

Article

Energy Intensity of Steel Manufactured Utilising EAF Technology as a Function of Investments Made: The Case of the Steel Industry in Poland

Bożena Gajdzik ¹, Włodzimierz Sroka ^{2,3,*} and Jolita Vveinhardt ²

¹ Department of Industrial Informatics, Silesian University of Technology, 40-019 Katowice, Poland; bozena.gajdzik@polsl.pl

² Department of Management, WSB University, 41-300 Dąbrowa Górnicza, Poland; jvveinhardt@wsb.edu.pl

³ College of Business and Economics, University of Johannesburg, Johannesburg 2006, South Africa

* Correspondence: wsroka@wsb.edu.pl

Abstract: The production of steel in the world is dominated by two types of technologies: BF + BOF (the blast furnace and basic oxygen furnace, also known as integrated steel plants) and EAF (the electric arc furnace). The BF + BOF process uses a lot of natural resources (iron ore is a feedstock for steel production) and fossil fuels. As a result, these steel mills have a significantly negative impact on the environment. In turn, EAF technology is characterised by very low direct emissions and very high indirect emissions. The raw material for steel production is steel scrap, the processing of which is highly energy-consuming. This paper analyses the energy intensity of steel production in Poland as a function of investments made in the steel industry in the years 2000–2019. Statistical data on steel production in the EAF process in Poland (which represents an approximately 50% share of the steel produced, as the rest is produced utilising the BF + BOF process) was used. Slight fluctuations are caused by the periodic switching of technology for economic or technical reasons. The hypothesis stating that there is a relationship between the volume of steel production utilising the EAF process and the energy consumption of the process, which is influenced by investments, was formulated. Econometric modelling was used as the research method and three models were constructed: (1) a two-factor power model; (2) a linear two-factor model; and (3) a linear one-factor model. Our findings show that the correlation is negative, that is, along with the increase in technological investments in electric steel plants in Poland, a decrease in the energy consumption of steel produced in electric furnaces was noted during the analysed period.

Keywords: Polish steel industry; energy intensity; BF + BOF technology; EAF technology



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1. Introduction

The energy intensity of the economy is an important factor in production costs. The steel industry has some of the highest levels of carbon emissions and energy consumption in Europe [1]. This applies, in particular, to energy-intensive sectors, which are characterised by high consumption of non-renewable energy resources and high emissions of pollutants into the environment. The steel sector is such an industry [2,3]. Therefore, improving energy efficiency (i.e., rational energy management) is a strategic goal for many production enterprises, especially steel producers. It is worthwhile noting that the basic energy resource used in industry is electricity. Improving the recovery of energy and material by-products in the steel industry should improve resource efficiency to 36% [4,5]. Energy efficiency covers all activities that result in reducing the amount of energy—especially from fossil fuels—per unit of a product. However, improving energy efficiency is a complex process that should be carried out consciously and consistently. This means taking appropriate actions, especially in the field of production management. In other words, the improvement of energy efficiency should be implemented in many dimensions and

in many processes, and ad hoc actions are not advisable. Moreover, production processes are complex in terms of, for instance, the type of raw materials, production volume, product range, and technology used. An energy efficiency policy (strategy) should then be implemented systematically in relation to many components of the production processes and the entire supply chain. This is due to the fact that modern enterprises operate in a permanently dynamic environment [6]. External factors (e.g., economic, environmental, legal, tax and others) must be included in business decisions.

Actions to improve energy efficiency should include all possible measures aimed at achievement of the basic goal (e.g., technological, economic, fiscal, price, organisational, administrative and others). In line with EU energy policy, Poland has started to reduce CO₂ emissions and increase the consumption of energy from renewable sources (green energy) throughout the whole economy. The activities of the Polish government in the field of energy policy are presented in a document outlining their energy efficiency policy: “Poland’s Energy Policy until 2030”. In recent years, activities in the field of diversification of energy sources have been identified. This was done in accordance with the EU “Green economy” policy, which aims to reduce waste—and thus costs—as well as redefine sustainable development [7–9]. The latter is a basic direction of changes [8] and is also associated with the implementation of the assumption that a Circular Economy is in operation among European countries (e.g., [7,10,11]). The iron and steel industry cannot remain indifferent to these changes. Two categories of factors are particularly important (and, at the same time, are strongly related to each other): economic and legislative factors. This means that the economy and law determine the actions of manufacturing companies in their efforts to improve energy efficiency and that increasing energy efficiency is a strategic goal of a sustainable production policy, regardless of the sector of activity. The list of environmental aspects in the steel industry in Poland is long. In addition to those aspects that are directly related to the environmental impact of production (e.g., CO₂ emissions), key aspects in the area of resource intensity are also classified [12,13]. Awareness of these environmental aspects, together with technological knowledge, should be foremost in the decision-making centre of the steel industry [14].

Given these deliberations, this paper analyses the energy intensity of steel manufactured utilising the EAF process in Poland. The basis for the analysis of energy consumption is the statistical data for the period 2000–2019. The analysis was carried out in accordance with the methodology of building statistical models. Based on an analysis of literature, a research hypothesis (H1) was formulated on the relationship between the volume of steel production utilising the EAF process and the energy consumption of the process and the impact of the investment on the decrease in energy consumption in the production of steel manufactured in electric arc furnaces. The rest of the paper is structured as follows. The next section presents the theoretical background, which is the basis for formulation of the research hypothesis. This is followed by the methodology section. Afterwards, we present the research findings, which consist of the analysis and econometric modelling of energy consumption in the steel industry in Poland (three models were presented). The final section provides a conclusion.

2. Literature Review

2.1. Theoretical Background

With the growing pace of globalisation, international competitiveness requires companies to place more emphasis on reducing their production costs, including those related to energy [15]. “Energy intensity” is one of the most frequently used terms in relation to the effectiveness of business performance. This is mostly because energy is a key production factor in many industries [16]. One study estimates that approximately 80% of energy is consumed by steel and chemical producers [17]. These data clearly show the need to increase efforts to reduce energy intensity and to increase transparency, regardless of the industry [18]. Energy intensity is measured by the utilisation of different metrics. Basically, the choice of a particular approach depends on two factors: (1) availability of the data,

and (2) the purpose of the study [19]. One of these approaches is used if one wants to present the performance of particular companies (or sectors). In other words, the higher the energy consumption, the higher the energy intensity. Given this fact, it is of pivotal interest for companies to concern themselves with energy efficiency. On the one hand, energy efficiency belongs to the key measures required to diminish both CO₂ emissions and energy consumption [20] and, on the other hand, energy efficiency has a direct impact on production costs. Therefore, a reduction in energy intensity is proof of efficiency improvement. Energy intensity is connected with the volume of steel production.

The issue of energy intensity is especially evident in highly energy-intensive sectors, such as the steel industry [21,22]. It is not easy to assess the energy intensity of the steel industry, especially on international scale. There are several reasons for this, such as limited access to the data or the calculation methods used by the steel companies [23,24]. There are two basic technologies used for the production of steel: the blast furnace and basic oxygen furnace (BF + BOF) (also known as integrated steel plants) and the electric arc furnace (EAF) [25]. In the first case, the production is carried out utilising coal and iron ore [26]. This is regarded as the traditional way to produce steel. In Polish steel manufacturing, only two technological processes are used: EAF and BOF [27,28]. The former uses scrap and electricity. The downstream processes are similar in both routes [29].

In 2017, 71.6 % of steel produced worldwide was produced using the BF + BOF process, whilst 28% of steel was produced using EAF technology [28]. The remaining of 0.4% was manufactured using open-hearth technology [30]. World leaders in steel production (i.e., China, Japan, Russia, Korea, Germany, Brazil and Ukraine) mostly use BF + BOF technologies. In turn, EAF technology is predominant in the USA, India and Turkey [29]. In the EU, the share of BF + BOF technology of the total production of crude steel is smaller and amounts to 60%. In Poland, the share of BF + BOF processes of total production is approximately 50%. EAF technology is characterised by high specific electricity consumption. A relatively new technology for steel production is direct reduction of iron ore (DRI). The share of this technology in world production does not exceed 5%. In EU countries, steel production utilising DRI technology is below 1%, and, in Poland, DRI technology is not used at all [30]. The unit production cost of the DRI process is very high at present; therefore, the key technologies used in the world are BF + BOF and EAF. These technologies have opposite features (if their description takes into account the impact on the environment) in terms of the intensity of resource and energy consumption (resource intensity and energy intensity). BF + BOF technology uses a lot of fossil fuels, which results in high greenhouse gas emissions to the environment (mainly CO₂).

In the literature, there is a debate surrounding the superiority of EAF technology over BF + BOF and vice versa (depending on the evaluation criterion of the adopted technology). One of the key issues raised by researchers is related to energy intensity [31]. There is no doubt that the BF + BOF route consumes significantly more energy and produces more carbon emissions than the EAF route, being responsible, as a whole, for around 5% of overall global CO₂ emissions [32], which is unfortunately associated with the fact that these emissions are some of the most difficult to reduce [33]. The steel industry is responsible for approximately 7% of CO₂ emissions [34]. This is a major concern, as one has to remember that issues related to environmental protection are one of the main problems faced by the modern world. Manufacturing companies are mainly responsible for these pollutants [16,35].

In contrast, the EAF technology requires approximately 30% of the energy required in the BF + BOF process [19,20]. This is due to the production of iron through blast furnaces. In turn, EAFs are used for steel making in smaller plants, and the production of steel is less energy-intensive due to avoidance of the energy-intensive production of iron. In the EAF process, energy is used to melt the scarp; therefore, its consumption is lower [36]. Economic factors (cost savings, energy tax, capital budget) determine energy intensity in the steel sector [37]. According to Rojas-Cardenas et al. (2017) [38], the capacity utilisation of the plants, cost of energy and raw materials as well as environmental regulations in the

particular countries also have an impact on the energy intensity of steel manufacturing. For example, using data on China's most energy-intensive enterprises, Fisher-Vanden (2016) [39] claim that if the prices of energy are higher, this causes a reduction in energy intensity. The same is observed in the EU, even with higher intensity, where regulations (e.g., higher and higher CO₂ emissions costs) have a direct impact on production costs, which in turn forces steel plants to use more efficient technologies. Given these facts, the energy efficiency of steel production is of primary concern to steel companies [29], as well as a key focus of sustainable policies and practices [40,41].

There are many studies that deal with analyses of energy intensity in the steel industry. For example, Worrell et al. (2007) [42] analysed best practices on energy intensity in different industries, including the steel sector. Reddy and Ray (2011) [43] studied the energy intensity of the steel industry in India in the years 1991–2005. Their findings show that energy intensity decreased by 5.17% for alloy steel over this time period, however this result was still higher compared with developed countries. In turn, Sheinbaum et al. (2010) [44] conducted a similar study in Mexico. The results indicate that reduction in energy intensity was mostly caused by a higher share of DRI and EAF technologies.

Carmona et al. (2019) [40] analysed the UK's steel sector in the years 1960–2009. The main factors that were analysed related to "resource efficiency" and "useful exergy efficiency" in relation to BF + BOF and EAF technologies. The results achieved show that the sector's overall resource efficiency rose from 19% to 32% over this time (the BOF's resource efficiency increased by 9%, whilst the EAF route rose by 20%). Furthermore, analysing the Indian steel industry, Dasgupta & Roy (2016) [19] stated that energy intensity declined from 41.9 GJ/tonne steel in 1990 to 27.3 in 2008. Nevertheless, it was still much more than in the USA (14.90 GJ/tonne) or even in China (23.11 GJ/tonne) [45]. The research of Wiboonchutikula et al. (2014) [46], conducted in Thailand, showed different results. However, although the EAF technology is much less energy-intensive, the BF + BOF route will still dominate in many, mostly emerging countries (Lu et al., 2016) [47].

One cannot forget that investments to reduce energy intensity in the steel industry are part of social responsibility. Since sustainability has been popularised, social responsibility has taken on a green colour [48,49], becoming one of crucial issues for modern organisations. Social responsibility encompasses a number of aspects that are sometimes related to very different issues in modern business, such as a company's performance (e.g., [50], luxury business [51,52], relations among employees and their well-being [53,54], brand management and communication [55,56] and many others. A part of environment sustainability is sustaining energy supply and energy consumption. According to Prindle et al. (2007) the "twin pillars" of sustainable energy are Energy Efficiency (EE), with innovative investments and new technologies of production, and Renewable Energy (RE) [57].

Moreover, the process of energy intensity in steel industry is part of the sustainability policy. A sustainable transformation of the steel plants will not happen without outside influence; governments will play a major role. According to a report by the International Energy Agency (IEA), the projection horizon of changes extends to 2050, however, 2030 should be taken as the critical moment for accelerating sustainable transformations [58]. A deep transformation is not possible without innovation in technologies for near-zero emission steelmaking and low energy intensity (especially from black energy). Energy prices, technology costs, feedstock availability and government policies are all determinants of the direction of change. According to the same IEA report, global steel demand is likely to increase by more than 30% by 2050. At the same time, it is worth mentioning that the Covid-19 crisis has caused disruption to the global economy, causing a decline of at least 5% in steel production in 2020 as compared to 2019. Now that the steel industry is returning to a growth trajectory and investment will again accelerate as a result, there is an emphasis on replacing the least efficient units. Both overarching government policies towards the steel industry and "grassroots innovations"—technological investments in steel plants—must be implemented in parallel in order to reduce energy intensity. Investments in the steel sector that reduce energy consumption and emissions to the environment are part of a

proactive energy management model for plants and supply chains [59]. Selko (2012) [60] emphasises that energy management becomes truly proactive when companies analyse their energy intensity in production, and energy intensity is considered to be an economic criterion for production. Energy efficiency belongs to the most important means by which the industry can diminish its greenhouse gas emissions, as well as lowering production costs [61].

2.2. Energy Intensity in Steel Industry in Poland

Energy intensity directly influences production costs and, thus, competitiveness of steel companies. The impact of investments on energy intensity in the steel industry is stretched over time. For example, Wolniak et al. show in their study that the more investments steel plants make, the more energy intensity decreases [3]. The same conclusions were reached by Gajdzik and Sroka in previous studies [2]. Gajdzik shows that in the period from 2000 to 2019, energy intensity was 0.2320 toe/tonne of steel. The energy intensity in Poland during the analysis period was lower than the average energy intensity in the EU. The average energy consumption in the EU was 0.3120 toe/tonne [62]. Wolniak et al. analysed the model of energy intensity in Polish steel industry for all technological processes. The correlation analyses carried out show the delay of the impact of technological investments on the reduction of energy intensity per 1 tonne of steel. In their model, an increase in investment by PLN 1 million (ca. 220 thousand Euro) causes the reduction in energy consumption per 1 tonne of steel by 0.0000357 toe/t. [3]. One should add that, in Poland, steel is manufactured in electric furnaces and converters. The average annual steel production in Poland in 2000–2019 amounted to 9.13 million tonnes. Since 2003, only two steel production technologies have been used in Poland: EAF and BOF. The third technology of steel smelting in open-hearth furnaces (Martins') has been withdrawn for economic and environmental reasons. The share of this technology in the total steel production in Poland in the last years before its withdrawal was low. In 2000, the share of open-hearth steel in the total of steel produced in Poland was 3.8%, the production dropped to 2.3% in 2001, and in the last year of using open-hearth furnaces, only 1.2% of crude steel was produced using this method. Due to the small share of open-hearth technology in the total of steel production in Poland in 2000–2002, it was not included in our analysis.

EAF technology is characterised by low direct emissions but high energy consumption. In Poland (due to the low share of energy produced from renewable raw materials), the energy consumption of steel mills is very high. According to the Central Statistical Office (Statistics Poland), there are three industries in the group of high energy consumption in the Polish processing industry: metallurgical, chemical and mineral. The share of energy consumption of these three highly energy-intensive industries in domestic industry is presented in Table 1 (energy consumption in 2000 was compared with energy consumption in 2018, as there was no data for 2019).

Table 1. Industries with high energy intensity in Poland [63].

	Metallurgical		Chemical		Mineral		Total		Industry Total
	%	Mtoe	%	Mtoe	%	Mtoe	%	Mtoe	
2000	26	4.86	21	3.81	14	2.67	61	11.34	18.56
2018	17	2.99	16	2.85	18	3.15	52	8.99	17.37

In 2018, the share of energy consumption in the Polish steel sector in the production sold was 1.356 kgoe/EUR. A comparison of the energy consumption of the steel sector in other industries based on the share of electricity in the production sold is shown in Figure 1.

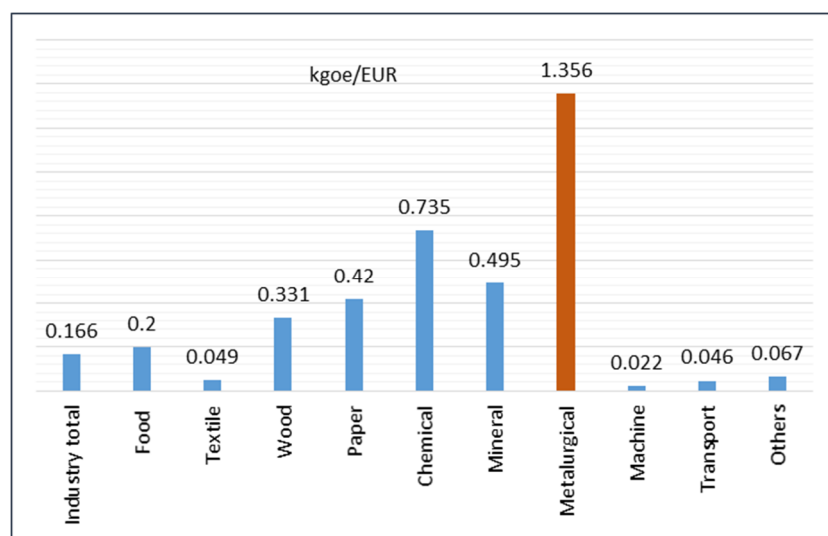


Figure 1. Share of energy intensity in sold production of industry branches in Poland in 2018. Source: own analysis based on [64].

In the analysed period from 2000 to 2019, the energy consumption per 1 tonne of steel dropped from over 0.3 toe to 0.19 toe. The data are presented in Figure 2. The trend of energy consumption showed a strong decrease until 2009 (a decrease by 0.13 toe/tonne of steel in 2009 compared to 2000). The year 2009 was marked by a decrease in production (Figure 3) as a result of the global financial crisis. After 2009, the average annual energy consumption per 1 tonne of steel produced was 0.19333 toe.

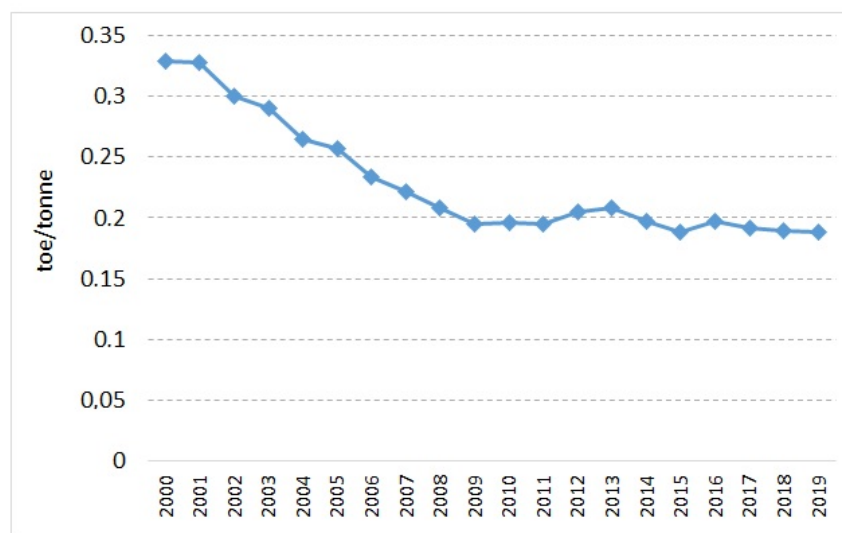


Figure 2. Energy consumption per tonne of steel produced in Poland in 2000–2019. Source: based on [65,66].

The energy consumption of metallurgy in Poland was compared with the production volume of crude steel (Figure 3). It is difficult to statistically analyse the trend of steel production in Poland, due to the occurrence of periodic fluctuations. In periods of boom for steel products, all the steel plants have a full portfolio of orders and produce more steel. The current production capacity of the Polish steel industry is not fully utilised, and it is estimated that the steel industry in Poland uses approximately 75% of the production capacity annually on average.

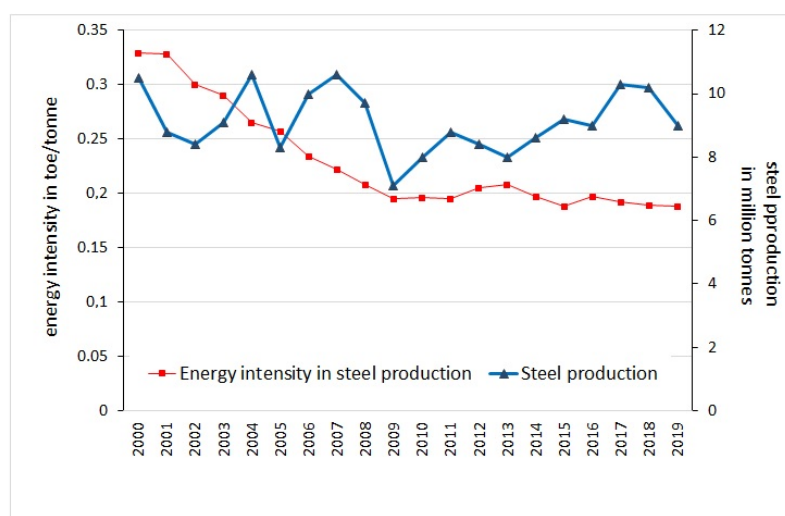


Figure 3. Energy consumption and steel production in Poland in 2000–2019. Source: own analysis based on [67].

Key technological investments were made in the steel industry at the beginning of this century. In 2007, the European Commission published a final report on the completion of the supervised restructuring of steelworks in Poland. Steel plants have been privatised, and the largest steel producers in Poland were purchased by strong foreign steel groups, such as Arcelor Mittal, Celsa and CMC [68]. A strong increase in spending on technological investments was conducted just prior to the global financial crisis. After the crisis, such a strong boom in investments, was not recorded, and energy consumption remains below 0.2 toe/tonne of crude steel produced. Trends in energy consumption in steel production and investment expenditure are summarised in Figure 4. Among the activities of steel plants that contributed to the decline in energy consumption in the analysed period, were: the withdrawal of steel production technology in open-hearth furnaces (in statistical summaries, 2002 was the last time steel was produced in Martins’ furnaces); the development of a continuous steel casting line in integrated steel mills (blast, furnace, converters, rolling); and the use of information systems (computer technology) to control the operation of steel smelting furnaces and other devices, production automation and shortened production cycles. In order to implement energy efficiency strategies, steel plants introduced ICT technology to monitor the production processes of steel and steel products. In the pursuit of production flexibility and process optimisation, mills began to use IT systems and real-time data collection technologies.

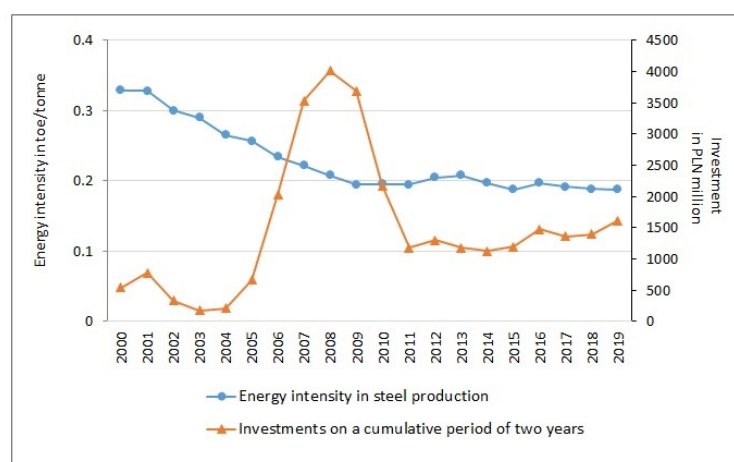


Figure 4. Energy intensity and investments in the Polish steel industry in 2000–2019. Source: own analysis based on [67].

Given the deliberations presented, we formulated the following research hypothesis:

Hypothesis 1 (H1): *There is a relationship between the volume of steel production utilising the EAF process and the energy consumption of the process and the impact of the investment on the decrease in energy consumption in the production of steel produced in electric furnaces.*

3. Materials and Methods

Data from the Polish Steel Association were used to assess energy consumption in the steel sector (iron metallurgy) in Poland. The scope of the analysis included the production of steel in electric arc furnaces (EAF). The data used for the analysis are summarised in Table 2.

Table 2. Empirical data used in the analysis [63–67].

No.	Year	EAF Production in Thousands of Tonnes	Steel Scrap Used in the EAF in Tonnes	Scrap per 1000 Tonnes of EAF Steel	Energy Used in the EAF in GWh	Energy kWh/1 Tonne of Crude Steel in the EAF	Investments (Cumulative) in PLN Million
1	2000	3290	3,540,209	1076	1860	565	272
2	2001	2814	3,054,446	1085	1599	568	389
3	2002	2561	2,872,406	1122	1362	532	439
4	2003	3037	3,178,588	1047	1693	557	477
5	2004	3717	4,177,197	1124	2036	548	546
6	2005	3443	3,926,662	1140	1870	543	810
7	2006	4241	4,796,388	1131	2278	537	1414
8	2007	4434	4,979,142	1123	2301	519	2324
9	2008	4503	5,044,314	1120	2264	503	3221
10	2009	3893	4,356,850	1119	1914	492	3983
11	2010	3998	4,459,250	1115	1958	490	4225
12	2011	4355	4,867,957	1118	2073	476	4575
13	2012	4132	4,612,867	1116	2011	487	4876
14	2013	3551	3,960,351	1115	1712	482	5163
15	2014	3492	3,883,164	1112	1621	464	5438
16	2015	3492	4,238,013	1214	1577	452	5763
17	2016	3877	4,366,044	1126	1771	457	6178
18	2017	4624	5,149,505	1114	2127	460	6443
19	2018	4765	5,258,195	1104	2092	439	6878
20	2019	4077	4,484,285	1100	1810	444	7228

Figure 5 shows the trends of the studied phenomena: steel production by EAF, scrap consumption and energy consumption in production. In order to produce one tonne of steel utilising the EAF process, 1.12 tonnes of steel and cast iron scrap are required (Figure 6). The average annual electricity consumption in electric furnaces is 1896.45 GWh, and periodic fluctuations were noted in the energy consumption trend (Figure 7). The energy consumption per 1 tonne of EAF steel is shown in Figure 8. The average energy intensity per 1 tonne of crude steel utilising the EAF process is 500.7 kWh.

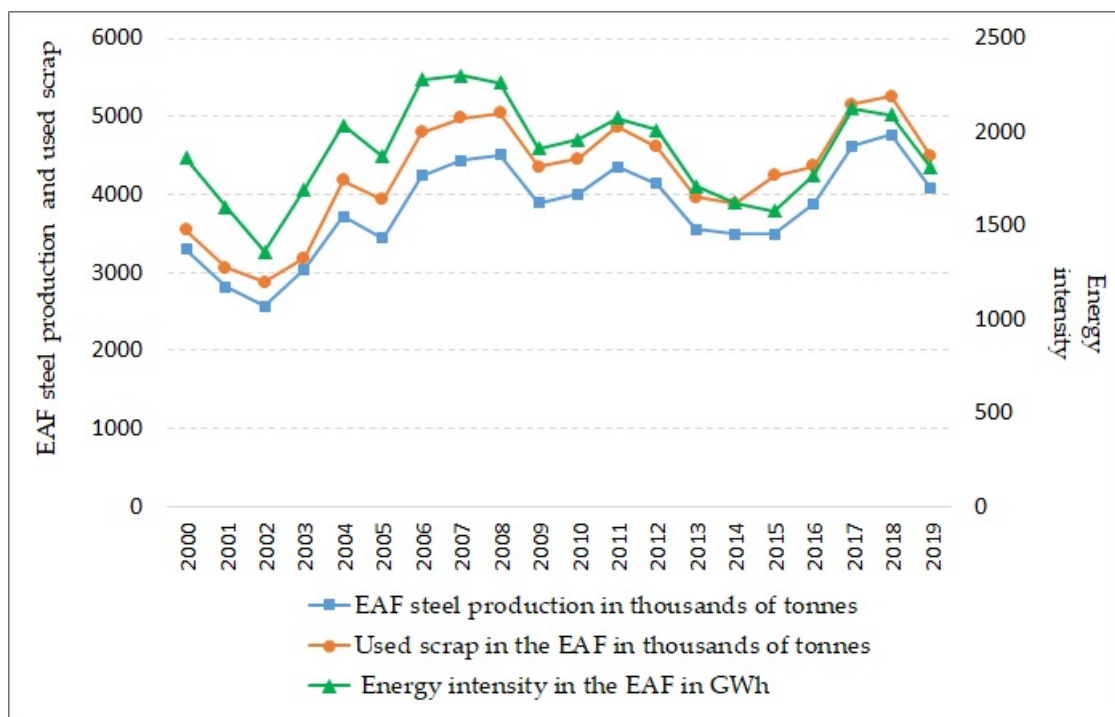


Figure 5. Steel production by EAF, used scrap and energy intensity.

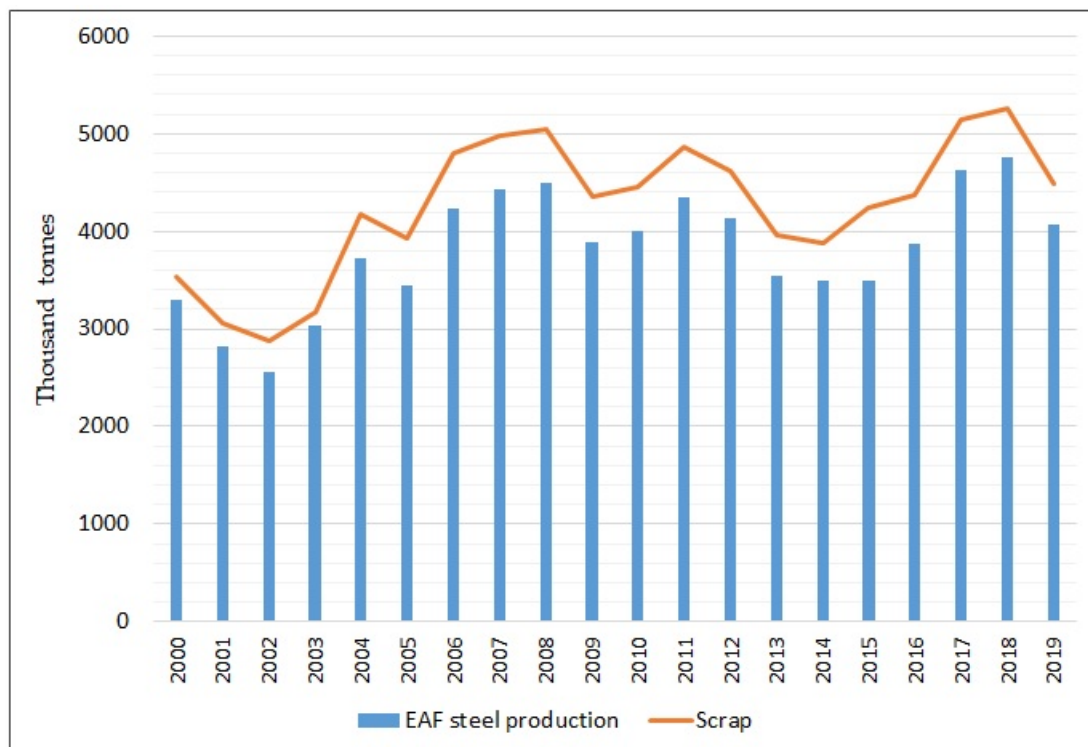


Figure 6. Steel production by EAF and used scrap in the production process.

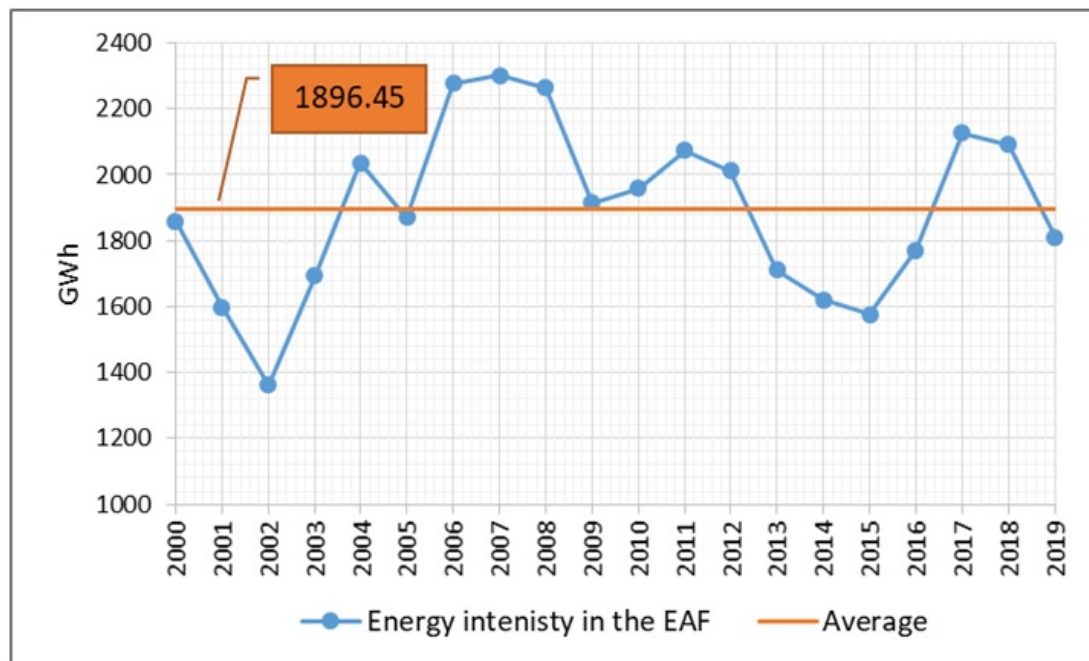


Figure 7. Energy intensity utilising the EAF process.

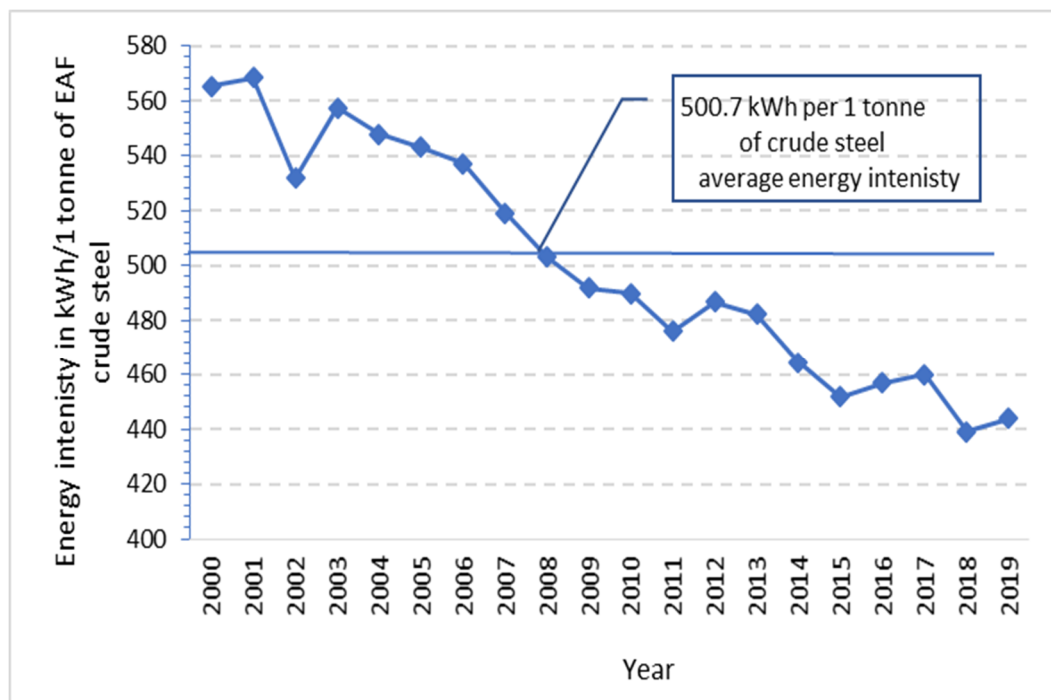


Figure 8. Energy intensity per 1 tonne of crude steel produced utilising the EAF process.

The data presented in Table 2 were used for econometric modelling. The econometric test procedure included: determining the model specification (determining the explanatory and explanatory variables, determining the model form, data sources and formal reliability), analysis of statistical data and assessment of their suitability for model building, estimation of model parameters based on static data (Table 2), verification of the model (using coefficients and econometric tests), and inference through the analysis of the influence of the model's explanatory variables on the explained variables.

The least squares method was used to estimate the econometric models. The choice of this method was dictated by the fact that no stochastic assumptions are required. This is the best known and most widely used method for estimating regression parameters. The available (licensed) Excel-Regression tool was used.

Single equation modelling was applied and no time factor was used (static models). In the paper, three single-equation models were quoted: a two-factor power model (1), a linear two-factor model (2), and a linear one-factor model (3). General forms of used models are:

For model (1):

$$Y = cX_1^a \times X_2^b \quad (1)$$

and its linear form:

$$\ln Y = \ln c + a \ln X_1 + b \ln X_2 \quad (2)$$

For model (2):

$$Y = c + aX_1 - bX_2 \quad (3)$$

For model (3):

$$Y = c - aX \quad (4)$$

where:

Y : is dependent variable

X_1 and X_2 (or X in model 3) are independent variables (explanatory variables)

c : is a constant intercept

a and b : are regression coefficients

The models presented in the paper have been verified in terms of their formal and content-related aspects. For verification, bulk tools and tests were used: coefficient of determination, R^2 fit coefficients, fit test (F statistic), expressiveness coefficient, parameter significance test (Student's t -statistic), Durbin–Watson test, residual randomness test (series test statistic), decomposition normality test residuals (Jarque–Bera statistic), residual symmetry test (t statistic), and the random component homoscedasticity test (White's test). For each of the models, using the aforementioned coefficients and tests, confirmation of the adequacy of the models to the actual data was obtained. The basic assumptions were met. At the present stage of the analysis, the models were found to be useful for the analysis of the studied phenomena. Efforts were made to determine the impact of scrap consumption and energy consumption on the volume of steel production in electric furnaces (1) and energy consumption of steel production utilising EAF technology by using explanatory variables X_i .

4. Results and Discussion

4.1. Model 1

For the purposes of this study, the model of an inverse relationship was analysed, i.e., the impact on the volume of steel production utilising the EAF (Y) (thousand tonnes) process and the consumption of the input material—scrap (X_1) (tonnes) and energy consumption (X_2) (GWh). The obtained power two-factor model of the form:

$$Y = 0.0859 \times X_1^{0.43} \times X_2^{0.54} \quad (5)$$

was very well fitted, the coefficient R^2 was 0.903, which means that 90.3% of the variation in Y is explained, the fit is very good ($R^2_d = 0.950$), and the coefficient $Se = 0.0067$. On the basis of the significance test of the parameters (statistics— t), the following was obtained: X_1 : $t = 5.23$ for $p < 0.99$ (parameter X_1 is significant); X_2 : $t = 4.12$ for $p < 0.99$ (parameter X_2 is significant). Figure 9 shows the trend of empirical data and the trend of the ex-post forecast obtained on the basis of model (1). In the period from 2000 to 2009, the adjustment of the actual data to the forecast is more accurate than in the period from 2010 to 2019. In the last three years (the period from 2017 to 2019), there were higher deviations (the model in these years is underestimated).

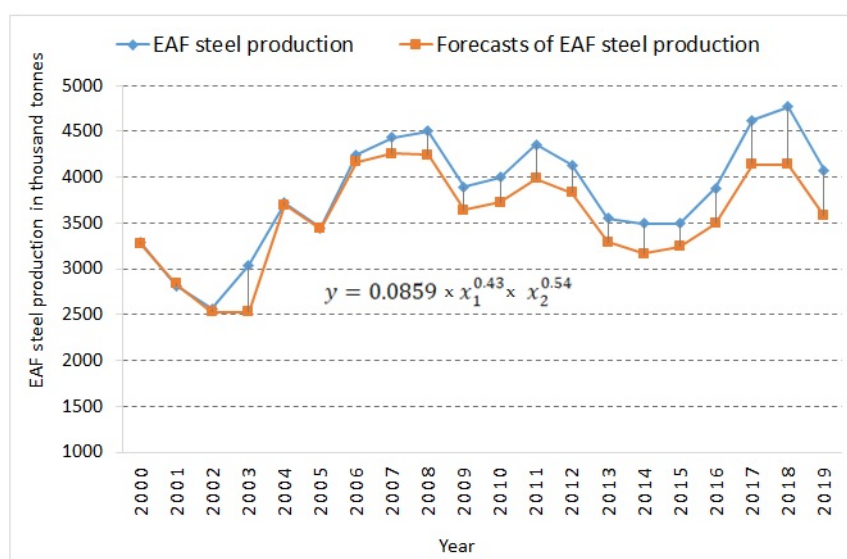


Figure 9. Comparison of the actual steel production data utilising the EAF process with the ex-post forecast based on model (1).

4.2. Model 2

The next is a two-factor linear model (2):

$$Y = 610.53 + 0.000356X_1 - 0.05985X_2 \quad (6)$$

The model describes the dependence of electricity consumption in electric furnaces (Y) (GWh) on the consumption of steel scrap in electric furnaces (X_1) (tonnes) and investments in enterprises with an electric furnace (cumulatively) (X_2) (million PLN). The model is well fitted, the R^2 coefficient was 0.804, which means that 80.4% of the Y variation is explained, the fit is very good ($R^2_d = 0.897$), and the Se coefficient = 0.0063. On the basis of the significance test of the parameters (statistics— t), the following was obtained: X_1 : $t = 58.32$ for $p < 0.99$ (parameter X_1 is significant); X_2 : $t = -4.31$ for $p < 0.99$ (parameter X_2 is significant). Figure 10 shows the trend of empirical data and the trend of the ex-post forecast obtained on the basis of model (2). The trend of the ex-post forecast reflects the empirical data well (greater deviations of the model from the empirical data were recorded for 2003 and 2015).

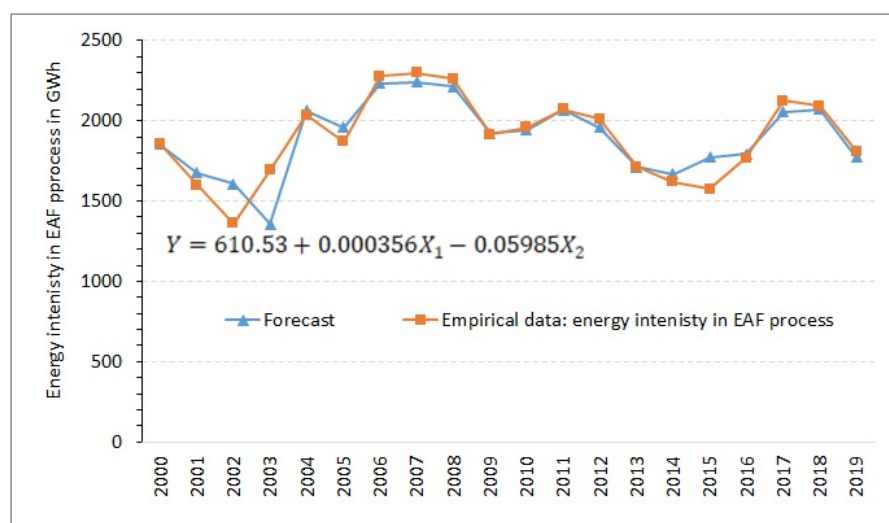


Figure 10. Comparison of the actual data of electricity consumption for steel production utilising the EAF process with the ex-post forecast based on model (2).

4.3. Model 3

The third model represents the dependence between the investments and energy consumption utilising the EAF process on 1 tonne of crude steel.

$$Y = 560.02 - 0.0168X \quad (7)$$

Model (3) is very well fitted to the actual data, 96.2% of Y variability explained ($R^2 = 0.9619$), the coefficient of fit $R^2_d = 0.9808$, the coefficient of clarity $Se = 0.017016$, the parameter X is significant ($X: t = -21.3$ for $p > 0.99$), statistical tests confirm the reliability of the model, and the residual distribution is a random distribution (series test statistic: $Ke = 13$ $K_1 < Ke < K_2$) and normal (Jarque-Bera test: $JB = 1.3$ $JB > 5991$). The simplest linear model turned out to be the model best suited to the actual data (Figure 11). Its interpretation indicates the existence of a negative relationship between the increase in technological institutions in steel mills and the energy consumption of steel production according to the EAF process. The downward trend in the analysed period (from 2000 to 2019) of energy consumption per 1 tonne of solid produced in electric furnaces is significant (a decrease of 21.44% in 2019 compared to energy consumption per 1 tonne of steel in 2000).

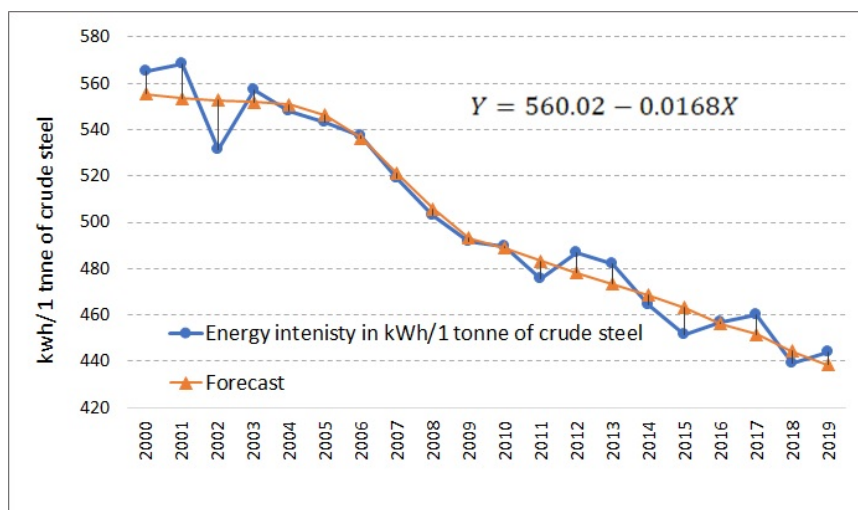


Figure 11. Comparison of the actual data of electricity consumption for steel production utilising the EAF process with the ex-post forecast based on model (3).

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

- *in accordance with model (1):*
 - an increase in the consumption of steel scrap (X_1) in electric furnaces by 1% will result in an increase in the production volume of EAF (Y) steel by 0.43%, with the second factor remaining unchanged, i.e., electricity (X_2), in this model,
 - an increase in electricity consumption (X_2) utilising EAF technology by 1% will increase the EAF steel production volume (Y) by 0.54%, with the first factor remaining unchanged, which, in this model, is scrap consumption (X_1).
- *in accordance with model (2):*
 - an increase in the consumption of steel scrap (X_1) in electric furnaces by a unit [tonne] will increase the consumption of electricity needed for the production of EAF (Y) steel by 356 kWh, with the second factor remaining unchanged, which, in this model, are investments (X_2),
 - an increase in investments by PLN 1 million (X_2) in electric steel mills will reduce electricity consumption in the production of EAF (Y) steel by 60 GWh, with the first factor remaining unchanged, which is the consumption of scrap in this model (X_1).

- *in accordance with model (3):*
 - an increase in investment outlays by PLN 1 million in the plants manufacturing steel in EAF technology will lead to a reduction in unit electricity consumption by 16.8 kWh/1 tonne of crude steel (assuming that other factors are unchanged).

Because the main raw material in EAF process is electricity, investments towards production efficiency also lead to a reduction in energy consumption. The final conclusion, which is the reference to the research hypothesis (H1), is that there is a relationship between the volume of steel production utilising the EAF process and the energy consumption of the process, which is influenced by investments. The correlation is negative, i.e., along with the increase in technological investments in electric steel plants in Poland, a decrease in the energy consumption of steel produced in electric furnaces was noted in the analysed period (2000–2019). Our findings are in line with the results of Arens et al. (2012) [20], who stated that energy consumption per tonne of crude steel in the German steel industry decreased by 6.3%, 4.6% of which occurred between 1994 and 2007. This decrease in energy consumption per tonne of crude steel originates from an increase in the share of EAF production. In a broader perspective, our research confirms the findings of Kim and Worrell (2002) [34], who stated that investments made in developing countries have led to increased energy efficiency in Korea, China, Brazil, Mexico and India. The same results were observed in China. According to the report of the National Bureau of Statistics of China (2018) [69], investments in the production capacities of steel plants had a positive impact on the energy efficiency in the said sector, as the energy intensity decreased by 11.5% in the period between 2006 to 2017 (the report does not differentiate the energy intensity among the technologies applied by the particular companies). On the way to saving energy, steel mills will retain the concept of sustainability, which is a key strategy for industries with a strong environmental impact. Even in new technological trends, the concept of sustainability remains relevant in industrial companies [70].

5. Conclusions

The steel sector is changing under the pressure of industrial trends. For a decade, it has been strongly influenced by Industry 4.0. and changes in the steel sector began with the digitalization of processes. IT technologies have created the conditions for new forms of business. Nevertheless, despite these changes the matter of energy intensity of the steel processes is of crucial importance for all steel plants. Therefore, the issue of energy consumption in steel production utilising both BF + BOF and EAF technology has become a topic of wide scientific discussion, both among researchers as well as business managers. There is no doubt that in order to save energy, the steel industry (which relies on high-intensity energy use) should improve its energy efficiency. In this study, we made reference to the research gap in the topic of energy consumption for steel production processes in terms of the EAF steel production route existing in Poland.

The findings also show that although important energy efficiency efforts in the analysed iron and steel industry have been carried out recently, there is a need for more efforts to reduce GHG emissions. It is very likely that with the growth of the world's steel industry, more energy-efficient technologies will be developed (this has already been observed in recent years in China).

Our study contributes to the theory in several ways. Firstly, it is a new analysis that raises a very important issue for the global steel industry—that is, the connection between the energy intensity and investments conducted in this sector—and thus reduces the research gap in this aspect. Secondly, we have built up three econometric models: a two-factor power model, a linear two-factor model and a linear one-factor model. These can be used to study the analysed phenomena in other countries manufacturing steel utilising EAF technology. This definitely constitutes a high added value within our study.

In addition, our analysis also presents some important implications. First of all, it shows very clearly that one has to create specific regulations and financial incentives to invest in energy efficient technologies. One may indicate that there is a need for regional

level policies in order to provide adequate incentives to firms for investment in energy efficient technology. Poland's steel plants are mostly located in the Silesia region, which is, on the one hand, the most industrialised and developed province in Poland, with a concentration of heavy industry; on the other hand, it is also the most polluted. Such policies would also help to diminish GHG emissions.

Our study is not free from limitations. The steel industry in Poland is not one of the major steel industries in the world. This is why our analysis is based on a relatively small number of steel plants. Another limitation may also be the use of secondary data. Nevertheless, the long period that was analysed and the credibility of the data results in a very good overview of the situation in the steel industry in Poland.

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References

1. Flues, F.; Rubbelke, D.; Vögele, S. An analysis of the economic determinants of energy efficiency in the European iron and steel industry. *J. Clean. Prod.* **2015**, *104*, 250–263. [\[CrossRef\]](#)
2. Gajdzik, B.; Sroka, W. Resource Intensity vs. Investment in Production Installations—The Case of the Steel Industry in Poland. *Energies* **2021**, *14*, 443. [\[CrossRef\]](#)
3. Wolniak, R.; Saniuk, S.; Grabowska, S.; Gajdzik, B. Identification of Energy Efficiency Trends in the Context of the Development of Industry 4.0 Using the Polish Steel Sector as an Example. *Energies* **2020**, *13*, 2867. [\[CrossRef\]](#)
4. Hernández, A.G.; Paoli, L.; Cullen, J. Resource efficiency in steelmaking: Energy and materials combined. *Energy Procedia* **2017**, *142*, 2429–2434. [\[CrossRef\]](#)
5. Grabara, J.; Tleppayev, A.; Dabylova, M.; Mihardjo, L.W.W.; Dacko-Pikiewicz, Z. Empirical Research on the Relationship Amongst Renewable Energy Consumption, Economic Growth and Foreign Direct Investment in Kazakhstan and Uzbekistan. *Energies* **2021**, *14*, 332. [\[CrossRef\]](#)
6. Grondys, K.; Androniceanu, A.; Dacko-Pikiewicz, Z. Energy Management in the Operation of Enterprises in the Light of the Applicable Provisions of the Energy Efficiency Directive (2012/27/EU). *Energies* **2020**, *13*, 4338. [\[CrossRef\]](#)
7. Shpak, N.; Kuzmin, O.; Melnyk, O.; Ruda, M.; Sroka, W. Implementation of a Circular Economy in Ukraine: The Context of European Integration. *Resources* **2020**, *9*, 96. [\[CrossRef\]](#)
8. Šebestová, J.D.; Sroka, W. Sustainable development goals and SMEs decisions: Czech Republic vs. Poland. *J. East. Eur. Central Asian Res.* **2020**, *7*, 39–50. [\[CrossRef\]](#)
9. Hussain, H.I.; Slusarczyk, B.; Kamarudin, F.; Thaker, H.M.T.; Szczepańska-Woszczyna, K. An Investigation of an Adaptive Neuro-Fuzzy Inference System to Predict the Relationship among Energy Intensity, Globalization, and Financial Development in Major ASEAN Economies. *Energies* **2020**, *13*, 850. [\[CrossRef\]](#)
10. Shpak, N.; Melnyk, O.; Horbal, N.; Ruda, M.; Sroka, W. Assessing the implementation of the circular economy in the EU countries. *Forum Sci. Oecon.* **2021**, *9*, 25–39. [\[CrossRef\]](#)
11. Popp, J.; Kovács, S.; Oláh, J.; Divéki, Z.; Balázs, E. Bioeconomy: Biomass and biomass-based energy supply and demand. *New Biotechnol.* **2020**, *60*, 76–84. [\[CrossRef\]](#)
12. Gajdzik, B. Environmental aspects, strategies and waste logistic system based on the example of metallurgical company. *Metalurgija* **2009**, *48*, 63–67.
13. Gajdzik, B. Comprehensive classification of environmental aspects in a manufacturing enterprise. *Metalurgija* **2012**, *51*, 541–544.
14. Gajdzik, B. Concentration on knowledge and change management at metallurgical company. *Metalurgija* **2008**, *47*, 142–144.
15. Gielen, D.; Taylor, P. Indicators for industrial energy efficiency in India. *Energy* **2009**, *34*, 962–969. [\[CrossRef\]](#)
16. Mariyakhan, K.; Mohamued, E.A.; Asif Khan, M.; Popp, J.; Oláh, J. Does the level of absorptive capacity matter for carbon intensity? Evidence from the USA and China. *Energies* **2020**, *13*, 407. [\[CrossRef\]](#)

17. Kan, K.; Mativenga, P.; Marnewick, A. Understanding energy use in the South African manufacturing industry. *Procedia CIRP* **2020**, *91*, 445–451. [\[CrossRef\]](#)
18. Androniceanu, A. Transparency in public administration as a challenge for a good democratic governance. *Adm. SI Manag. Public* **2021**, *36*, 149–164. [\[CrossRef\]](#)
19. Dasgupta, S.; Roy, J. Analysing energy intensity trends and decoupling of growth from energy use in Indian manufacturing industries during 1973–1974 to 2011–2012. *Energy Effic.* **2016**, *10*, 925–943. [\[CrossRef\]](#)
20. Arens, M.; Worrell, E.; Schleich, J. Energy intensity development of the German iron and steel industry between 1991 and 2007. *Energy* **2012**, *45*, 786–797. [\[CrossRef\]](#)
21. Quadera, M.; Ahmed, S.; Ghazillaa, R.; Ahmed, S.; Dahari, M. A comprehensive review on energy efficient CO2 breakthrough technologies for sustainable green iron and steel manufacturing. *Renew. Sustain. Energy Rev.* **2015**, *50*, 594–614. [\[CrossRef\]](#)
22. Mousa, E.; Wang, C.; Riesbeck, J.; Larsson, M. Biomass applications in iron and steel industry: An overview of challenges and opportunities. *Renew. Sustain. Energy Rev.* **2016**, *65*, 1247–1266. [\[CrossRef\]](#)
23. Chan, D.Y.-L.; Huang, C.-F.; Lin, W.-C.; Hong, G.-B. Energy efficiency benchmarking of energy-intensive industries in Taiwan. *Energy Convers. Manag.* **2014**, *77*, 216–220. [\[CrossRef\]](#)
24. Oda, J.; Akimoto, K.; Tomoda, T.; Nagashima, M.; Wada, K.; Sano, F. International comparisons of energy efficiency in power, steel, and cement industries. *Energy Policy* **2012**, *44*, 118–129. [\[CrossRef\]](#)
25. He, H.; Guan, H.; Zhu, X.; Lee, H. Assessment on the energy flow and carbon emissions of integrated steelmaking plants. *Energy Rep.* **2017**, *3*, 29–36. [\[CrossRef\]](#)
26. International Energy Agency. *Energy Technology Perspectives 2012*; International Energy Agency: Paris, France, 2012.
27. Gajdzik, B.; Gawlik, R.; Skoczypiec, S. Forecasting-Scenario-Heuristic method proposal for assessment of feasibility of steel production scenarios in Poland—Managerial implications for production engineering. *Arch. Civ. Mech. Eng.* **2018**, *18*, 1651–1660. [\[CrossRef\]](#)
28. Gajdzik, B.; Piątkowski, J.; Kliś, P. Prognostic methodology of forecasts steel production for Poland until 2022. *Metalurgija* **2020**, *51*, 129–132.
29. He, K.; Wang, L.; Li, X. Review of the energy consumption and production structure of China's steel industry: Current situation and future development. *Metals* **2020**, *10*, 302. [\[CrossRef\]](#)
30. World Steel Association. *Steel Statistics Yearbook 2018*; World Steel Association: Belgium, Brussels, 2019.
31. Androniceanu, A.-M.; Caplescu, R.D.; Tvaronavičienė, M.; Dobrin, C. The interdependencies between economic growth, energy consumption and pollution in Europe 2021. *Energies* **2021**, *14*, 2577. [\[CrossRef\]](#)
32. Arasto, A.; Tsupari, E.; Kärki, J.; Sihvonen, M.; Lilja, J. Costs and Potential of Carbon Capture and Storage at an Integrated Steel Mill. *Energy Procedia* **2013**, *37*, 7117–7124. [\[CrossRef\]](#)
33. Flores-Granobles, M.; Saeys, M. Minimizing CO2 emissions with renewable energy: A comparative study of emerging technologies in the steel industry. *Energy Environ. Sci.* **2020**, *13*, 1923–1932. [\[CrossRef\]](#)
34. Kim, Y.; Worrell, E. International comparison of CO2 emission trends in the iron and steel industry. *Energy Policy* **2002**, *30*, 827–838. [\[CrossRef\]](#)
35. Kot, S.; Haque, A.U.; Kozlovski, E. Strategic SCM's Mediating Effect on the Sustainable Operations: Multinational Perspective. *Organizacija* **2019**, *52*, 219–235. [\[CrossRef\]](#)
36. Haider, S.; Mishra, P.P. Benchmarking energy use of iron and steel industry: A data envelopment analysis. *Benchmarking Int. J.* **2019**, *26*, 1314–1335. [\[CrossRef\]](#)
37. Lee, K.-H. Drivers and Barriers to Energy Efficiency Management for Sustainable Development. *Sustain. Dev.* **2014**, *23*, 16–25. [\[CrossRef\]](#)
38. Rojas-Cardenas, J.C.; Hasanbeigi, A.; Sheinbaum-Pardo, C.; Price, L. Energy efficiency in the Mexican iron and steel industry from an international perspective. *J. Clean. Prod.* **2017**, *158*, 335–348. [\[CrossRef\]](#)
39. Fisher-Vanden, K.; Hu, Y.; Jefferson, G.; Rock, M.; Toman, M. Factors influencing energy intensity in four Chinese industries. *Energy J.* **2016**, *37*, 153–178. [\[CrossRef\]](#)
40. Carmona, L.G.; Whiting, K.; Carrasco, A.; Sousa, T. The evolution of resource efficiency in the United Kingdom's steel sector: An exergy approach. *Energy Convers. Manag.* **2019**, *196*, 891–905. [\[CrossRef\]](#)
41. Haseeb, M.; Kot, S.; Hussain, H.I.; Kamarudin, F. The natural resources curse-economic growth hypotheses: Quantile-on-Quantile evidence from top Asian economies. *J. Clean. Prod.* **2020**, *279*, 123596. [\[CrossRef\]](#)
42. Worrell, E.; Price, L.; Neelis, M.; Galitsky, C.; Zhou, N. *World Best Practice Energy Intensity Values for Selected Industrial Sectors*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2007.
43. Reddy, B.S.; Ray, B.K. Understanding industrial energy use: Physical energy intensity changes in Indian manufacturing sector. *Energy Policy* **2011**, *39*, 7234–7243. [\[CrossRef\]](#)
44. Sheinbaum, C.; Ozawa, L.; Castillo, D. Using logarithmic mean Divisia index to analyze changes in energy use and carbon dioxide emissions in Mexico's iron and steel industry. *Energy Econ.* **2010**, *32*, 1337–1344. [\[CrossRef\]](#)
45. Hasanbeigi, A.; Price, L.; Chunxia, Z.; Aden, N.; Xiuping, L.; Fangqin, S. Comparison of iron and steel production energy use and energy intensity in China and the US. *J. Clean Prod.* **2014**, *65*, 108–119. [\[CrossRef\]](#)
46. Lu, B.; Chen, G.; Chen, D.; Yu, W. An energy intensity optimization model for production system in iron and steel industry. *Appl. Therm. Eng.* **2016**, *100*, 285–295. [\[CrossRef\]](#)

47. Wiboonchutikula, P.; Chaivichayachat, B.; Chontanawat, J. Sources of Energy Intensity Change of Thailand's Steel Industry in the Decade of Global Turbulent Time. *Singap. Econ. Rev.* **2014**, *59*, 1450027. [\[CrossRef\]](#)
48. Dans, E. Corporate Social Responsibility is Turning Green, and That's A Good Thing. *Forbes* **2018**. Available online: <https://www.forbes.com/sites/enriquedans/2018/09/14/corporate-social-responsibility-is-turning-green-and-thats-a-good-thing/#50f3472a4dca> (accessed on 14 June 2019).
49. Hodulova, K. *Green Corporate Social Responsibility*; Cards Climate Change Platform: Sofia, Bulgaria, 2019; Available online: <https://co2cards.com/green-corporate-social-responsibility> (accessed on 14 June 2019).
50. Popescu, C.R.G. An Exploratory Study Based on a Questionnaire Concerning Green and Sustainable Finance, Corporate Social Responsibility, and Performance: Evidence from the Romanian Business Environment. *J. Risk Financ. Manag.* **2019**, *12*, 162. [\[CrossRef\]](#)
51. MacGregor, R.K.; Sroka, W.; Pelikánová, R.M. A comparative study of the CSR attitude of front-line employees of luxury fashion businesses: Fun or free for sustainability? *Pol. J. Manag. Stud.* **2020**, *21*, 240–255. [\[CrossRef\]](#)
52. MacGregor, R.K.; Sroka, W.; Pelikánová, R.M. The CSR perception of front-line employees of luxury fashion businesses. *Organizacija* **2020**, *53*, 198–211. [\[CrossRef\]](#)
53. Sroka, W.; Vveinhardt, J. Is a CSR policy an equally effective vaccine against workplace mobbing and psychosocial stressors? *Int. J. Environ. Res. Public Health* **2020**, *17*, 7292. [\[CrossRef\]](#)
54. Sroka, W.; Vveinhardt, J. Nepotism and favouritism: How harmful are these phenomena? *Forum Sci. Oecon.* **2020**, *8*, 79–91. [\[CrossRef\]](#)
55. Nadanyiova, M.; Majerova, J.; Gajanova, L. The usage of the CSR concept and its communication in Slovak companies in the process of globalization. *SHS Web Conf.* **2021**, *91*, 01024. [\[CrossRef\]](#)
56. Nadanyiova, M.; Gajanova, L.; Majerova, J. Green Marketing as a Part of the Socially Responsible Brand's Communication from the Aspect of Generational Stratification. *Sustainability* **2020**, *12*, 7118. [\[CrossRef\]](#)
57. Prindle, B.; Eldridge, M.; Eckhardt, M.; Frederick, A. The Twin Pillars of Sustainable Energy: Synergies between Energy Efficiency and Renewable Energy Technology and Policy. ACEEE Report Number E074. 2007. Available online: http://www.paenergyfuture.psu.edu/pubs/aceee_reports/aceee2007sustainable.pdf (accessed on 28 June 2013).
58. Report IEA (International Energy Agency). *Iron and Steel Technology Roadmap*; Launch Webinar; IEA: Paris, France, 08 October 2020; Available online: <https://www.iea.org/reports/iron-and-steel-technology-roadmap> (accessed on 10 August 2021).
59. Paladan, N.N.; Florida, J.S. Reducing Energy Consumption as a Social Responsibility: Towards a Sustainable Energy Supply. *Int. J. Innov. Manag.* **2013**, *1*, 29–40.
60. Selko, A. Steps Industry can Take to Reduce Energy Consumption. An Action Guide to Reduce Consumption of Water, Air, Gas, Electric, and Steam. 2012. Available online: <http://www.industryweek.com/companies-amp-executives/steps-industry-can-take-reduce-energy-consumption> (accessed on 28 June 2013).
61. Bonvoisin, J.; Stark, R.; Seliger, G. Field of Research in Sustainable Manufacturing. In *Sustainable Manufacturing: Challenges, Solutions and Implementation*; Stark, R., Seliger, G., Bonvoisin, J., Eds.; Sustainable Production, Life Cycle Engineering and Management; Springer International Publishing: Cham, Switzerland, 2017. [\[CrossRef\]](#)
62. Gajdzik, B. Modelling the impact of investments on energy intensity in the Polish steel industry as a step towards Industry 4.0. In *Proceedings of the 29th International Conference on Metallurgy and Materials-Metal*, Brno, Czech Republic, 20–22 May 2020; pp. 1210–1215.
63. *National Report Energy Efficiency Trends and Policies in Poland in Years 2006–2016*; Prepared in Framework of ODYSSEE-MURE Project Entitled "Monitoring EU and National Energy Efficiency Targets"; Central Statistical Office & The Polish National Energy Conservation Agency, Warsaw, Poland, 2018. Available online: <https://www.odyssee-mure.eu/> (accessed on 10 June 2021).
64. Gospodarka Paliwowo-Energetyczna w Latach 2017 i 2018. Available online: <https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/gospodarka-paliwowo-energetyczna-w-latach-2016-i-2017,4,13.html> (accessed on 10 June 2021).
65. Efektywność Wykorzystania Energii w Latach 2000–2010. Warszawa 2012. Available online: https://stat.gov.pl/cps/rde/xbcr/gus/SE_efektywnosc_wykorzystania_energii_2000-2010.pdf (accessed on 10 June 2021).
66. Efektywność Wykorzystania Energii w Latach 2008–2018 (Table 3: Energy Intensity of Production). Available online: <https://stat.gov.pl/obszary-tematyczne/srodowisko-energia/energia/efektywnosc-wykorzystania-energii-w-latach-2008-2018,5,15.html> (accessed on 10 June 2021).
67. Hutnicza Izba Przemysłowo-Handlowa. Polish Steel Association. Available online: <https://www.hiph.org/GLOWNA/aktual.php> (accessed on 10 June 2021).
68. Gajdzik, B.; Sroka, W. Analytic study of the capital restructuring processes in metallurgical enterprises around the world and in Poland. *Metalurgija* **2012**, *51*, 265.
69. National Bureau of Statistics of China. *China Energy Statistics Yearbook 2016–2017*; China Statistics Press: Beijing, China, 2018.
70. Gajdzik, B.; Grabowska, S.; Saniuk, S.; Wieczorek, T. Sustainable Development and Industry 4.0: A Bibliometric Analysis Identifying Key Scientific Problems of the Sustainable Industry 4.0. *Energies* **2020**, *13*, 4254. [\[CrossRef\]](#)