 emissions compared to production from iron ore [35].

Another approach to decreasing the amount of energy used in the steel industry is connected with the improvement of energy-efficient motors. Motors, similar to pumps, compressors, or fans, play an important role in the steel production technology line. Using better technology in motor efficiency systems, we can reduce the total amount of energy used in steel production [36].

The efficiency of steelmaking facilities from an energy point of view depends strongly on the production route, quality and type of iron ore and the quality of used coal, the technology in the plant, the steel production mix, and the material efficiency of the production processes [37,38].

Because the problem of energy efficiency is very important, governments and industries use various types of indicators to measure this phenomenon. When we try to measure energy efficiency, we can find two types of indicators: descriptive and explanatory [39]. Generally, descriptive indicators are used when someone wants to deal with the characteristic of the trend, which is measured by indicators. Those indicators can be estimated because of the lack of data. In energy efficiency, descriptive indicators are connected with thermos-physical, thermodynamic, and thermos-economic problems. Especially important from the business point of view are indicators connected with the thermos-economy. They are, for example, the ratio between the cost of the energy in the production process and the market value of products and services. In the literature are many examples of indexes that can be used to measure energy efficiency, for example, Salta [40], Xu and Flapper [41], Odyssee energy efficiency index [42], Sheinbaum [43], as well as Farla and Block [44]. Among these authors, particularly interesting is the methodology prepared by Farla and Block [44], because it was developed for the iron and steel sectorThey proposed methods on how to differentiate the product in their analysis. The particular weight used in the index was based on best practices in the production of iron and steel.

The typical technology used in melting operations is conventional combustion to heat transfer [45,46]. Because of that, the steel industry is the second largest sector of heat used in the world [47]. For now, fossil fuel, especially coal, is very important for steel production processes. Particularly, coking coal is very widely used in the steel industry [48]. Duda and Valverde think that to ensure the amount of supply necessary in today's steel production processes, new mines should be opened or the mining industry should develop new deposits in existing mines [49]. That research points out that using coal mines in today's steel production is not obsolete, and especially in times of energy crisis, should be used to achieve a sufficient supply of steel products [50,51].

The improvement of energy efficiency in existing plants can be achieved when we take into account keeping plants competitive and maintaining jobs [52]. It is especially important nowadays in the time of an approaching recession and rising prices of energy. The traditional approach of replacing coal energy by using gas energy in the process of energy production may be difficult due to the pandemic crisis and the war in Ukraine. The troublesome political situation can lead to slowing down the process of improving the efficiency of energy consumption in the steel industry and the transformation towards green steel production.

To decrease the amount of energy and heat usage in steel production the plant can use various technological approaches. The most worth mentioning, in this case, are [52,53]:

- The increase in transformer capacity
- Installation of supporting burner
- The reduction in the time of melting by injection of oxygen gas
- The reduction in melting time using the method of carbon injection
- Installation of scrap pre-heater
- Reduction in power-off time
- Installation of a new secondary smelting plant
- Reduction in tapping process temperature
- Optimum control of the input of electric power
- Reduction in heat loss by cooling water of technological furnace body
- Reduction in tap-to-tap time
- Improvement in air ratio
- Pre-heating of air combustion by waste heat recovery
- Lower discharging billet temperature
- Hot charge ratio improvement
- Heat loss from furnace wall reduction
- Prevention of loss of heat from openings, such as inspection ports or charging ports
- Insulation of water-cooled skid pipe reinforcement
- Regenerative burner introduction
- Improvement in rolling yield

Using those approaches, plants can decrease the amount of energy and heat used in production processes. It is especially important in the case of the present situation when we can observe a highly increasing level of prices of energy and all fossil fuels.

2.2. Sustainable Fuel and Energy Management in the Polish Steel Industry Report

The Polish steel industry travelled a difficult road to functioning in a market economy. In the 1990s, Polish steel mills embarked on restructuring programmes. The scope of the programmes was very broad from the privatisation of steel mills to the establishment of the foundations of market entrepreneurship [54]. One area of restructuring concerning environmental policy included a detailed classification of environmental aspects of steel companies [55]. In 2001, the Polish government enacted one of the most important legal requirements for environmental protection: the Act of 27 April 2001 Environmental Protection Law [56]. This law was aligned with EU requirements and the Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control, commonly referred to as the IPPC Integrated Pollution Prevention and Control Directive [57]. The steel industry in Poland had to strongly reduce the negative impact of metallurgical processes on the environment. Steel mills in Poland had to phase out the technology of steel production in open-hearth furnaces (steel production in open-hearth furnaces was in Poland until 2002) [54].

Legislative changes in the field of environmental protection, introduced in recent years, increased the number of legal acts in force. The surplus of acts created difficulties in enforcing them. Therefore, the European Union introduced the Industrial Emissions

Directive (IED) (24 November 2010) [58], the aim of which was to unify and consolidate existing community legislation on industrial emissions to improve the system for the prevention and control of pollution caused by industrial activities. In terms of energy intensity, the steel industry was obliged, similar to the rest of the Polish economy, to move in a low-carbon direction. The IED was introduced mainly through the need to comply with Best Available Technology (BAT) requirements and mandatory environmental impact reporting [57]. The steel industry also had to adapt to the requirements of the subsequent Emissions Trading System (ETS) periods (EU ETS period III from 2013 to 2020) [59]. The emission period from 2021 to 2030 is currently being implemented [60]. For this period, the Modernisation Fund was established, and its most important objective is to support economies (industries) to meet the target set at the EU level, to reduce greenhouse gas emissions by 40% in 2030 compared to 1990 [60]. Strategic documents published by the European Union emphasise the importance of environmental protection.

The Polish steel industry occupies a high position among industries in Poland in terms of CO_2 emissions—the fifth position after power and heat plants and the refining, cement, and chemical industries (Table 1). The share of the Polish steel industry in the total amount of CO_2 produced in 2021 is shown in Figure 1.

Table 1. CO_2 emissions in Polish industry by branches.

Branch	CO_2 Emissions (Tonnes)		2021/2020
	2020	2021	%
Main activity producer power plants	87,918,825	104,965,331	19.39
Main activity producer combined heat and power plants	21,692,971	23,635,764	8.96
Main activity producer heating plants	5,631,168	6,210,186	10.28
Industrial CHP plants	6,297,335	6,372,520	1.19
Cement industry	11,153,180	10,597,955	−4.98
Refinery industry	10,739,707	9,968,433	−7.18
Chemical industry	9,708,163	9,787,938	0.82
Iron and steel industry	5,289,065	5,813,034	9.91
Non-ferrous metals smelting	1,885,839	2,004,405	6.29
Sugar industry	1,166,264	1,133,573	−2.80
Wood-based industry	277,828	298,034	7.27
Coking industry	1,741,844	2,025,507	16.29
Mineral industry	35,070	35,830	2.17
Other industries	2,161,224	2,106,693	−2.52
Glass industry	2,053,338	2,283,326	11.20
Lime industry	1,600,969	1,797,803	12.29
Ceramics	1,017,156	1,102,688	8.41
Paper industry	1,359,473	1,328,832	−2.25
Total	171,729,419	191,467,852	11.49

Source: Statistics Poland (GUS), Warsaw, Poland. Environment 2021. Available online: www.stat.gov.pl, accessed on 10 September 2022 [61].

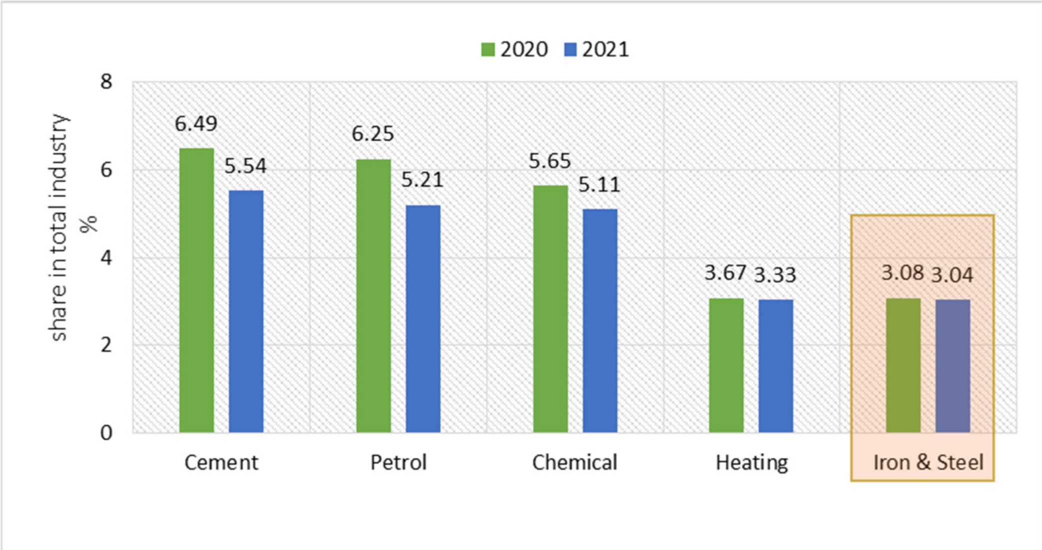

Figure 1. Share of Polish steel industry in total industry CO_2 emissions. Source: own elaboration based on [61].

In addition to reducing carbon dioxide emissions, its management is also an issue. In August 2013, the Polish Sejm passed a law on underground storage of this gas (CCS—Carbon Capture and Storage) [62]. The implementation of the act, at the current stage, includes the creation of research (pilot) CCS installations for the capture and sequestration (storage) of carbon dioxide. The method involves capturing the gas produced during the combustion of coal (coke), liquefying it, transporting it to a storage site and injecting it into an isolated geological formation for permanent storage [63]. In the Polish steel industry, steel production accounts for about 60% of energy demand. Lower is rolling (25%), sintering (9%), and the coking process (about 7%); including electricity (Figure 2). As the majority of CO_2 emissions in steel production are related to processes and the use of coal, emissions can only be reduced by improving the energy efficiency of the process [64].

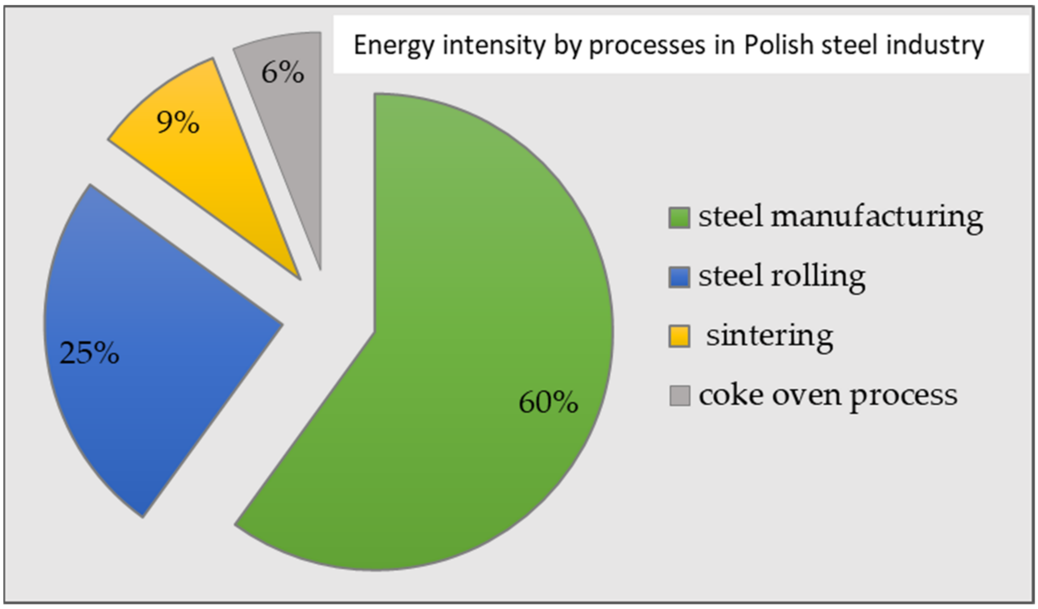

Figure 2. Energy intensity in Polish steel industry by process. Source: own elaboration based on Polish Steel Technology Platform (in Polish: PPTS) [64].

Among energy-intensive industries, iron and steel production ranks third after the chemical and petrochemical industries, and after the food industry (Table 2). The top four ranked industries (in terms of the largest shares of electricity in the total industry in Poland) together account for more than 50% (Figure 3). The highest rate of decrease in energy intensity of value added in 2020 compared to 2010 was observed in the machinery and textile industries, while an increase in energy intensity was observed in the metallurgical, food, paper, and transport equipment industries (Table 2).

Table 2. Electricity and energy intensity in Polish industry by branches.

Specification	Electricity	Specification	Energy Intensity in Value Added
	2020		Average Annual Change (2020 to 2010)
Branches	**Ktoe**	**Branches**	
Chemical and petrochemical	789	Machinery	−5.7%
Food, beverages and tabacco	639	Textilie	−3.9%
Iron and steel	479	Mineral	−2.6%
Non-metallic minerals	478	Chemical	−0.7%
Paper, pulp and printing	423	Wood and wood products	−0.2%
Machinery	406	Paper, pulp, and printing	0.3%
Transport equipment	255	Iron and steel	0.4%
Mining and quarrying	238	Food	0.9%
Wood and wood products	210	Transport equipment	2.9%
Non-ferrous metals	196		
Textilie and leather	50		
Construction	33		
Others	473	Others	−0.7%
Total	4670		

Source: Own elaboration based on: Efektywność wykorzystania energii w latach 2010–2020. GUS: Statistics Poland. (15 June 2022) [65].

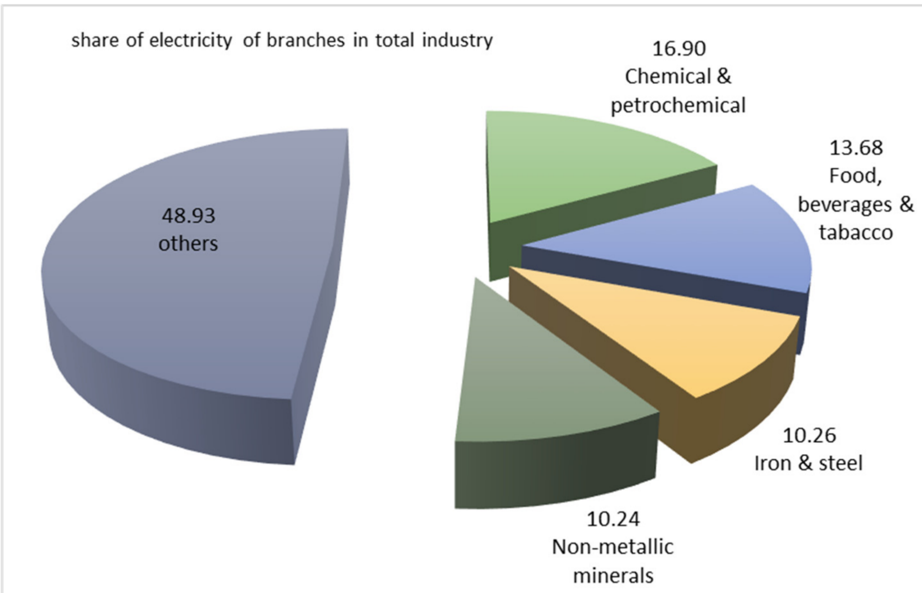

Figure 3. Shares of electricity in Polish industry by branches in total industry. Source: own elaboration based on: Gospodarka paliwowo-energetyczna w latach 2011–2020. Statistics Poland (GUS) [66].

The implementation of environmental restrictions in steel mills was accompanied by an increase in spending on technological investments. In the last decade (2011–2021), the total amount spent on investments was over PLN 7 billion (Figure 4). Annual investment expenditure ranged from PLN 400 to 900 million. A significant decrease in investment expenditure was recorded in the Polish steel industry in 2020, the pandemic period (COVID-19). Investment expenditure in the Polish steel industry, in the cited decade, was lower than in previous years. Going back in time, it was found that between 2004 and 2021, the Polish steel industry spent PLN 15.5 billion on investments. The highest investment spending, by far, was recorded in 2006–2009 (Figure 5).

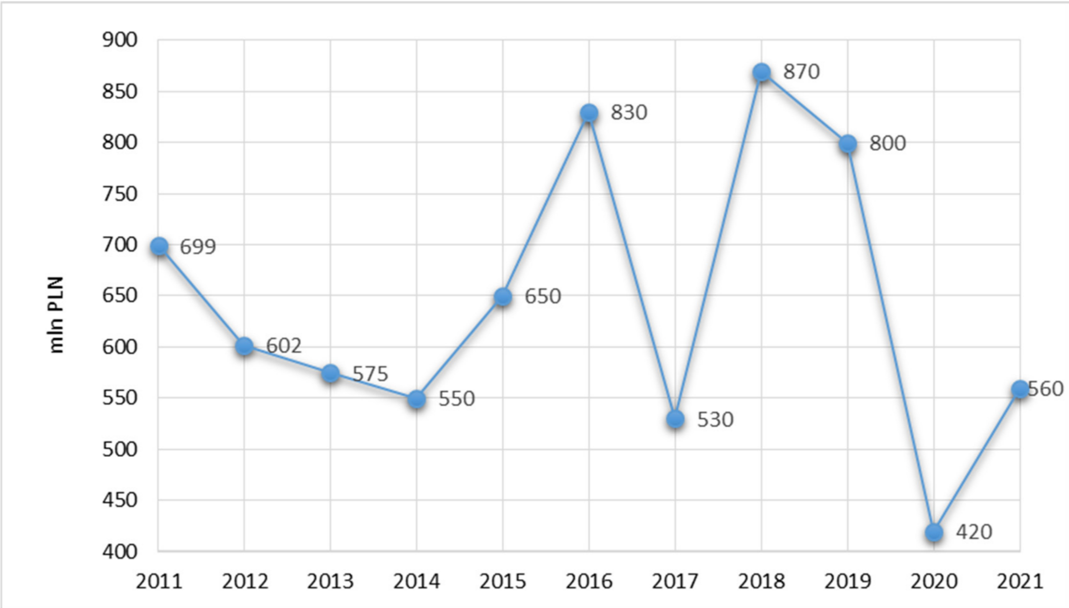

Figure 4. Expenditure on investment in the Polish steel industry in the last decade. Source: Polish Steel Association, Katowice, Poland [67].

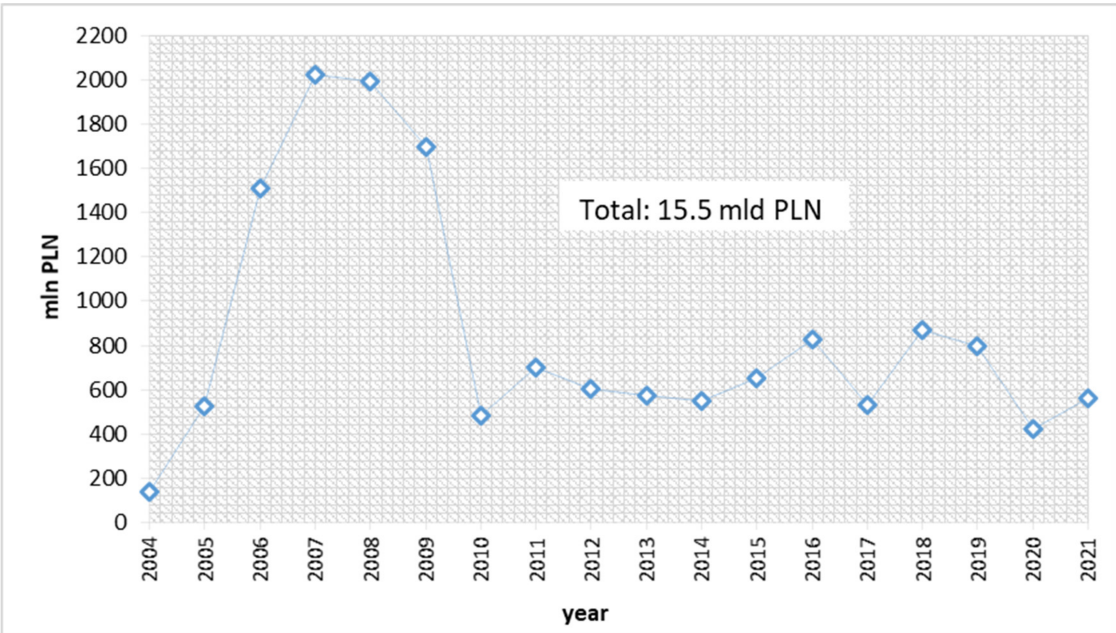

Figure 5. Expenditure on investment in the Polish steel industry from 2004 to 2021. Source: Polish Steel Association, Katowice, Poland [67].

Key technological changes in the Polish steel industry over the last two decades include: (i) the phasing out of the marten's steel melting technology (2002), (ii) the shortening of the length of production lines, (iii) the shortening of the production time of steel products [64], (iv) the increase in the share of scrap in steel production at the expense of iron ore, and (v) the reversal of the proportion of the share of electric and converter processes in the overall volume of steel production (in 2011 more than 50% of steel was produced in blast furnaces, in 2020 the share of BOF technology was close to the share of EAF technology in overall steel production and amounted to 50.1%, compared to 49.9% to EAF) [68]. Analysis of annual steel production by Electric Arc Furnace (EAF) and Basic Oxygen Furnace (BOF) processes over a long period shows slight fluctuations between the shares of both technologies in the total volume of steel produced in Poland (Figure 6).

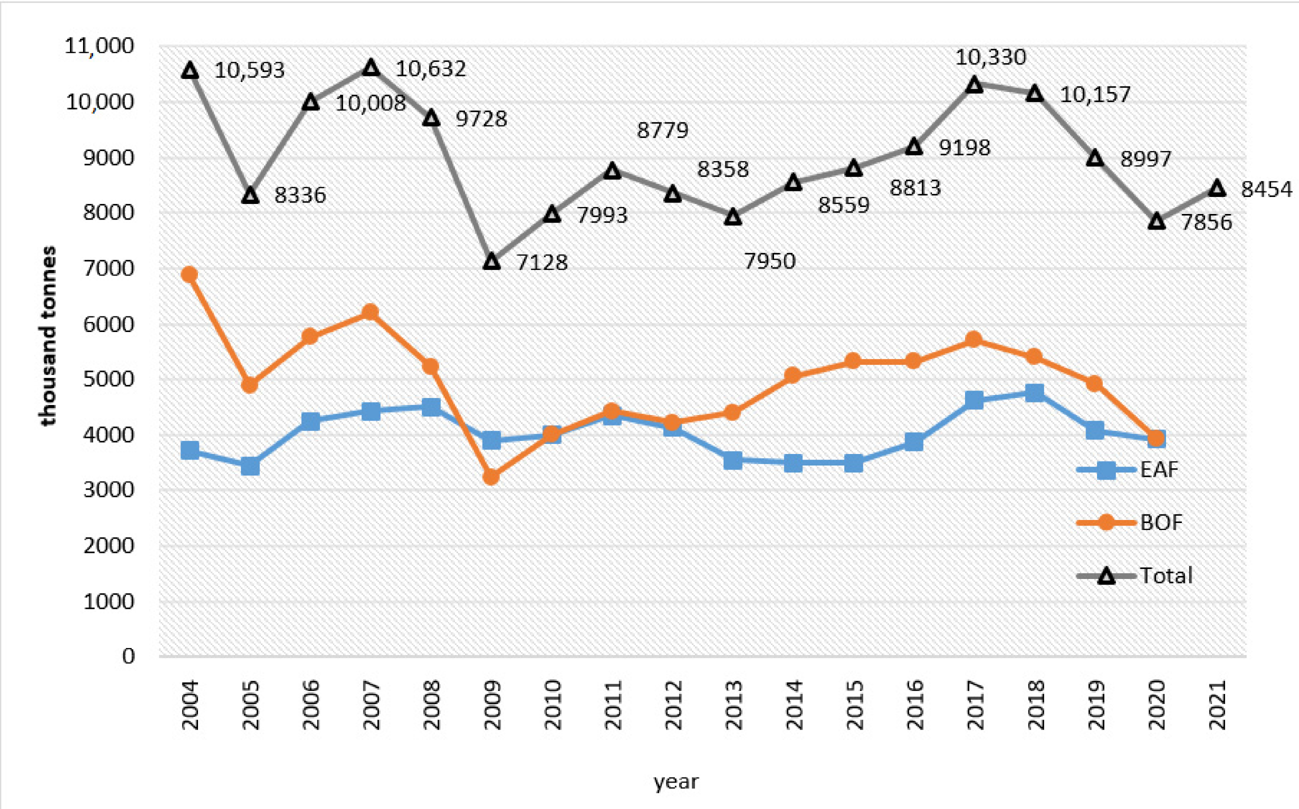

Figure 6. Steel production in Polish steel industry from 2004 to 2021. Total = EAF + BOF. Source: own elaboration based on Reports: Steel production in figures. World Steel Association [69].

In the last decade, the Polish steel industry produced an annual average of about 9 million tonnes of steel [70]. Models of steel production have evolved with the development of the sector [71]. The wide range of technological improvements in steel production, in addition to ecology, was determined by quality requirements [72]. In the analysed period, there were slight decreases or increases in production (production volume adjusted to the demand for steel in steel consumer markets (construction, automotive, machinery industry, etc.) and economic downturns or downturns (decreases in steel production volume in the period from 2009 to 2010 (effect of the global economic crisis, initiated in the real estate market in the US) and in 2020 ("pandemic" crises—economic problems caused by trade barriers due to the COVID-19 virus)) [73]. The steel industry in Poland is not fully utilizing its capacity. Capacity utilisation is just over 70%. The problem is the influx of steel products from abroad. A negative foreign trade balance in the Polish steel market was recorded for the first time in 2005 and still exists. The share of imports in apparent consumption is steadily increasing. In 2020, imports of steel products amounted to 10.8 million tonnes and exports of steel and steel products from Poland amounted to 5.1 million tonnes [68]. Domestic regulations promote sustainable development but with some safeguards, e.g., in energy policy ('compensation' for highly energy-intensive sectors) [74]. Steel mills in

Poland and the EU as a whole will undergo further transformation based on the strategic direction of governmental, administrative, and legislative institutions. The Europe 2020 development strategy singles out three directions for development [75]: (i) growth based on knowledge and innovation (smart growth), (ii) energy, economic, and consumption efficiency (sustainable growth), and (iii) employment, economic, and spatial cohesion (inclusive growth). In a circular economy and green economy, the key goal is reducing waste (and therefore minimising costs) and redefining sustainable development is more and more important. Sustainability was and continues to be a key focus for the global industry.

However, it is important to recognise emerging threats to the development of the steel industry in Poland, such as the reduction in carbon dioxide emissions (50% by 2050 compared to 2005). Limiting free CO_2 emission allowances results in lower steel production and the need to purchase additional CO_2 emission packages. As recently as 2013, the limits were at 11.4 million tonnes with the production of 8 million tonnes and employment of 20,000 people. In 2020, with allowances at 9.9 million tonnes, steel production dropped to 7.8 million tonnes with slight fluctuations in employment (note: this was the period of the COVID-19 pandemic). In 2021, steel production in Poland increased again to pre-pandemic levels. In 2021, Poland produced 8.5 million tonnes of steel (an 8% increase compared to steel production in 2020) [68,69].

Poland's energy economy is based on a document adopted in 2021 called the Energy Policy until 2040 (PEP2040) [76]. The Polish policy is based on the assumptions of the world and EU energy policy called green energy due to the need to diversify thermal raw materials (limiting coal mining) and diversify energy sources (e.g., green hydrogen). The whole world is pursuing a policy of using non-carbon energy sources [77]. Industry can use energy recovered from production equipment, energy extracted from industrial waste, solar and wind energy, etc. [78,79]. Unconventional and renewable energy is developing in many countries. The world is constantly looking for other sources of energy besides coal to contribute to reducing adverse climate change [77–83]. The world, especially in highly developed countries, is building strong links between climate change and sustainable development [80]. Governments in many countries built the prevention of further climate change into strategic economic development goals. The development of the world's economies must take place following the laws of the environment. The Polish government, in its system of strategic documents on sustainability, operationalises the "Strategy for Responsible Development" (with an outlook to 2030) [81] in line with EU policy. The industry is rationalising the use of resources and reducing the negative environmental impact of manufactured products, which should remain in the economy for as long as possible, and waste generation should be minimised as much as possible [82–84]. In the energy economy, the direction of the diversification of energy sources and reduction in energy and heat obtained from coal is being pursued.

3. Modelling the Heat and Power Management of the Polish Steel Industry, Materials and Methods

Econometric modelling involves looking for correlations between the heat and energy economy in the steel production process in Poland. Data on the entire sector called the steel industry, which is made up of producers of steel (steel mills) and steel products, were used to describe the energy and heat economy in the steel industry in Poland. The data used to select the econometric model concerned the period from 2004 to 2020 (n = 17, where n is the number of elements in the time series and T is the period from 2004 to 2020 (t-year)). The beginning of the analysis was taken as the year in which the main steel producers in Poland completed their mandatory corrective restructuring to meet the EU viability requirements. Data from 2021 and 2022 (steel production and energy price) were used to forecast changes in heat intensity in the Polish steel industry. The empirical (statistical) data from 2004 to 2020 were used in the econometric model. Data came from reports of Polish reporting units: Statistics Poland, Warsaw (in Polish: Główny Urząd Statystyczny—GUS) and the Polish Steel Association, Katowice (in Polish: Hutnicza Izba Przemysłowo-Handlowa—

HIPH). The data categories used to search for optimal model parameters are summarised in Table 3. The authors searched for single-parametric or two-parametric models. The basis for assessing the significance of the models was R^2, where R^2 is the determining factor.

Table 3. Tested one- and two-parametric econometric models with linear function in the period T: from 2004 to 2020, *t*-year, (*n* = 17).

No.	Y^*_t	X_t			R^2	Result
			X_{1t}	X_{2t}		
1.	Heat intenity in BF process (pig iron) per 1 tonne of product	Energy intensity in BOF process per 1 tonne of steel produced in BOF	-	-	0.556242	no statistical significance
2.	Energy intensity in EAF process per 1 tonne of steel produced in EAF	All taxes and levies inculded	-	-	0.578502	no statistical significance
3.	Energy intensity in steel production per 1 tonne of crude steel		Steel production (total)	Excluding taxes and levies	0.4193	no statistical significance
4.	All taxes and levies included	Energy intensity in steel production (total)			0.531025	no statistical significance
5.	Energy intensity in steel production (total)	Steel production by process: EAF	Heat intensity in steel production (total)		0.505108	no statistical significance
6.	Energy intensity in steel production (total)	Steel production by process: EAF	All taxes and levies included		0.598897	no statistical significance
7.	Heat intensity in steel production (total)		Energy prices: all taxes and levies included	Steel production total	0.88064	model is statistical significance

Source: own econometric testing.

Model No. 7 from Table 3 was statistical significance. This model was estimation based on data from Table 4.

Table 4. Data used in the econometric model No. 7.

T	Year (*t*)	Total Heat Intensity in Steel Production in Poland [GJ]	Price of Energy in Poland: All Taxes and Levies Included [PLN/kWh]	Total Steel Production in Poland [Thousand Tonnes]
1	2004	9,176,746	0.2355	10,593
2	2005	5,582,352	0.2361	8336
3	2006	8,115,360	0.2427	10,008
4	2007	8,620,203	0.2482	10,632
5	2008	7,714,424	0.2984	9728
6	2009	4,995,698	0.3873	7128
7	2010	5,563,254	0.3762	7993
8	2011	5,619,256	0.3813	8779
9	2012	5,937,344	0.3855	8358
10	2013	6,110,152	0.3506	7950
11	2014	6,741,570	0.3127	8559
12	2015	6,966,449	0.3319	8813
13	2016	6,768,135	0.3195	9198
14	2017	7,560,971	0.3331	10,330

Table 4. *Cont.*

T	Year (t)	Total Heat Intensity in Steel Production in Poland [GJ]	Price of Energy in Poland: All Taxes and Levies Included [PLN/kWh]	Total Steel Production in Poland [Thousand Tonnes]
15	2018	7,379,043	0.3370	10,157
16	2019	6,689,118	0.4031	8997
17	2020	4,411,638	0.4362	7856

4. Econometric Model

The basic element of the analysis was an econometric model (No. 7 from Table 3) with the construction written in Equation (1). The model is a one-equation linear function with a two-parametric general form:

$$Y = \alpha_1 X_1 + \alpha_2 X_2 + \xi \tag{1}$$

The model represents the essential quantitative relationships between the phenomena under study, which were the heat intensity of the steel production process (random variable), the factor explained by the price of electricity and the volume of steel production (non-random variables), and the explanatory factors. The structural parameters of the model (1) expressing the influence of a given variable on the explained variable were determined on the basis of statistical data (Table 4) in the model estimation econometrical process. In the obtained model (2), the parameter describing energy prices (X_1) is negative. The econometric verification of the model (2) consisted of checking with the help of the coefficient of convergence for the degree of fit of the model to the empirical data, testing the statistical significance of the model's structural parameters, examining the residuals of the model, and verifying the autocorrelation of the random factor and the model residuals.

Using the computer programme Excel, the following description of the model was obtained (Table 5):

Table 5. The econometric estimation and verification of the analysed model.

SUMMARY-EXIT								
Regression statistics								
Multiple R	0.938424							
R square	0.88064							
Matched R square	0.863588							
Standard error	479017.9		0.071463					
Observations	17							
VARIANCE ANALYSIS								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	2	2.37×10^{13}	1.19×10^{13}	51.64598	3.45×10^{-7}			
Residual	14	3.21×10^{12}	2.29×10^{11}					
Total	16	2.69×10^{13}						
	Coefficients/factors	*Standard error*	*t Stat*	*Value-p*	*lower 95%*	*upper 95%*	*lower 95.0%*	*upper 95.0%*
Cut/cuuting/cut through	64,352.28	1,933,324	0.033286	0.973917	−4,082,214	4,210,919	−4,082,214	4,210,919
All taxes and levies included	−5,290,326	2,474,402	−2.13802	0.050633	-1.1×10^{7}	16,739.2	-1.1×10^{7}	16,739.2
Steel Production	929.276	145.1161	6.403674	1.64×10^{-5}	618.033	1240.519	618.033	1240.519

The econometric model for which the required high R^2 (R^2 = 0.88064) in the significance assessment was obtained is of the form:

$$y_t^* = -5,290,326 x_{1t} + 929.276 x_{2t} + 64,352.28 \tag{2}$$

where:

y^*_t—heat intensity in steel production [GJ] in the period (T) from 2004 to 2020,
x_{1t}—energy price (all taxes and levies included) [PLN/kWh] in the period (T) from 2004 to 2020, and
x_{2t}—steel production [thousand tonnes] in the period (T) from 2004 to 2020.

Table 6 summarises the statistics of the model using the computer programme Excel. Figure 7 presents the results of the econometric analyses.

Table 6. Statistical data for the econometric model no. (2).

Statistical Indicator	Indicator Value	Assessment on the Basis of an Indicator
1. Determination factor	$R^2 = 0.88$	An 88% variability of y is explained by the model; match of the model to empirical data are very good
2. Indicator: $R_d{}^2$	$R^2{}_d = 0.94$	Do porównania z modelami o innej liczbie zmiennych
3. Statistics F	$F = 51.7$ $p > 0.99$	There is a linear relationship (statistics based on linearised empirical data: LN)
4. Expressiveness factor	$Se = 0.07$	Good match
5. Significance test: t Student test	x_1: $t = -2.1$ $p > 0.95$ x_2: $t = 6.4$ $p > 0.99$	Parameter x_1 is relevant Parameter x_2 is relevant

Source: obtained from computer programme Excel by using the function REGLIN.

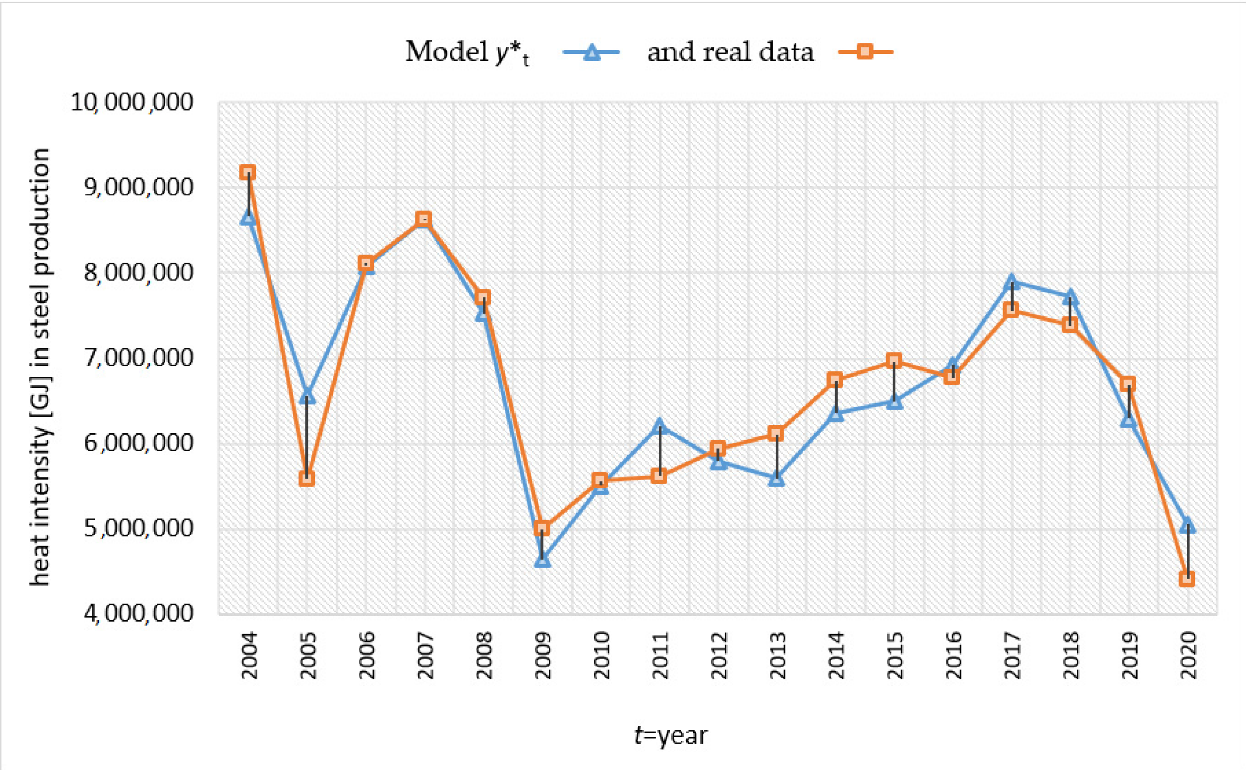

Figure 7. Model: $y^*_t = -5{,}290{,}326x_{1t} + 929.276x_{2t} + 64{,}352.28$ for Polish steel industry for T: from 2004 to 2020. Where: Y_t—real data: heat intensity in steel production (total) [GJ]. Y^*_t—heat intensity in steel production (total) [GJ] from model (2). Source: own elaboration.

Interpretation of the obtained model:

- An increase in the energy prices: all taxes and levies included by a unit [PLN/kWh] (x_{1t}) will reduce the heat intensity in steel production (y^*_t) by 5,290,326 GJ, with the first factor remaining unchanged, which is the steel production in this model (x_{2t}).
- An increase in the steel production (x_{2t}) by a unit [thousand tonnes] will increase the heart intensity in steel production (y^*_t) by 929.274 GJ, with the second factor remaining unchanged, which, in this model, is energy prices (x_{1t}).

Table 7 shows the projected heat intensity of the steel industry in Poland with the actual data and the residual components obtained.

Table 7. Comparison of heat intensity in the Polish steel industry based on the real data and data from model No. 2.

t = Year	y^*_t Data from Model No. 2 Obianted for Heat Intenisty [GJ]	y_t Real Data about Heat Intenisty [GJ]	Residual Components $y-y^*_t$ [GJ]
2004	8,662,032	9,176,746	514,714
2005	6,561,921	5,582,352	−979,569
2006	8,080,134	8,115,360	35,227
2007	8,631,003	8,620,203	−10,801
2008	7,525,355	7,714,424	189,068
2009	4,640,001	4,995,698	355,697
2010	5,501,857	5,563,254	61,397
2011	6,205,529	5,619,256	−586,274
2012	5,791,820	5,937,344	145,523
2013	5,597,308	6,110,152	512,844
2014	6,363,276	6,741,570	378,294
2015	6,498,017	6,966,449	468,432
2016	6,921,838	6,768,135	−153,703
2017	7,901,566	7,560,971	−340,595
2018	7,720,433	7,379,043	−341,390
2019	6,292,518	6,689,118	396,600
2020	5,057,104	4,411,638	−645,466

In the analysed period from 2004 to 2020, the average annual heat demand (according to the model) was 6,703,041 GJ. The decrease in heat intensity in the steel sector will depend (according to the model determined) on electricity prices and ancillary charges; any increase in these prices (x_{1t}) (according to the models) with unchanged steel production (x_{2t}) will result in a decrease in heat consumption of the total steel production (y^*_t). Real data about steel production in 2021–2022 [thousand tonnes] obtained from the Polish Steel Association (Katowice Poland) and energy prices in the Polish steel industry [PLN/kWh] in the same period were (Source: Eurostat NRG_PC_205 for 2021 and F-forecast for 2022) used to forecast the heat intensity (according to model no. 2) in the period of 2021 and 2022. The results are presented in Table 8 and Figure 8.

Table 8. Forecast of the heat intensity in the Polish steel industry based on model no. (2).

t = Year	y^*_t Forecasting Data from Model No. 2 Obianted for Heat Intenisty in Polish Steel Industry [GJ]	Energy Prices x_{1t} [PLN/kWh]	Steel Production x_{2t} [Thousnad Tonnes]
2021	5,277,065	0.4875	8454
2022	4,051,253	0.6500 F	8060 F

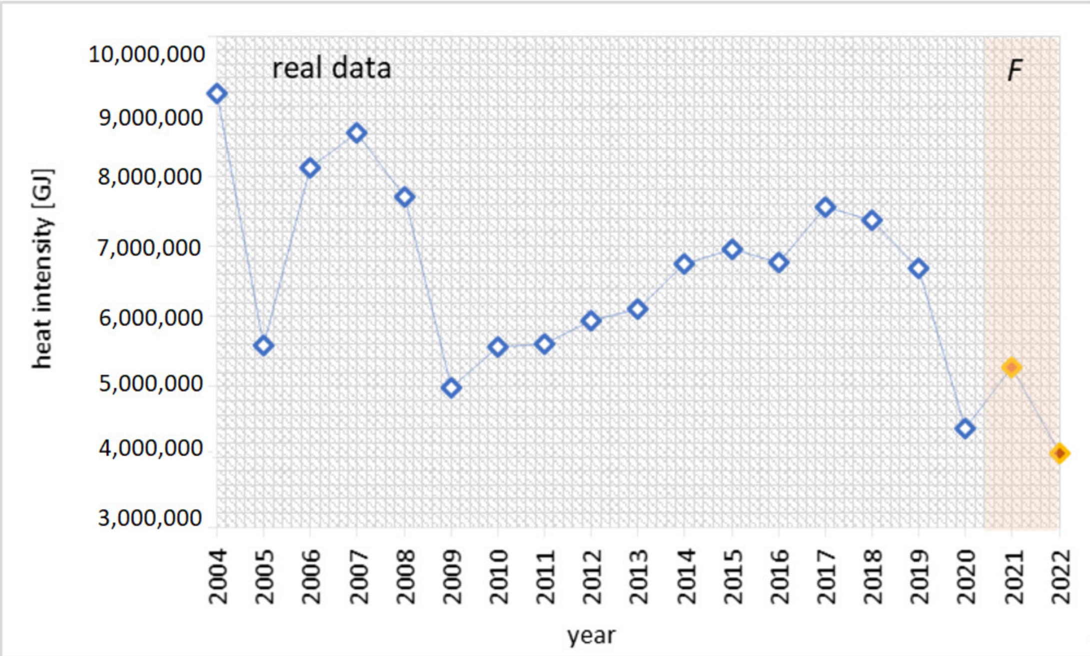

Figure 8. Heat intensity in Polish steel industry in the period 2004–2022. Source: own elaboration.

The Polish steel industry so far incurred very high electricity prices. In addition to energy prices, the structure of electricity prices in the Polish steel sector includes regulatory costs, which are presented in Figure 9. These costs are related to the transition of the economy to renewable energy sources, taxes, cogeneration support costs, energy efficiency support costs, or distribution fees and costs.

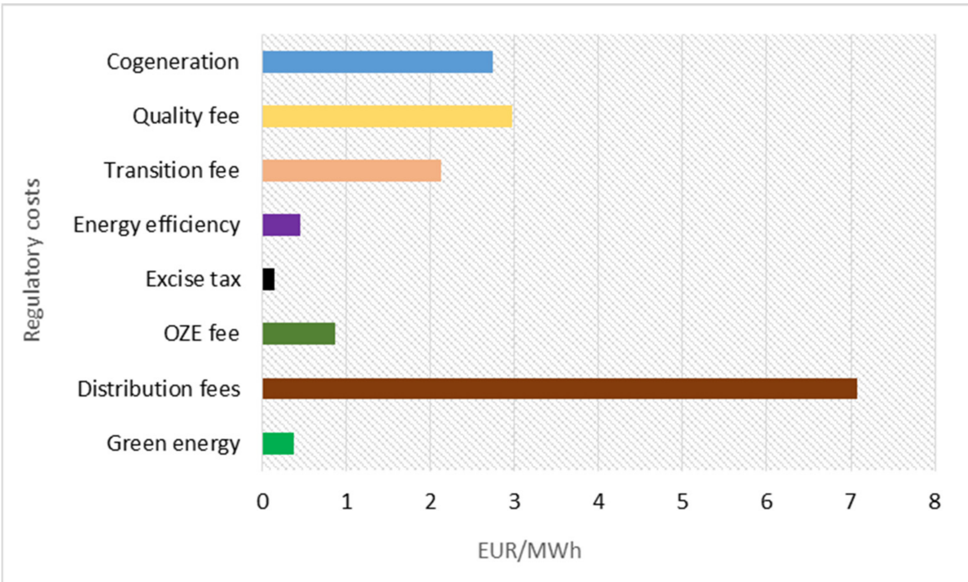

Figure 9. Regulatory costs incurred by steel mills in Poland by item. Source: own elaboration based on [85].

Electricity prices on the wholesale market in Poland are among the highest in the European Union and the highest compared to industrialised neighbouring countries. On average, during the analysed period, prices in Poland were 24% higher than in Germany in 2020. Figure 10 compares electricity costs in Poland and Germany in 2020.

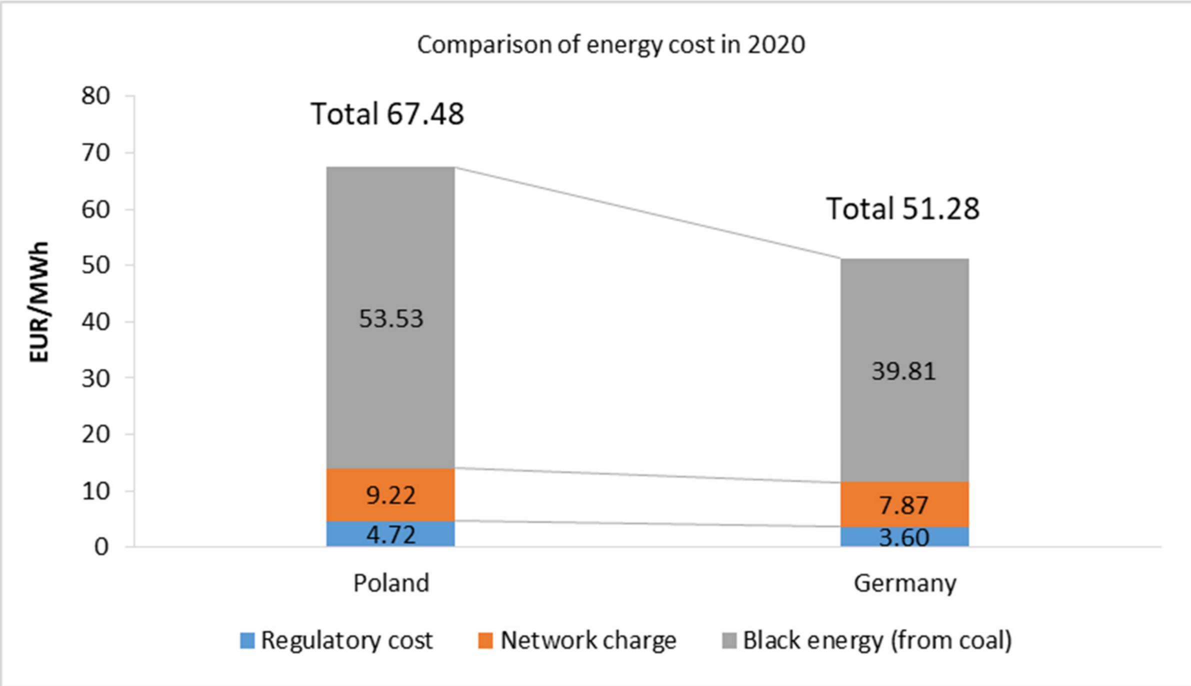

Figure 10. Comparison of energy cost: Poland and Germany [EUR/MWh] in 2020. Source: own elaboration based on [86].

Note also the high value of the fixed component of the network rate of distribution charges in 2020 (Figure 10). In Germany, energy-intensive customers enjoy significant regulatory cost reductions, an individualised approach to the calculation of distribution charges or the possibility of generating additional revenue through the provision of DSR services tailored to the specific characteristics of energy-intensive customers. After 2020, the cost of energy in Poland increased to 2021, with the introduction of a new regulatory component charged to consumers—the power fee (covering the costs of the power market). The commencement of the power charge without the application of the allowance for energy-intensive consumers further widened the differences in the costs of supplying electricity to steel mills in Poland and Germany in 2021, and was no longer 24% (as in 2020), but 33% (Figure 11). The increase in electricity procurement costs for Polish steel mills carries the risk of losing their international competitiveness. The additional cost of the power market, combined with high energy prices, may make production profitable.

Referring to the obtained model (1), an increase in electricity purchase costs is realistic, therefore a decrease in heat consumption can be expected with each increase. Energy efficiency and decarbonisation of the energy sector are key elements of Poland's current energy policy, and their role will increase in the future in order to meet the ambitious objectives of the EU climate policy [87,88]. Market-based financing mechanisms for investments aimed at improving energy efficiency are needed. It is still necessary to strengthen support systems in the form of concessions and exemptions for the most energy-intensive sectors, including metallurgy. The structure of Poland's energy source diversity differs significantly from the average structure in EU countries, where RES have the largest share (33% in 2018), followed by nuclear (26%) and fossil fuels only 20%. When analysing the sources of electricity in EU countries with a steel industry, a higher share of 'black energy' than the EU average is mainly in Poland (77%), followed by Germany (35%) (Figure 11).

The philosophy of sustainable development embodied in the EU's Green Deal strategy [8] influences energy and heat management in the Polish steel sector. The Polish steel sector faced several challenges in the last decade. The reasons for this include rising energy costs. Steel production in Poland, in the analysed period from 2004 to 2020, fell below 9 million tonnes (8.793 million tonnes were produced on average annually). Forecasts for the coming years are not optimistic. In the moderate scenario, production is expected to remain at the level of 9 million tonnes of steel produced in Polish mills, but after the COVID-19 period, the production of steel in Poland did not exceed 8.5 million tonnes per year. In 2021 the Polish steel mills produced 8.454 million tonnes of steel [68,69]. In 2022 experts from PSA forecast the steel production in Poland at the level of 8.060 million tonnes (data were used in forecasting based on model no. 2—Table 8).

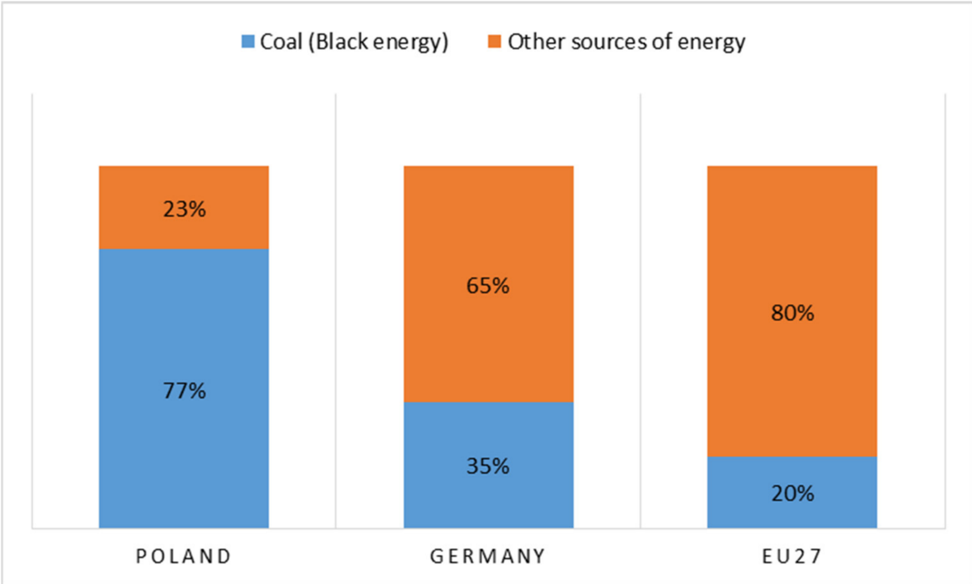

Figure 11. Comparison of the share of black energy in total for Poland, Germany, and EU 27 in 2018. Source: own elaboration based on [86].

5. Discussion

The model presented in this publication shows the correlation between heat intensity and energy price and steel production in Poland. Based on the model, the predicted heat intensity of the steel industry and the parameters influencing this heat intensity were determined [89–91]. Research shows that electricity prices and steel production (volume) influence heat consumption (heat intensity in the sector). In literature, a very interesting analysis of energy consumption in the steel industry was carried out by Mohsen and Akash [92]. It should be taken into account that the steel industry is very intensive from the point of view of energy and heat consumption. A very important issue in production processes is how to reduce the amount of heat loss in the production line. According to the aforementioned authors, about 36% of the amount of heat loss in steel production is related to loss in the furnace. This heat is recoverable and, with appropriate process modifications, can be recovered. Crucible and mould losses are also very important (17%). This can be partially recovered using steam treatment. Another loss (more than 26%) is the amount of heat rejected in the cooler—in this case it is not easy to recover most of the heat, but in some situations, it is possible to use space heating or technology based on reheating from scrap to achieve a higher initial temperature. Our results can be compared with those obtained by J. Morfeldt [39]. He conducted an analysis about factors affecting energy efficiency indicators. According to his research and analysis factors, the use of raw materials, price levels of those materials' domestic development, amount of energy sold, and investment in energy are affecting the amount of energy use in steel production. It is similar to results obtained in our model; in our model, prices of the energy have important influence on heat intensity in the steel industry.

The energy market always has a very big impact on the steel industry, especially when it comes to prices of energy, because this industry consumes a very large amount of the worldwide production of energy (about 5%) [52]. The benefits of energy efficiency are very important to the steel sector and this is a commonly accepted fact [93–97]. Additionally, it is very important to improve the productivity and competitiveness that are associated with improving energy management in steel-producing plants. For example OECD conducted very interesting project to analyses on why some steel sector companies are not implementing energy efficiency measures [98]. The results of this research show that the steel sector is slightly implementing innovative energy efficiency projects. Those projects are realized due to individual initiative of the particular companies to save the amount of costs. The problem is that many (about 43% of surveyed organization) had negative experiences connected with the implementation of energy efficiency projects. This can be dangerous in the context of the current situation, when a higher amount of new investment in energy efficiency solutions is urgently needed [99–101]. Those bad experiences can be a problem and can decrease the willingness of organizations to invest in new, innovative projects, even if it is needed.

The rising energy costs can stimulate industry to increase energy efficiency. Baláž and Bayer found that there is a very close correlation between electricity prices and energy intensity usage in the steel industry [89]. However, according to their research, it can be observed that there are negative impacts of prices on the competitiveness of this industry, which are measured using the RCA indicator or using the export intensity indicator. The rising prices of energy in the European Union can lead to the situation of some steel plants migrating to countries with lower energy prices. To avoid this, organizations should invest in new innovative solutions based on green sustainable steel working and renewable energy resources.

The rising energy prices that we are currently observing, according to the model presented, may contribute to inhibiting the decarbonisation processes of the economy and the steel industry. Since a very large increase in energy prices may lead to a halt in steel production with a shortage of green energy, allowing governments to continue to use coal in steelmaking processes may be a serious problem. While this may have a positive effect on product prices, it is dangerous because of the potential for very negative environmental effects. The model presented here suggests that rising energy prices could lead to a slowdown in the energy transition of the steel industry and even stall processes towards green steel [101–104]. Similar results concerning the potentially detrimental effect of the pandemic and the war on energy transition were obtained by Zakeri et al. [105], an international team of researchers. According to their analysis, the current war gives us the possibility to observe the vulnerability of today's economy and supply chains. The energy price shock may not pave the way for decarbonisation and green energy [106–109]. We can observe that governments are more focused on the security of energy from a sort-term point of view and are abandoning the long-term vision of sustainability and green transformation [110–112]. This is very dangerous for the natural environment and our future, but another approach needs to rethink consumption, which is not easy from a political point of view [113–118].

In the steelmaking industry, we see that energy and social safety are required more now than compared to times after the pandemic and Ukraine war. This is the potential risk of excluding the steel production industry from access to essential energy. This, without the implementation of strong policies for how to protect the industry and its customers, can lead to a step back from the pathway towards the green steelmaking industry. The government policy should reduce the impact of energy pricing on the industry as a whole and they should be linked with careful balanced energy efficiency programs. It could lead to stabilizing the situation in the steelmaking industry without detrimental effects on sustainable development [119]. In particular, the steel industry is threatened by the aforementioned fact that energy prices in Poland are among the highest in the European Union, which means that the current crisis could have a strongly negative impact on the Polish steel industry. Data on the global steel industry also demonstrate the risks facing the industry as a result of the energy crisis. For example, ArcelorMittal is planning to close two steel plants amid the European energy crisis [120]. Additionally, the big energy prices may lead to the shooting down of the Dutch steel factories [121] and Italian steel factories [122,123].

European steelmakers should try to prepare their businesses for a new round of energy crisis. They are between two negative market trends—low prices of steel and heightening the cost of steel production. In the situation of gas, shortage producers will be forced to reduce the volume of production to use coal instead of gas. For example, ThyssenKrupp, in the case of gas shortage, may face stoppages in production and even equipment damage because it will not be able to switch its production from natural gas to other fossil fuels, such as coal [124–126].

Up till now, much of crude steel was produced (about 70%) using blast furnace technology [127–129]. This method is used when iron ore and coal are used to convert coal to coke and then sinter and pelletise the iron ore. Next, the iron ore is converted into hot metal and it is then refined [130]. Now the energy crisis has a big impact on looking for new, innovative solutions to decreasing the energy demand of this process [131,132]. Changes in the steel production industry should be innovative, cost efficient, and achieve cheap and sustainable steel production.

The model developed can find applications not only for analyzing historical data, but also for predicting future trends in the steel production market. It can be used to analyse the impact of external factors affecting the steel industry, such as energy prices, the operation of the industry, and production volumes. This provides opportunities to use the model as a managerial tool in the model management process. The model could be used by energy policy planning agencies at a national level to analyse different scenarios that the steel industry may face. The analysis of different scenarios and their impact on the industry's operation allows different options to be analyzed and government policies to be adapted accordingly.

6. Conclusions

The analyses presented in the publication allowed, on the basis of the data collected, for the development of an econometric model for the Polish steel industry from the point of view of the relationship between heat and energy management in the steel production process. The analyses carried out showed that there is an inversely proportional relationship between electricity prices and the intensity of heat consumption by the steel industry.

The econometric model, for which the high R^2 required in the significance assessment (R^2 = 0.88064) was obtained, has the form:

$$y^*_t = -5{,}290{,}326 x_{1t} + 929.276 x_{2t} + 64{,}352.28$$

The developed model is a useful analytical tool, as it not only allows the analysis of historical data, but can also be used to predict how steel industry parameters will change in the future under the influence of changes in external factors, such as energy prices. This gives a wide range of analytical possibilities for the use of the model.

Research also shows that rising energy prices lead to lower steel production. This is a dangerous phenomenon for the steel industry in the context of the current energy crisis caused by the pandemic and war in Ukraine.

Rising energy prices could lead to a significant reduction in steel production and a crisis in the steel industry as a whole. The alternative is a return to the use of fossil fuels, including, in particular, greater use of coal in steel production. Such an approach would be a step backwards from the decarbonisation policy pursued in recent years and the transformation of the entire industry towards green steel. The steel industry faces a difficult situation in this context. In the short term, either sustainability and the transition towards green steel can be achieved at the expense of a significant reduction in production volumes, or production can be maintained at the expense of a return to greater use of fossil fuels. Both alternatives have their drawbacks and governments will need to consider which solution to choose. In the long term, there seems to be no turning back on the implementation of the green steel concept due to the increasing threat of climate change, but the steel industry must survive the current energy crisis.

The end of the COVID-19 pandemic is not an end of the crisis in the steel sector. The war in Ukraine, which started this year, may have an even more detrimental effect on the steel sector than the COVID-19 pandemic. After the pandemic, the economy struggled with the lack of some resources, increased prices of energy and fossil fuels, and problems with the resiliency and continuity of supply chains. Now, because two of the main producers of many fossil fuels, grains, and row materials (Russia and Ukraine) are at war, the problem is worse. From February, we observed a very big increase in the energy and fossil fuel prices and also an increase in the prices of other row materials. This can have a very big negative effect on the steel industry. We will see how the steel industry will deal with this difficult situation. The best option is to invest in new, innovative solutions, which can decrease the demand of steel production on energy and heath. Without new, innovative solutions, the amount of steel produced may decrease this year and until the war ends.

The main limitation of this study was that it was based on data obtained from Poland. Poland is a very important country from a steel production point of view, but in other countries, we could obtain slightly different results due to the other technologies used in plants. In the econometric method used, we utilised data from 2004 to 2020. This is a limitation because it would be possible to obtain data from earlier years. In addition, taking into analysis data from 2021 to 2022 (for now impossible because we do not have full data for analysis) could change some parameters of the models—it is especially important to note that the COVID-19 pandemic and war in Ukraine in 2022 had a very important impact on the steel production market. We think that it will be very interesting in 2–3 years to conduct another analysis to check what changed in the steel market and how this difficult situation impacted its functioning. Maybe after this analysis, some part of our econometric model will be changed. Additionally, in the process of model building, we took into account some data about the steel industry functioning in Poland—it is possible to use other data or other statistical methods for data modeling.

Author Contributions: The main activities of the team of authors can be described as follows: Conceptualization, B.G.; methodology, B.G.; software, B.G.; validation, B.G.; formal analysis, B.G. and B.G.; investigation, B.G.; resources, B.G.; data curation, B.G.; writing—original draft preparation, B.G.; writing—review and editing, B.G., R.W. and W.W.G.; visualization, B.G.; supervision, B.G. and R.W.; funding acquisition, R.W. All authors have read and agreed to the published version of the manuscript.

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