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# Electricity and Heat Demand in Steel Industry Technological Processes in Industry 4.0 Conditions

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**Abstract:** The publication presents heat and electricity management in the Polish steel industry. The paper is based on actual data on heat and electricity consumption and intensity by processes in the steel industry in Poland in Industry 4.0 conditions. Two steel production processes are used in Poland: EAF Electric Arc Furnace and BOF Basic Oxygen Furnace. The analysis is an analysis of actual data is used to characterise the electricity and heat consumption by processes in the Polish steel industry. The analysis shows that the EAF technology is always more electricity intensive and the BOF technology more heat intensive. On the basis of conducted analysis, it can be concluded that pro-environmental innovations in the steel industry should first aim to reduce the electricity consumption of EAF technology and the heat consumption of BOF. An analysis of data for Poland for the period 2004–2020 shows that both cases occurred. The study shows that the heat consumption of BOF technologies has been steadily decreasing since 2010, and the electricity consumption of EAF technologies has been decreasing throughout the period under review. It can be concluded from this that the Polish steel industry is adapting to pro-environmental requirements and, through the introduction of technological innovations, is moving towards the concept of sustainable steel production according to green steel principles. The decrease in energy intensity (means electricity) of steel produced according to EAF technology is an important issue, as the high energy intensity of EAF processes affects the overall energy intensity of the steel production in Poland. In the future, the use of new innovative technological solutions, including solutions based on Industry 4.0 principles, should help the Polish steel industry to further reduce the level of electricity and heat consumption. The driving force behind the investment is the boom in the steel market. The authors made a short-term forecasts of steel production (2022–2025). The annual forecasts determined and analyses made were used to determine the heat and energy consumption of the Polish steel industry up to 2025.

**Keywords:** Industry 4.0; steel industry; electricity; heat; steel production; Electric Arc Furnace (EAF); Basic Oxygen Furnace (BOF)

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## 1. Introduction

One of the important aspects of Industry 4.0 implementation in the steel industry is that it is better adapted to environmental requirements, which has to do with its sustainability. The steel industry is today one of the largest emitting industries. This industry is accounting for about 7% of global emissions of greenhouse gases [1]. The development of the low-carbon process and innovation towards decarbonisation of steelmaking processes is a very important part of the development of steel making industry in the future.

Environmental impact is intrinsic to production processes and environmental management is firmly embedded in business management in the industry worldwide. Reducing the environmental nuisance of the industry is one of the main aspects of business operations in highly developed countries [2]. The strategic objective of companies operating in the European Union is to meet the stringent environmental regulations of the European

Commission, by continuously reducing emissions of pollutants and greenhouse gases, as well as managing and recycling waste and reducing the consumption of raw materials. A prerequisite for the development of the industry is to maintain the environmental sustainability of all processes in accordance with the implementation of the concept of sustainable development. The concept of sustainability, despite its long history, was reformulated at the end of the 1990s and new intensive restrictions on the negative impacts of industry intensified in the following years of the first decade of the current century, now adopting radical restrictions on electricity and $CO_2$ emission. Active environmental policies of countries have created a demand for new technologies to reduce pollutant emissions, especially $CO_2$, and new energy sources. Legal environmental mechanisms introduced on a mandatory basis in the industry have become the basis for the operation of companies in various industrial sectors in many countries around the world.

The transformation of companies towards sustainability has involved many industrial sectors, including the steel industry [3]. Technological innovations are helping industries to build sustainability. In the ongoing fourth industrial revolution, active industrial sustainability is a strategic direction for the development of Industry 4.0 [4]. Companies implementing smart manufacturing systems rely on advanced technologies, especially connected with digitalisation, that will increase productivity on the one hand. A smart manufacturing implementation may also lead to a reduction of resource (raw materials) consumption and emissions of greenhouse gas. Given the importance of the topic of fuel and energy economy and the need to reduce electricity by industry, a study was carried out on the sustainability of the steel industry in Poland. The choice of the steel industry as a research area was dictated by the high energy consumption of the steel industry in Poland and also the high $CO_2$ emissions from technological processes needing technological heat [5–7]. In the literature, we can spot a very important concept "green steel" which concentrates on increasing the innovativeness of the steel industry towards adjusting the production systems to climate change [8,9]. According to World Steel Association [10] in the last several years, we can observe many innovative changes in the industry towards the reduction of their carbon footprint. For example, we can describe the following innovations based on Industry 4.0 principles: the increase in the development of new solutions to improve the level of energy efficiency of steel-using solutions and products in the whole society; the increase of money spent on research and development of an innovative solution to identify the new steelmaking technologies with the possibility of reducing the emission of carbon dioxide emission in a significant way, the improvement of the performance of plants using benchmarking solutions and technology transfer; and the implementation of the system of measurement and reporting for steel plants about emissions of carbon dioxide.

In terms of the amount of electricity used in production, the steel industry in Poland is in second place, after the chemical industry, in the ranking of highly energy-intensive industries and first place in terms of electricity per unit of production sold [11,12]. The steel industry in Poland produces an average of about 9 million tonnes of steel per year (captured for the period from 2010 to 2021). Short-term production volume forecasts indicate production of fewer than 9 million tonnes of steel being produced annually in Poland [13]. In Europe, steel producers from Poland are in position 5 with a share of 5.5% (ranking by crude steel production volume) [14,15]. Currently, producers in Poland, as in other countries, have fallen into an economic crisis. First there was the post-COVID-19 crisis (from March 2020) and now, from February 2022, the crises caused by war (war in Ukraine). A huge problem now is electricity and gas prices with increases on an unprecedented scale, destabilising production. An example from Poland: in September 2022, energy prices were 4 times higher than the year before, gas prices in August 2022 were 6 times higher than the year before (data from TGE, EEX). Rising energy prices are a problem primarily for steel mills with electric furnaces (EAF technology) and rolling mills. To remain internationally competitive, steel mills need cheap green energy. Due to rising energy prices and restrictions on energy supply, the EU has announced a 10% reduction in industrial electricity consumption in the energy-saving programmes.

We think the problem is very important from scientific and especially up-to-date economy point of view. The policy of European Union towards decarbonisation leads to the importance of green energy and green steel production. To implement the green steel concept, steelworks should decrease the amount of energy used [16–19]. The methods of how to predict the demand of the energy in a particular country (in this paper, an example of the Polish steel industry) are very important because it gives the authorities the possibility to adjust policy to change the energy mix and push the steel industry towards the decrease of energy demands. Today, the macroeconomic situation connected with skyrocketing energy prices makes the severity of the problem even greater [20,21]. Decarbonisation and rising energy prices lead to the situation in which only those steel mills which will have the lowest energy demand will have chance to survive on the competitive market. [22–26] The first step in this process is the thorough full analysis of the existing historical data about the electricity and heat demand in steel industry with the prognosis for the future. The problem is also connected with the Industry 4.0 implementation because some of the Industry 4.0 related solutions can lead to innovation which can decrease energy demand in this industry.

On the basis of literature analysis (we have analyzed Scopus and Web of Science databases using keywords such as: electricity, industrial heat consumption, green steel, energy intensity, heat intensity; steel production), we have not encountered the analysis about energy and heat demand in the Polish steel industry [27–33]. In addition, there was not analysis about forecasting the further demand up till 2025. We think that prepared electricity and heat forecasts for the Polish steel industry are interesting for the steel mills in Poland.

In light of the arguments presented, the authors have prepared this publication. The literature part served to build the background for the study. The literature part presented the issues of evolving sustainability of the steel industry and its innovation based on the environmental aspects included in the topic of the publication. An essential (key) part of the publication is the analysis and forecasts of the heat and energy intensity in Polish steel production. About the analysis, the authors formulated the following research questions:

- What was the heat consumption in the Polish steel industry in the years 2004–2020?
- What was the energy consumption in the Polish steel industry in the years 2004–2020?

In the following section, the authors presented heat and energy forecasts for the Polish steel industry. The first step was to set the steel forecasts for 2022, 2023, 2024 and 2025. The steel production volume forecasts were used to determine energy and heat demand by 2025. About forecasting, the authors formulated the following research questions:

- What will be the expected heat demand in the Polish steel industry until 2025?
- What will be the expected energy demand (electricity) in the Polish steel industry until 2025?

## 2. Green Steel Industry in Industry 4.0 Conditions—Literature Review

Governments around the world are adopting the orientations enshrined in the United Nations documents—the Agenda for Sustainable Development document—when transforming the industry by 2030. The Document consists of 17 Sustainable Development Goals and 169 targets. Among the Sustainable Development Goals are sustainable energy and clean emission and $CO_2$ reduction [34]. Following the development of sustainable development, it can be seen that new concepts, doctrines, ideas and practices are constantly emerging in this field of knowledge. Some authors argue that the discipline has deeper historical roots and emerged much earlier, with the awareness of business that it needs the environment and the environment needs it, but sustainability was not yet a mass development concept [35,36]. In 1992, the Earth Summit was convened in Rio de Janeiro, where several documents were adopted, including the Rio Declaration, the Global Programme of Action—Agenda 21, the Framework Convention on Climate Change and the Convention on Biological Diversity, among others. Companies have embedded sustainability into their development strategies. Companies in a dynamic environment are forced to constantly seek new directions of development that are in line with the Green Economy in Europe 2020 [37]. Due to environmental and ecological problems, companies, in line with government policies, set directions relating to the process of environmental degradation as a result of manufacturing activities and the significant depletion of natural resources. The popularity of sustainability has contributed to the development of new business models in which business is strongly linked to the environment and vice versa [38,39]. The concept of sustainability is both an idea and a practical-economic (economic) direction for the business. The concept of sustainability applies to all industries, including the steel industry. The steel industry is highly energy-intensive and highly emission-intensive. Introduced into business strategy, sustainability is a key determinant in building the competitive advantage of steel producers worldwide [40]. Environmental legislation for the steel sector has been changing over the years [41]. Legislative changes are driven by the wide range of environmental aspects of the steel industry and the technological advances taking place [42]. In order to meet the increasing environmental demands of governments worldwide, steel mills are continuously improving steelmaking technologies. The direction of change being pursued involves innovation, which requires advanced manufacturing technologies [43]. Among the directions of change in the steel industry are advancements in the process of domestic production which use direct reduced iron (DRI) and hot briquetted iron (HBI) instead of pig iron in both integrated and EAF steelmaking and increased use of renewable energy in steel production. HBI and DRI technologies use natural gas as a reductant which will lead to a further increase in electric and blast furnace productivity and reduce $CO_2$ emissions [44–46]. The energy and heat management of the steel industry is strongly linked to the need to reduce $CO_2$ emissions. Even at the beginning of this century, there was more than 1 tonne of $CO_2$ emissions per 1 tonne of steel produced in Poland per year (in 2005, 1.4 tonnes of $CO_2$ emissions per 1 tonne of steel) [47]. In 2020, $CO_2$ emissions are less than 1 tonne (0.63) [48].

Improving steelmaking technology means: using fossil fuels more sparingly; looking for alternative energy sources, but not forgetting a full life-cycle analysis; reducing the use of coal as an energy carrier. Modern technologies, through innovation, have already contributed to reducing environmental nuisance [49,50]. $CO_2$ emissions from steel processes relate to both the combustion of fossil fuels and the use of the reducing coke in the production of pig iron and crude steel. The pig iron and crude steel production stage is the most electricity and heat intensive and also produces one of the highest $CO_2$ emissions in industry total. The majority of $CO_2$ emissions (more than 50%) in the steelmaking process are related to technological processes and the use of coal (coke) in production processes. Reduction of gas emissions into the air is possible by improving the energy efficiency of steelmaking processes and reducing the use of coal (replacing it with green hydrogen) [51]. In terms of liquid steelmaking technology, the greatest advances are currently taking place in coke-free direct liquid-solid reduction processes [52].

The environmental strategies of the steel industry, over the last two decades, have changed significantly with the increase in corporate environmental responsibility [53]. Companies have also enriched the ways and methods of analysing environmental aspects, paying attention to their multifaceted consideration in relation to processes and products [54,55]. The development of new, innovative metallurgical technologies for the basic production line (i.e., producing steel and processing it into steel products) without emitting $CO_2$ is an undertaking planned for many years because the investments are very capital-intensive and involve significant investment risk (including a long payback period for the capital spent on investments—ROI). The challenge for the steel industry is Industry 4.0, which will turn the existing steel production process using advanced and autonomous technologies supported by IoT and Big Data processing into a smart manufacturing process [56,57]. The leaders in innovation are large organisations with significant development funds. These are metallurgical concerns (capital groups) cooperating on various principles with scientific institutions or, less frequently, individual concerns, regional (e.g., within the EU) or national institutions supporting research, as well as partnership agreements grouping representatives of various sectors of the economy [58,59]. Achieving a high level of innovation in the steel industry requires networked support systems, exchange of good practices, simplified environmental impact assessment tools and protection of sustainable steelmaking from the influence of products from markets with lax environmental requirements (legislation). Industry action requires support at local and international levels. In the pursuit of sustainable steel production, steel producers cannot operate in isolation from other participants in the value chain [60]. The cooperation of companies in the supply chain is a driver of strong network linkages, including in energy supply and intensity [61,62]. Cross-sectoral collaboration promotes good environmental practices and joint environmental responsibility strategies (in industrial partnerships). Changes include the selection of raw materials, energy, manufacturing processes and generally thinking in terms of the life cycle of a product [63]. This broad framing of sustainability in the steel industry has been the subject of much academic research.

A very interesting concept to implement sustainability into the steel industry is the so-called Green Steel. Green technology is the application of environmental and technological solutions to model, monitor and conserve natural resources and the environment and reduce the negative impact of human activities [64]. The implementation of these principles into the steel industry can be called green steel [65]. The conception is closely related to a strategy to make a potential production of so-called decarbonized steel. Due to large investments into innovative technologies, industry should go towards decarbonisation of the production processes. Endorsing the wrong option and not investing in that technological solution should lead to a situation when the industry will lock in carbon-intensive usage of energy and can be prematurely closed because they will not meet the future climate requirements and may face big carbon emission costs [66]. The Fit for 55 packages announced last year, currently in the process of negotiating legislation, aims to accelerate decarbonisation, including the phase-out of free emission allowances and the introduction of a carbon CBAM. Legislation for the steel sector in Poland is extensive (Figure 1).

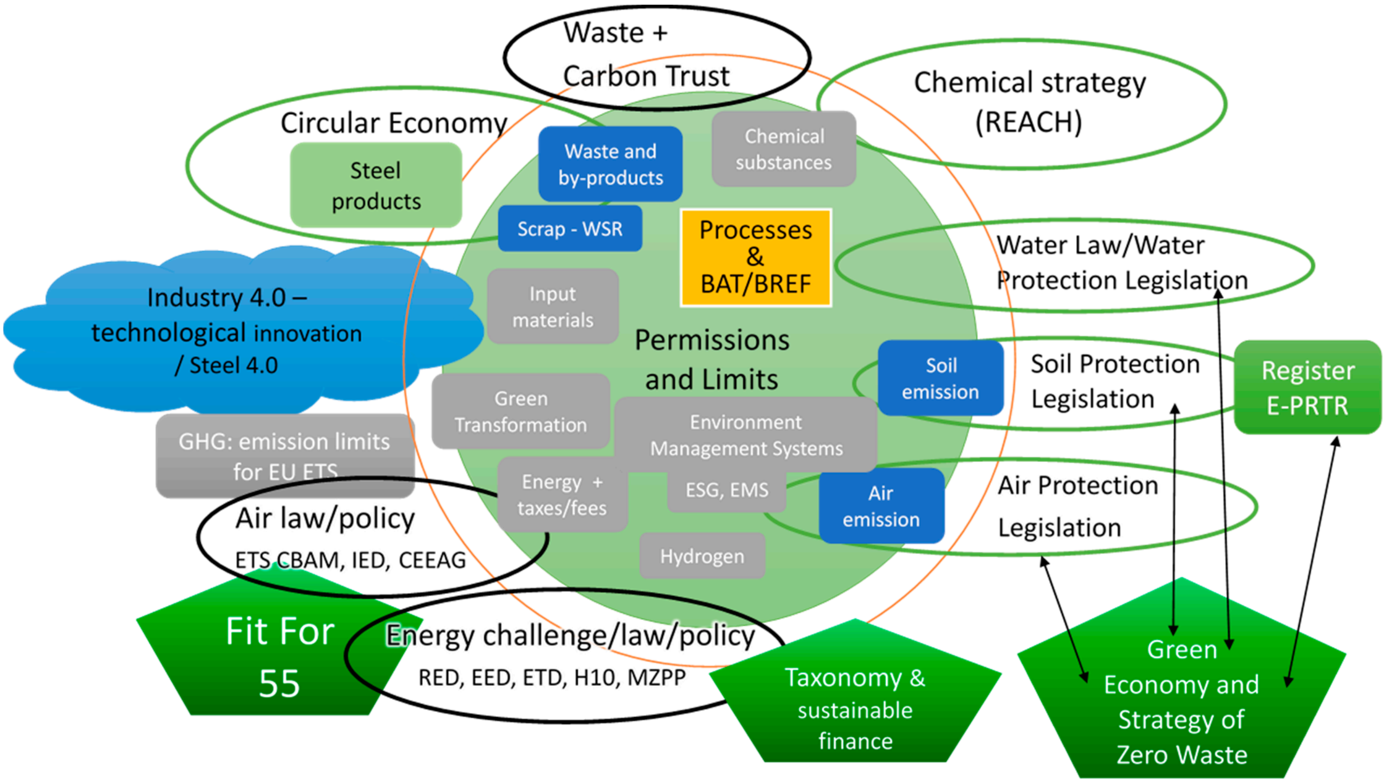


**Figure 1.** Environmental segments determining the development of the steel sector in Poland in Industry 4.0 conditions.

Description for Figure 1:

- BAT and BREF: The original best available techniques (BAT) reference document (BREF) on Iron and Steel. Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and Control;
- WST: The European Waste Shipment Regulation. In the EU, transboundary shipments of waste are currently regulated by Regulation (EC) No 1013/2006 on shipments of waste, commonly referred to as the Waste Shipment Regulation. The Regulation implements the Basel Convention, which bans exports of hazardous waste from OECD countries to non-OECD countries;
- ESG: Environmental, Social, and Governance. ESG practices are now being integrated into various regulatory frameworks. The EU is working with the UN Global Compact to encourage responsible business practices (the field: managing ESG risks);
- EMS: Environmental Management System is a set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency;
- Register E-PRTR: The European Pollutant Release and Transfer Register (E-PRTR) provides easily accessible key environmental data from industrial facilities in European Union Member States;
- RED: The Renewable Energy Directive establishes common rules and targets for the development of renewable energy across all sectors of the economy (2009/28/EC, revision 2018/2021/EU);
- EED: Energy Efficiency Directive (2012/27/UE);
- ETD: Energy Tax Directive (2018/410);
- ETS: the EU Emission Trading System. The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one;
- CBAM: Carbon Border Adjustment Mechanism (the border carbon tax, one of the key elements of the EU's 'Fit for 55′ package).
- IED: Industrial Emissions Directive (Industrial production processes account for a considerable share of the overall pollution in Europe due to their emissions of air pollutants, discharges of waste water and the generation of waste). Directive 2010/75/EU;
- CEEAG: Climate, Energy and Environmental Aid Guidelines (27 January 2022). The CEEAG replace the guidelines that were in force since 2014 (EEAG) and integrate the new objectives of the EU Green Deal of a reduction of 55% net greenhouse gas emissions compared to the 1990 levels by 2030 and of carbon neutrality by 2050.

The implementing of green steel conception needs the usage of new technologies in steel industries. Those new, innovative solutions should be based on a traditional innovation spread approach, but it is also worth implementing a new conception based on an open innovation approach [67–69]. This approach can be seen as an alternative to the traditional innovation approach and can be used to develop new innovative solutions using not only internal but also external knowledge in the process of development and implementation of new, innovative solutions [70–72]. The open innovation model was for many years not connected with big traditional industries such as the steel industry [73]. However, in the last 5 years, the situation is slightly changing. For example, Matsuzaki describes the open innovation strategy used in the Kawasaki Steel company [74]. In this company, they created the special department responsible for creation and implementation of open innovation based solutions. Open innovation can be positively utilized to create new markets and increase the usage of external resources in innovation processes in Industry 4.0 conditions [75,76]. Opening internal resources and working to cooperate with external partners can be very beneficial in the case of innovativeness [77].

The electric energy usage in the economy is an important factor which can be used to measure production costs. The steel industry is one with some of the highest levels of energy consumption and carbon emissions in Europe [78]. The area of research into the rational use of energy resources (raw materials) in steelmaking processes was the subject of a study [5]. Steelmaking technology seeks to reduce demand for iron ore while increasing demand for scrap. The share of scrap in global steel production is projected to increase from 45% at present to 60% at the expense of iron ore [79–82]. In terms of electric energy intensity, researchers have presented the current state of the steel industry and built forecasting models. Ref. [5] built a model and statistically tested it, which indicated that an increase in investment expenditures in organizations producing steel in electric furnaces by PLN 1 million can finally lead to a decrease in measure in unit electricity by 16.5 kWh/1 tonne of crude steel. Ref. [83] presented an econometric model with strong correlation is between the investment and the drop in energy intensity per 1 tonne in the Polish steel industry (a model similar to the study presented in reference [5]). A strong correlation of steel production in Poland using EAF (electric furnace) technology with electric energy intensity was reported in the publication [7]. Based on the resulting econometric model, the authors concluded that an increase in energy intensity when EAF technology is used by 1% could increase the EAF steel production volume by 0.54%. In the process, the first factor remaining unchanged, which, in this model, is scrap consumption. Other authors (none from Poland) also note that the iron and steel industry is one of the most energy-consuming industries which has very big impacts on the word economy [84]. The processes of manufacturing used in the case of steel production lead to high energy intensity and greenhouse gases emission. For example, in China, the amount of iron and steel production is one of the very important $CO_2$ and air pollutant emitters because of the very large amount of the extensive electricity. The most extensive area of research in analysing the applicability of innovations in steel production processes is the manufacturing processes, analysed with a view to optimising them using the latest technologies [85]. The research areas presented are very often hooked (linked) to the life cycle analysis. Life Cycle Assessment (LCA) is the main stream tool used to analyse the environmental impact of various industries, for example, the steel industry [86,87]. Some analysis of using the LCA method in the steel industry concentrates on the usage of new, innovative technologies to replace existing once technologies and reduce the amount of energy intensity and reduce pollutant emissions. The LCA method is very useful to classify the environmental load of the particular technology used in steel plants and to calculate of the environmental impact of the production processes [88–90]. In the steel industry, LCA analysis starts with energy intensity and heat intensity in technological processes. Steel production technologies use electricity. Heat is also needed to keep the processes running. The steel produced and withdrawn from the market is processed in processes—scrap 'feedstock' for electric furnaces (EAF technology).

## 3. Materials and Methods

The research topic is energy and heat management in metallurgical processes in the Polish steel industry. The research areas are two key environmental aspects: electricity and heat consumption. The choice of research areas was dictated by the strong influence of these two environmental aspects on sustainable steel manufacturing. The research part consisted of two parts. The first part was based on real data from statistical reports. In this part, the authors analysed data about heat and energy consumption in the Polish steel industry. The second part was forecasting. In this part, the authors present the steel forecasts and heat and energy forecasts determined for the Polish steel industry. Data were identified to describe the energy and heat consumption of the steel industry in Poland (the sectoral approach was analysed for the steel producers industry, i.e., steel mills in total):

- heat
    - per unit of production [MJ/t] including by processes: EAF and BOF;
    - total [GJ] used in steel production in Poland;
- energy
    - per unit of production [kWh/t], including by processes: EAF and BOF;
    - total [MWh] used in steel production in Poland.

Data analysis was performed, thus describing the annual energy and heat consumption in steel production in Poland. In our analysis, we used data from 2004 to 2020. In our analysis, we used the following symbols: $n$—is a number of elements of the time series; $T$—is time period from 2004 to 2020; $t$—is year. $T$ = 17. The analysis starts in a year in which the main steel producers in the analysed country—Poland started to complete the mandatory information that met the EU requirements. Due to the lack of data (or lack of formal confirmation of its reliability) for 2021, the analysis was terminated at 2020. Actual (empirical) data were collected and categorised and used for the analysis (data were sourced from reports of recognised reporting bodies in Poland: Polish Steel Association, Katowice (in Polish: Hutnicza Izba Przemysłowo-Handlowa—HIPH and Statistics Poland, Warsaw (in Polish: Główny Urząd Statystyczny—GUS).

Time series with data were used to determine forecasts. The forecasting was realized for:

- steel production [thousand tonnes];
- energy and heat consumption for total energy [MWh] and total heat [GJ] and per tonne [t] of steel for energy [kWh/t] and for heat [MJ/t].

On the basis of actual data on the volume of steel production in Poland for the period from 2004 to 2021, forecasts up to 2025 were determined. To forecast the volume of steel production for the next four years, a simple moving average method was used for a series formed around a constant (average) value for $k$ = 3. When selecting the method, the course of the trend of the studied phenomenon was taken into account. The authors tested many forecasting methods, but the forecasting errors were higher than the used method and obtained forecasts were so higher in comparison to real data After the post-COVID-19 year, the trend of steel production in Poland is flat (this will not be an optimistic scenario).

In order to estimate the level of acceptability of the adopted forecasting methods, as well as to select the best forecasts, errors of apparent (expired that is ex post) forecasts were calculated.

Errors were calculated in the forecasting (for ex post forecasts):

- Root Mean Square Error (*RMSE*): the square root of the mean square error of the ex-post forecasts (ex post: $y_t^*$) (Formula (1)):

$$RMSE = \sqrt{\frac{1}{n-m}\sum_{t=m+1}^{n}(y_t - y_t^*)^2} \quad (1)$$

- ψ (fi): mean value of the relative error of the expired forecasts $y_t^*$ (Formula (2)). This error reports the proportion of the absolute error per unit of the actual value of the variable $y_t$. The optimisation of forecast values was prepared on the basis of search for the minimum value of one of the -mentioned earlier errors, taken as an optimisation criterion:

$$\psi = \frac{1}{n-m}\sum_{t=m+1}^{n}\frac{|y_t - y_t^*|}{y_t} \quad (2)$$

The authors assumed that random factors, such as the shutdown of all blast furnaces in Poland, would not occur. Currently, in Poland, pig iron steel is no longer produced in Krakow. The blast furnace was shut down in 2020. In addition, temporarily, the blast furnace in Dąbrowa Górnicza was shut down in 2022. All pig iron production in Poland takes place in one blast furnace. Such boundary (surprise) situations are difficult to present (capture) in trends and forecasts, as the researcher operates with a time series.

The methodology for determining future heat and energy consumption was staged. First, the authors matched the determined steel production forecasts with the level of heat and energy consumption using data averaged from the analysis. Then, using a simple moving average method for a series formed around a constant (average) value for $k$ = 3, they determined the forecasts:

- energy demand [MWh] and energy intensity [kWh/t] on steel production in Poland until 2025;

- heat demand [GJ] and heat intensity [MJ/t] on steel production in Poland until 2025.

The resulting forecasts were compared with the predicted energy and heat demand calculated for the steel production forecasts using averaged actual data (historical data).

## 4. Heat and Energy Consumption in the Polish Steel Industry—Analysis of Empirical Data

### *4.1. Analysis of Heat Consumption in Metallurgical Processes*

The variability in the heat intensity of technological processes in Polish steel mills in different years is directly influenced by the volume of steel production. Since in the Polish steel industry about 50% of steel is produced using the BOF process and the other 50% using the EAF process, it can be assumed that both processes (at the current stage) of technological change in Polish mills are equally important and the technologies used are ranked as key. The heat intensity is shown in the figures (comparison of Figures 2 and 3). The EAF process is more sensitive to the economic situation for steel. In the event of a decline in market demand for steel, as occurred during the economic crisis in 2008 (Figure 2) and in 2020 (during the COVID-19 pandemic), the heat intensity of the EAF process showed a strong decline, while the heat intensity trend of the BOF process showed no decline (Figure 3). The heat intensity trend of the BOF process, compared to the trend of the EAF process, was increasing. The reason for this lies in the specifics of the processes; in the event of a downturn in steel, it is easier to reduce the capacity of electric furnaces (EAF) than to shut down blast furnaces, which is part of the BOF technology. BOF technology (Figure 4) has a higher heat demand than EAF technology. This situation of strong trend similarities is no longer repeated in the case of EAF technology (Figure 5), as this technology is more flexible compared to BOF technology (it is easier to decrease and increase the capacity of electric furnaces). With strong seasonal fluctuations for steel, EAF technology is more cost-effective to maintain than BOF technology. For this reason, EU industrial policy focuses on the development of micro-furnaces equipped with EAF technology. The heat intensity trend of the BOF process is similar (similar) to the trend of pig iron (pig iron) and crude steel (crude steel) production. This similarity is due to the fact that pig iron is only produced by BOF technology. This strong convergence of trends is particularly evident in the analysis performed in Figure 6, in which the heat demand is compared with the production volume of steel obtained exclusively with BOF technology. The course of both trends (Figures 6 and 7) is identical, with trends showing decreases or increases over the same period. The electric furnaces that are being implemented in the steel industry are getting better and better every year in terms of energy requirements (analysis in Section 4.2, Figure 8).

The heating of air and gas in smelter furnaces is aimed at increasing the combustion temperature. In the paper, two processes of steel production were analysed: BOF (Basic Oxygen Furnace) and EAF (Electric Arc Furnace). In the analysed period from 2004 to 2020 in the Polish steel industry, the average value of heat intensity per tonne of steel produced was higher in the BOF converter process (961.0865 MJ/t) with average annual steel production using this technology of 4994 thousand tonnes of steel than in the EAF electric arc furnace process (66.38824 MJ/t) with average annual steel production using this technology of 4030 thousand tonnes. In the crude steel production process alone, steel mills consumed 737.8908 MJ/t between 2004 and 2020 (Figure 4). The dynamics of steel production volumes by process and heat intensity in the analysed technological processes of steelmaking are shown in Figures 2 and 3.

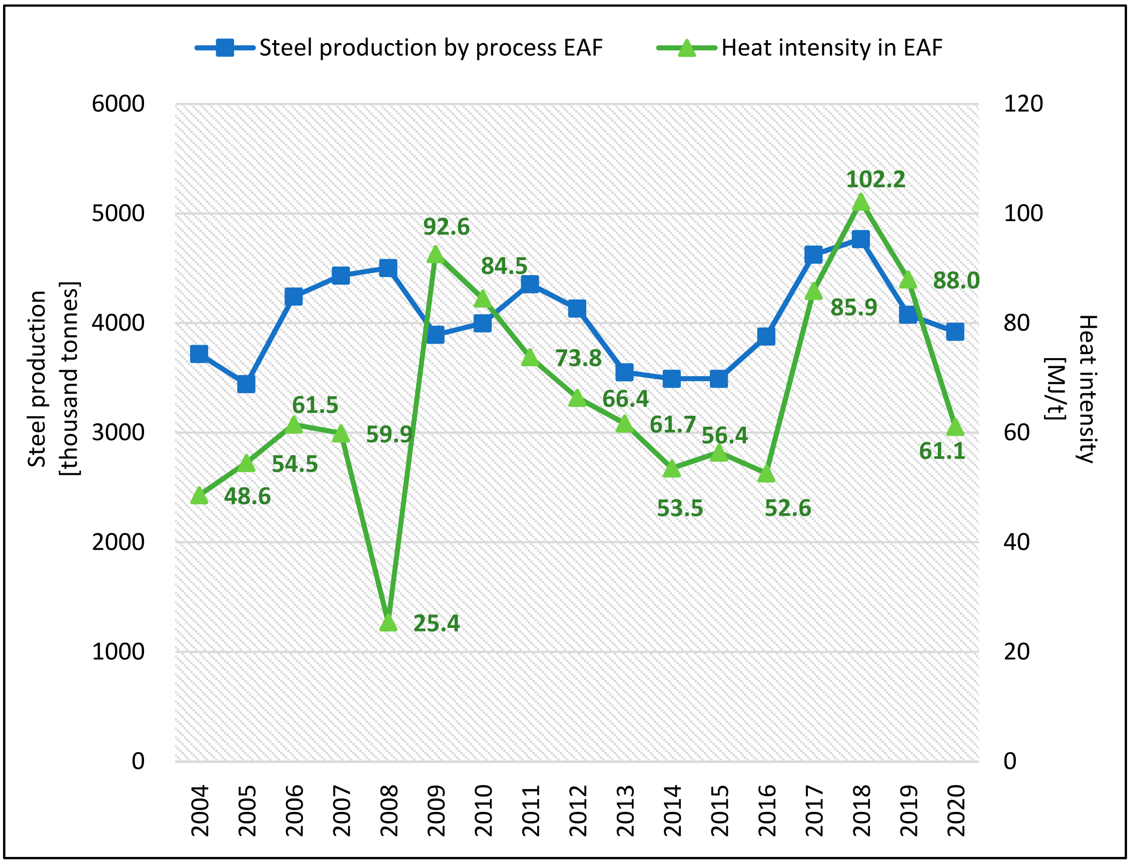


**Figure 2.** Heat intensity per 1 tonne of steel in the EAF process in Poland from 2004 to 2020. Source: Own elaboration based on data from [11].

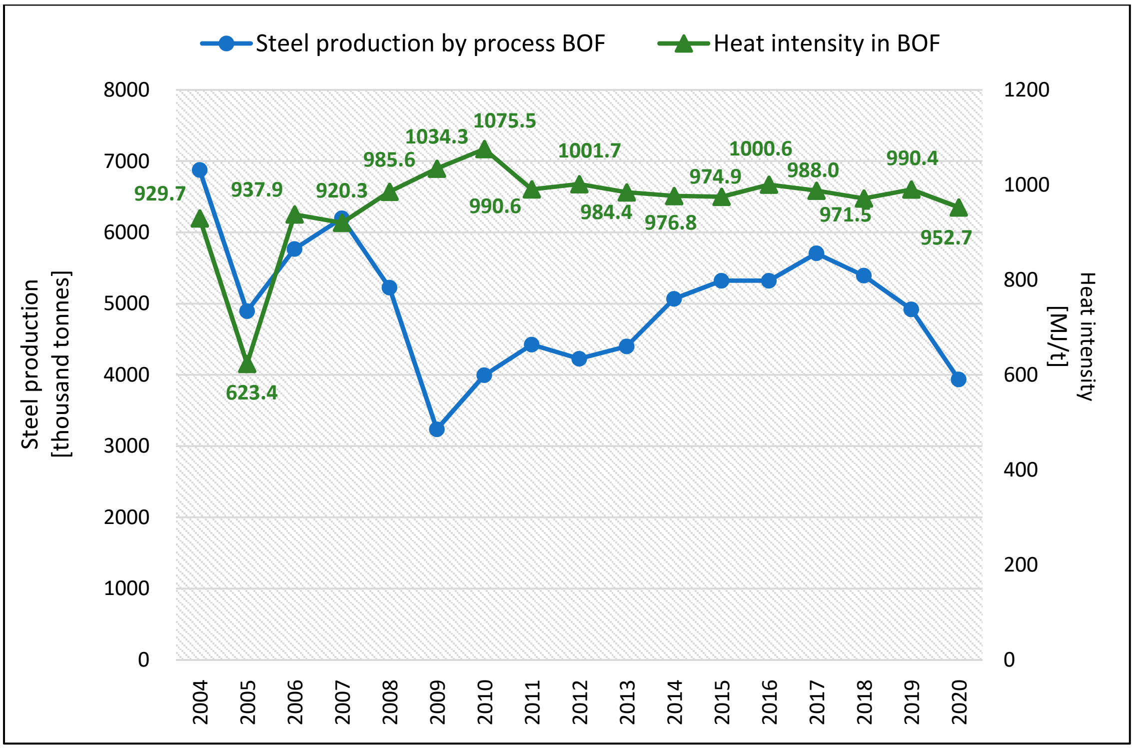


**Figure 3.** Heat intensity per 1 tonne of steel in the BOF process in Poland from 2004 to 2020. Source: Own elaboration based on data from [11].

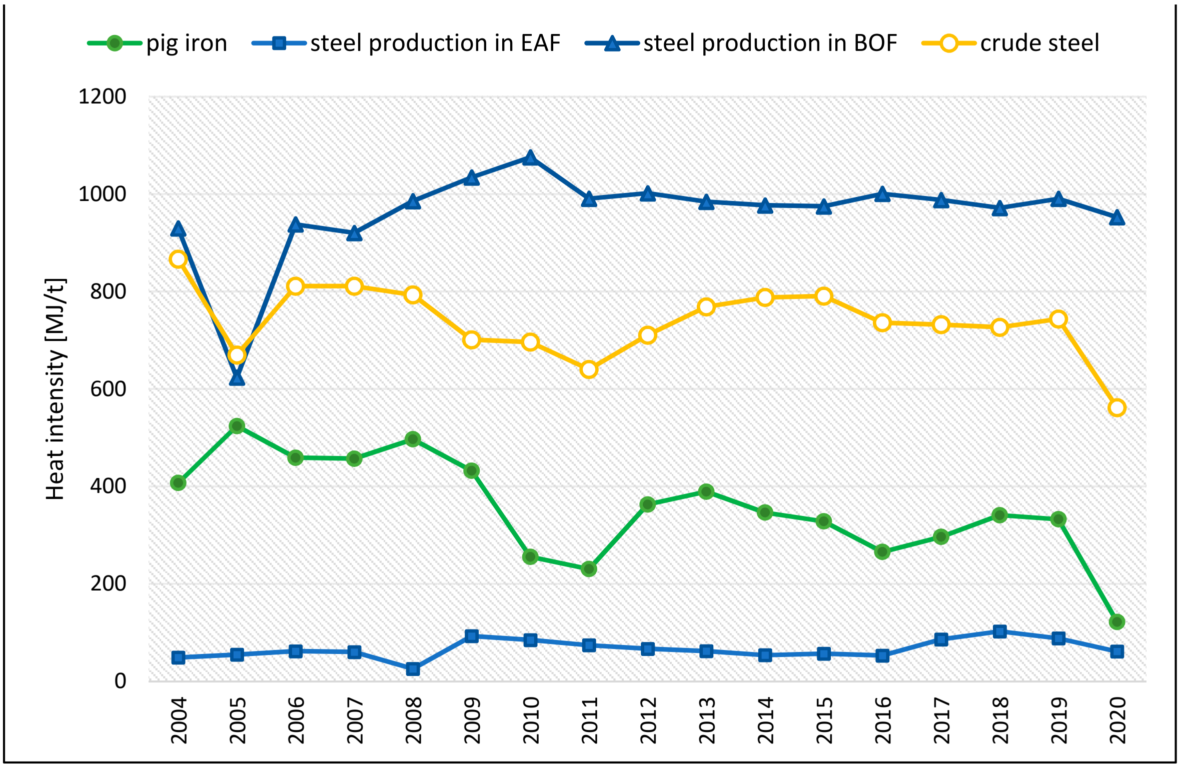


**Figure 4.** Heat intensity per 1 tonne of steel in all the metallurgical processes in Poland from 2004 to 2020. Source: Own elaboration.

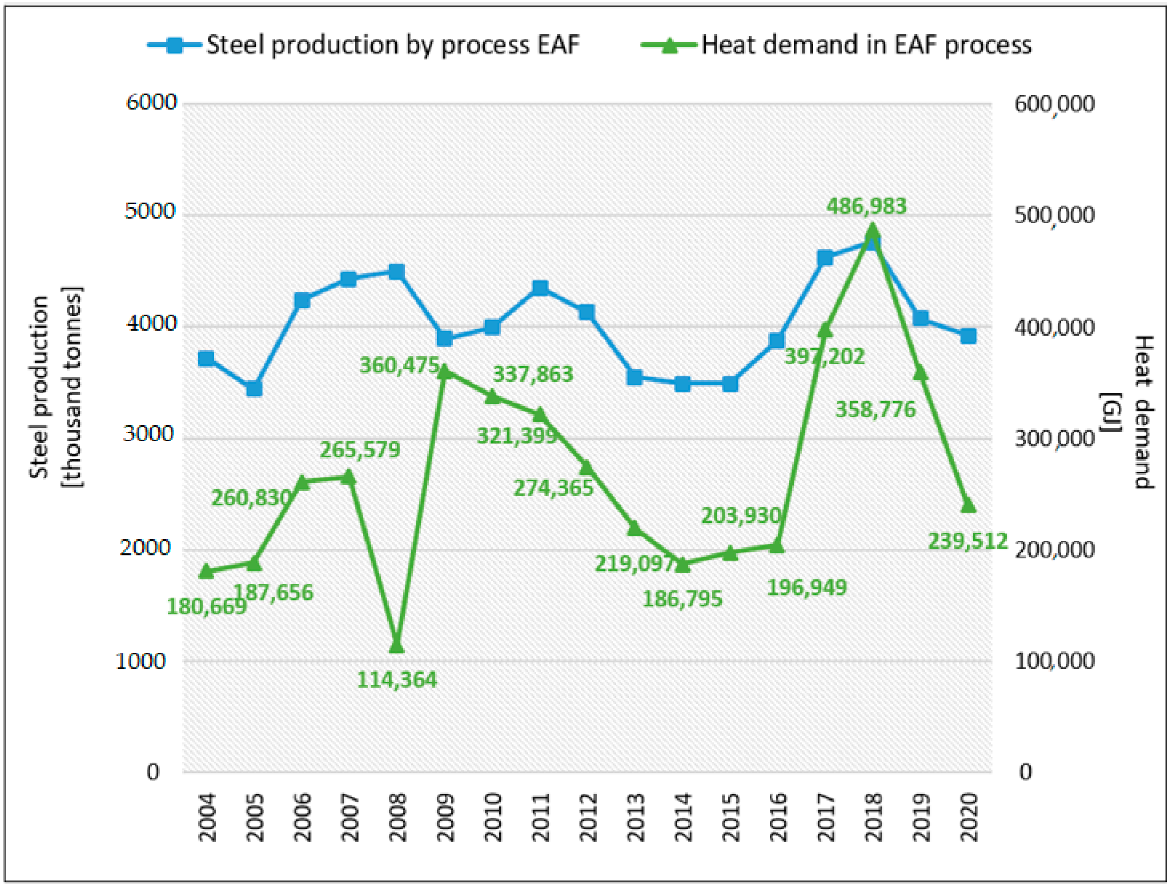


**Figure 5.** Total heat demand in the EAF process in Poland from 2004 to 2020. Source: Own elaboration.

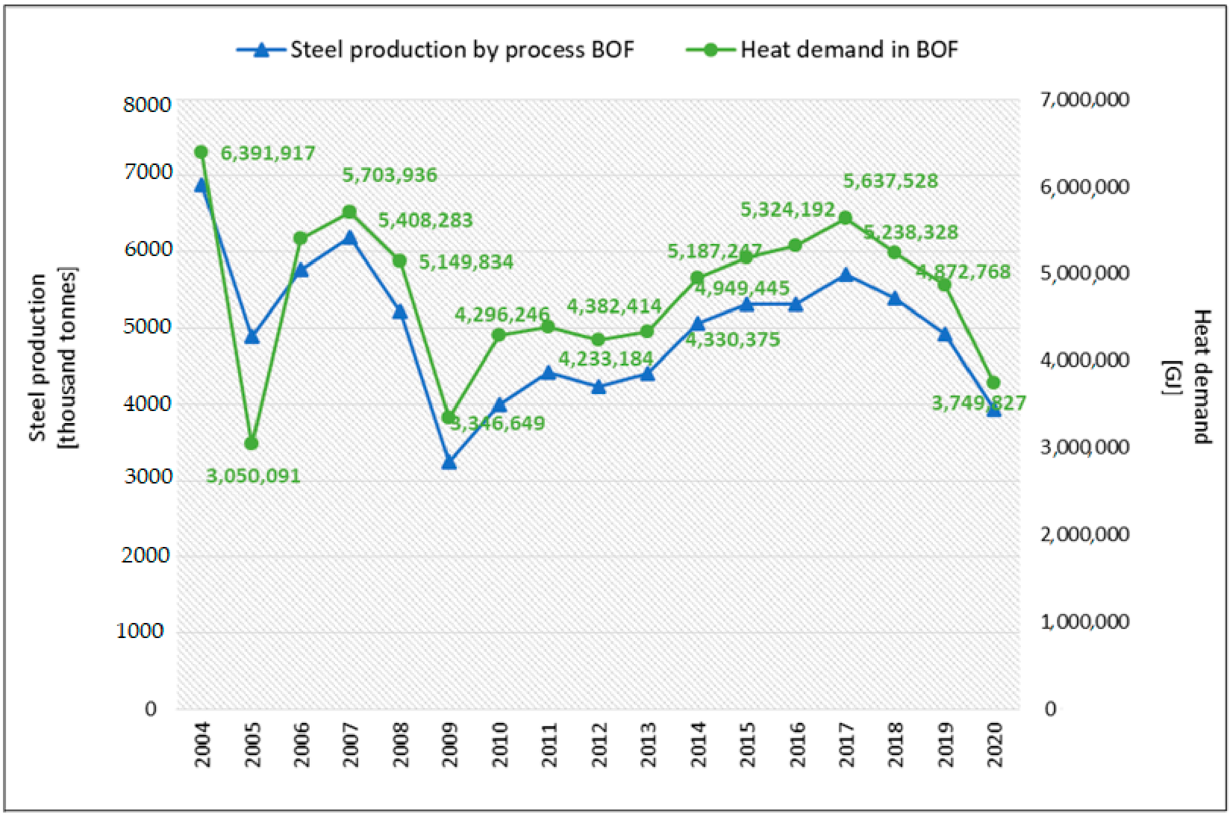


**Figure 6.** Total heat demand in the BOF process in Poland from 2004 to 2020. Source: Own elaboration.

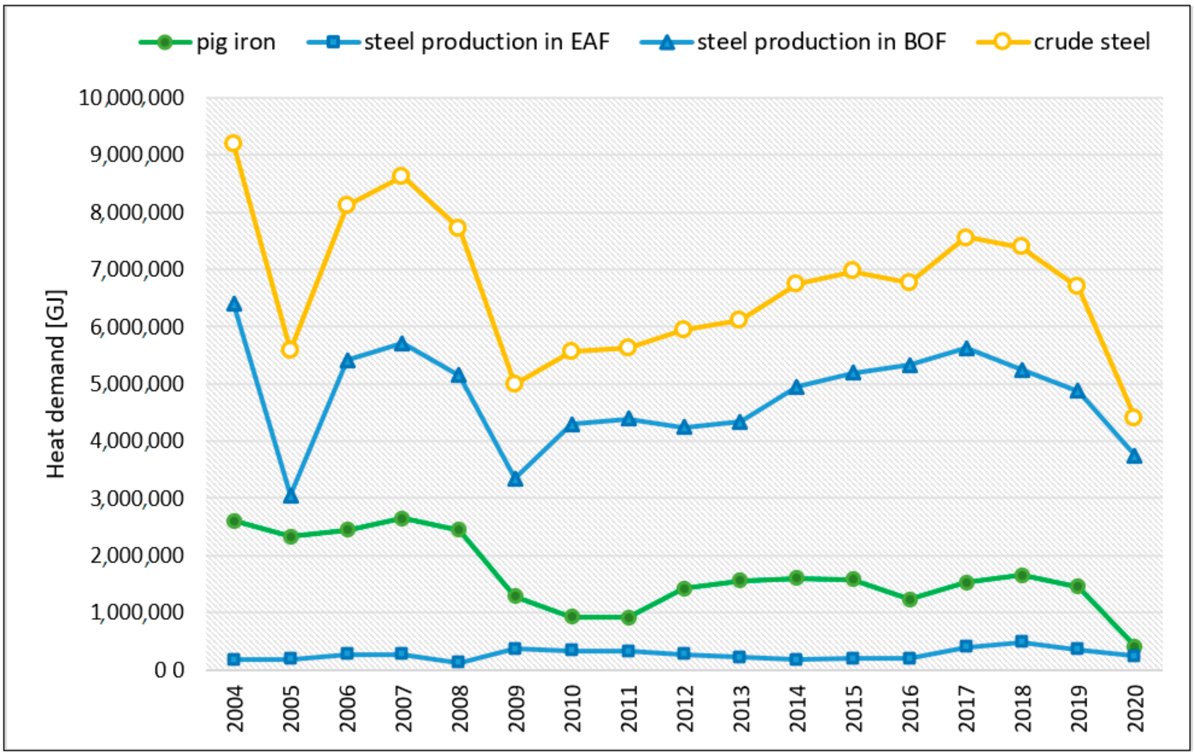


**Figure 7.** Total heat demand in all of the metallurgical processes in Poland from 2004 to 2020. Source: Own elaboration. Heat intensity for the category: crude steel is the sum of heat intensity for production of pig iron with BOF and EAF.

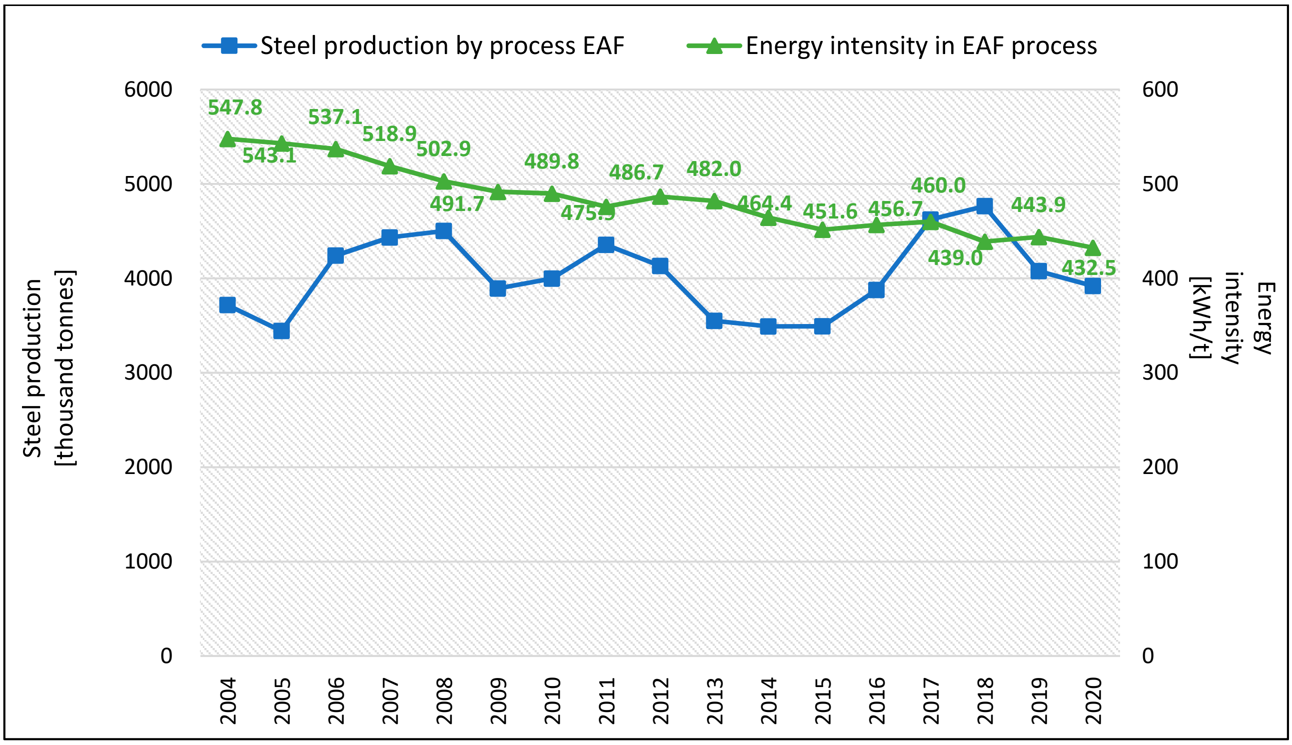


**Figure 8.** Energy intensity per 1 tonne of steel in the EAF process in Poland from 2004 to 2020. Source: Own elaboration based on data from [11].

The amplitude of the spread of heat intensity in the technological processes of steel production in Poland in the analysed period was high, for the EAF process from 25.4 MJ/t in 2008 (with steel production in the EAF process in 2008 amounting to 4503 thousand tonnes) to 102.2 MJ/t in 2018 (with production of 4765 thousand tonnes of steel in the EAF process), and for the BOF process from 623.4 MJ/t in 2005 (with production of 4893 thousand tonnes) to 1075.5 MJ/t in 2010 (with steel production of 3995 in BOF technology). Figure 3 shows the heat intensity of all processes per tonne produced steel, i.e., from iron pig through crude steel total and steel production by processes: EAF and BOF.

On the basis of Figure 4, we see that the highest heat consumption per 1 tonne of steel produced in the process occurs with BOF technology. In the production of crude steel and pig iron, the heat intensity per 1 tonne of steel or 1 tonne of pig iron, depending on the process, is lower than in the BOF process.

The following figures (Figures 4–6) summarise the total heat demand by process. In the EAF technology, the least heat was used in steel production in 2008, only 114,364 GJ, and the most in 2018, 486,983 GJ (Figure 4). In the BOF process, the least heat was used in 2005, i.e., 3,050,091 GJ, and the most in the previous year, i.e., 2004, 6,391,917 GJ (Figure 5). The BOF technology is always more heat intensive than the EAF technology, in contrast to energy intensity, in which case the EAF technology is more energy intensive than the BOF technology (compare Figures 5 and 6).

The last figure (Figure 7) in this area of analysis shows the heat demand by all processes in steel plants in Poland.

### *4.2. Analysis of Energy Consumption in Metallurgical Processes*

The electric energy intensity of EAF technology has a downward trend (Figure 8). The downtrend in the energy intensity of EAF technology can be attributed to improvements in the technology (better furnace specifications, higher productivity). In Figure 8, the downward trend in electrical intensity is clearly visible. The two trends juxtaposed (Figure 8), one being the energy intensity and the other being the volume of steel production in EAF technology, are not identical in terms of the directions and periodic fluctuations that occur.

The trend in electricity is downward for EAF technology, despite the strong variability in the volume of steel produced in electric furnaces. The downward trend in energy intensity of EAF technology is a good situation for the Polish steel industry, especially if one takes into account the strong increase in electricity prices in recent years, related to additional charges and taxes imposed on the purchase price of electricity, which is caused by the EU policy of diversification of energy sources. The authors wrote about electricity prices and the additional costs of electricity purchase by Polish steel mills in a previous publication [91]. When it comes to the energy intensity of BOF technologies, as shown in Figure 9, the trend has been upward in recent years (the upward trend has continued from 2010, i.e., after the Polish steel industry recovered from the effects of the global economic crisis, until 2012 and in the last two years, with a slight decrease between 2012 and 2018). When the energy consumption of both technologies is compared (Figures 8 and 9), more energy is consumed by electric furnaces than by blast furnaces, whose technical parameters allow the use of other substitute energy sources. The trend in energy intensity for the BOF technology, as with the trend in heat intensity, coincides with the trend in pig iron production volume (Figure 10). The main conclusion from the analysis of the energy consumption in technological processes of steel production in Poland and the overall demand for electricity (Figures 11 and 12) is that the volume of steel produced in BOF and EAF processes in Poland is a direct determinant of the increase or decrease in electricity consumption in these technological processes, which will be improved in the coming years in accordance with the energy policy of the EU and Poland as a member of the EU.

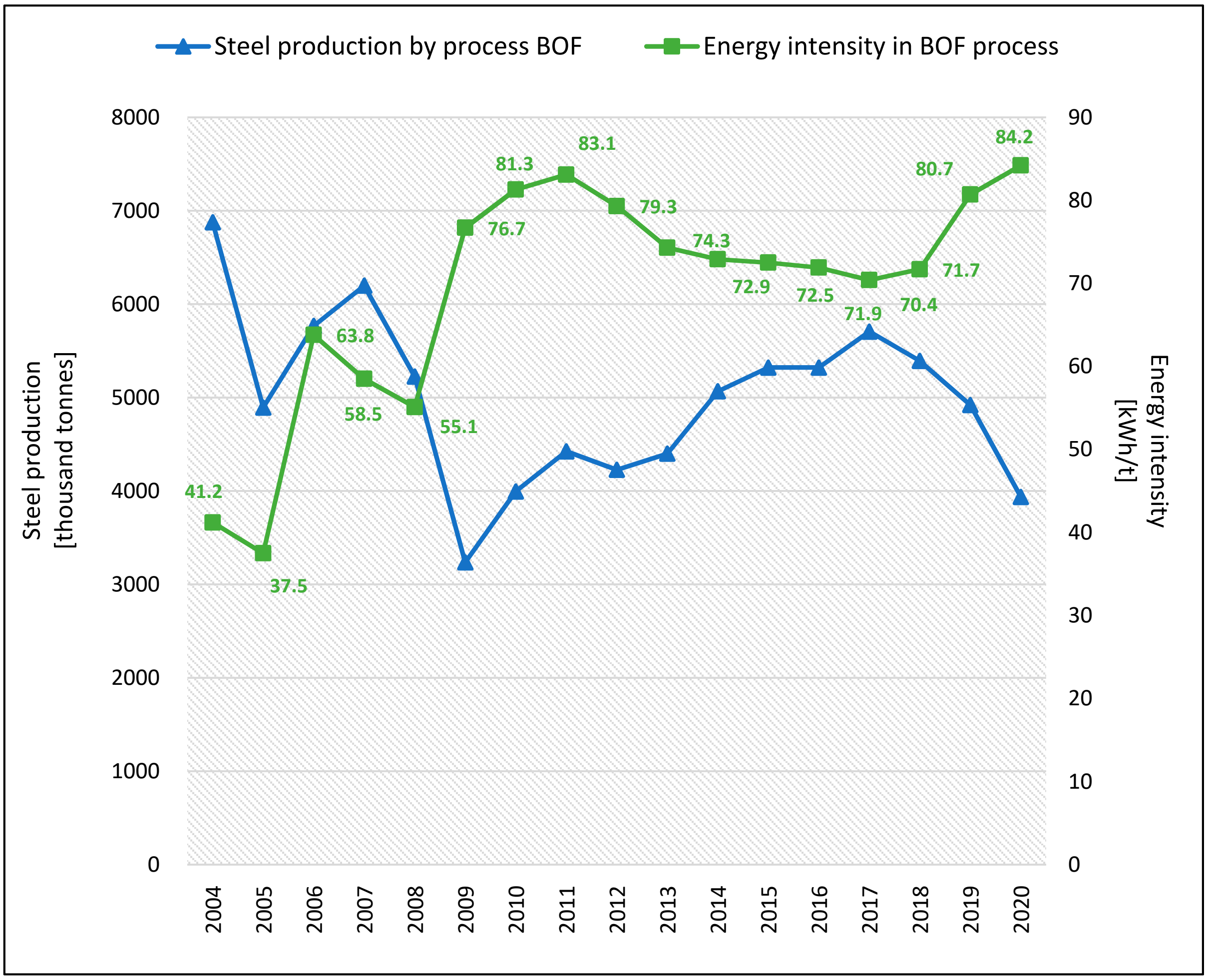


**Figure 9.** Energy intensity per 1 tonne of steel in the BOF process in Poland from 2004 to 2020. Source: Own elaboration based on data from [11].

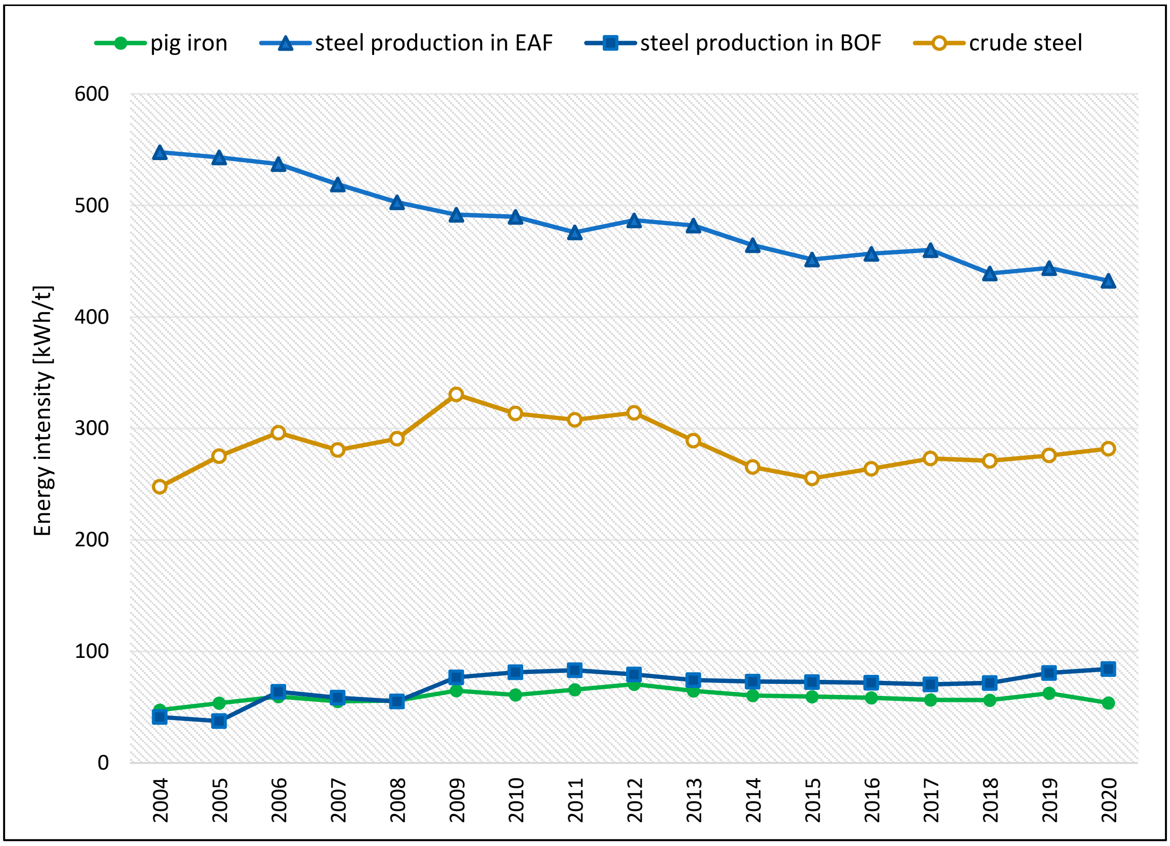


**Figure 10.** Energy intensity per 1 tonne of steel in Poland from 2004 to 2020. Source: Own elaboration.

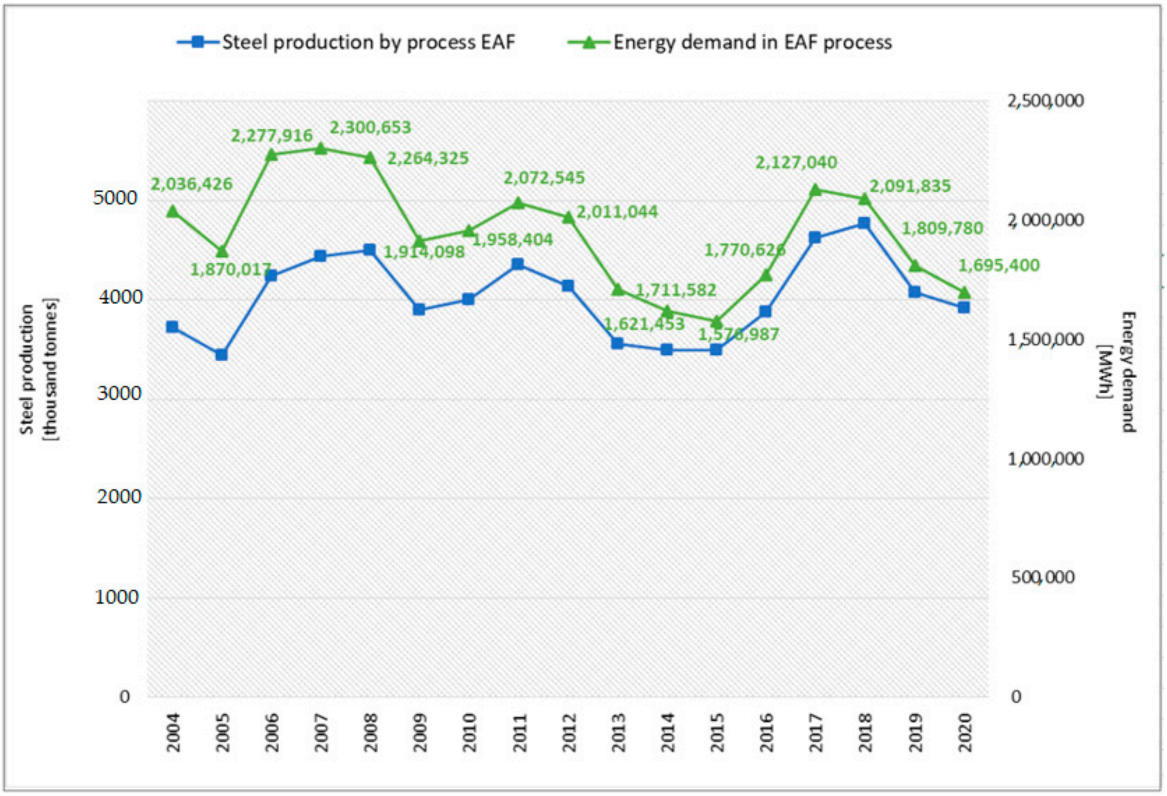


**Figure 11.** Total energy demand in the EAF process in Poland from 2004 to 2020. Source: Own elaboration.

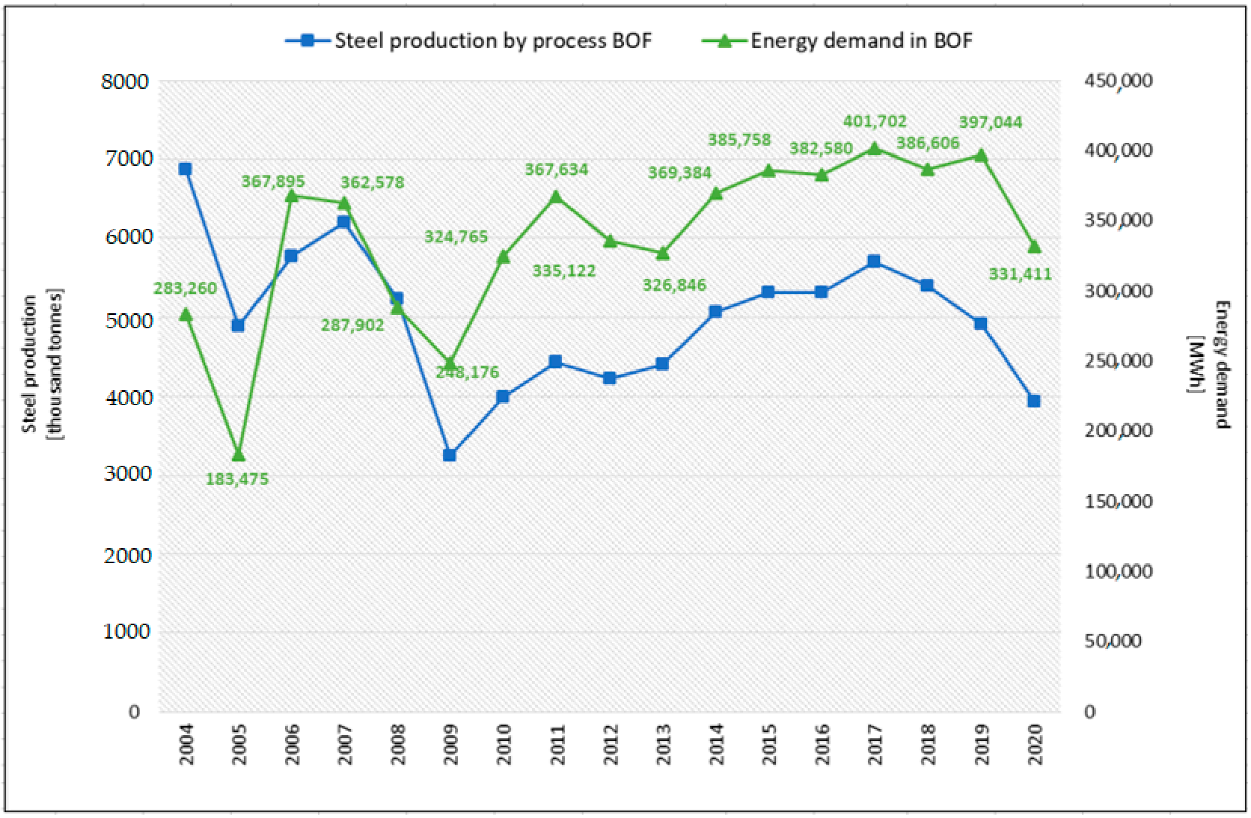


**Figure 12.** Total energy demand in the BOF process in Poland from 2004 to 2020. Source: Own elaboration.

In the analysed period from 2004 to 2020 in the Polish steel industry, the average value of energy consumption per tonne of steel produced in the EAF electric process was 483.7647 kWh/t), and in the BOF converter steelmaking process (69.12343/t), with energy intensity to produce pig iron of 59.15294 kWh/t. In the BF + BOF processes, annual energy intensity is below 100 kWh/t. For the EAF electric steelmaking process, the annual average energy intensity is more than four times higher compared to the energy intensity of the BF + BOF process (blast furnace and converter). BF pig iron process alone consumed 59.15294 kWh/t by the steel mills between 2004 and 2020. The dynamics of steel production volumes by technological process and energy intensity in the analysed technological processes (BOF and EAF) of steelmaking are shown in Figures 8 and 9.

The amplitude of the spread of energy intensity in technological processes of steel production in Poland in the analysed period was, for the EAF process, from 547.8 kWh/t in 2005 (in the process 3717 thousand tonnes of steel was produced in that year) to 432.5 kWh/t in 2020 (steel production in the EAF process in 2020 amounted to 3920 thousand tonnes) and for the BOF process from 37.5 kWh/t in 2005 (in the process, 4893 thousand tonnes of steel was produced in that year) to 84.2 kWh/t in 2020 (in the process, 3936 thousand tonnes of steel was produced). The downward trend in energy intensity in the EAF process is a good development (Figure 10). This area of research was presented in previous publications of the authors: [5,7,83].

The associated BF + BOF processes are almost equally energy intensive, but their energy consumption is much lower than that of steel production using the EAF technology. The high energy consumption in the EAF process contributes to the overall quite high energy intensity of crude steel in Poland (the annual average per tonne of crude steel produced was 284.1454 kWh (Figure 10).

The following figures (Figures 11 and 12) present the total energy consumption by the technological processes. The amplitude of the spread of electricity in technological processes of steel production in Poland in the analysed period was, for the EAF process, from 1,576,987 MWh in 2015 (steel production in the EAF process in 2015 amounted to

3492 thousand tonnes) to 2,300,653 MWh in 2007 (in the EAF process, 4434 thousand tonnes steel was produced), and, for the BOF process, from 183,475 MWh in 2005 (in the process 4893 thousand tonnes of steel was produced in that year) to 401,702 MWh in 2017 (in the BOF process, 5706 thousand tonnes of steel was produced in that year).

The last figure, in this area of analysis (Figure 13), summarises energy consumption by all processes in the Polish steel mills. It can be seen from the figure that the highest levels of heat demand in the period from 2004 to 2020 are during the production of steel in the BOF technology and during the production of total crude steel. The structure of the BOF technology, according to its process requirements, always has more heat consumption than the EAF technology, in contrast to energy consumption, in which case the EAF process is more energy intensive than the BOF process.

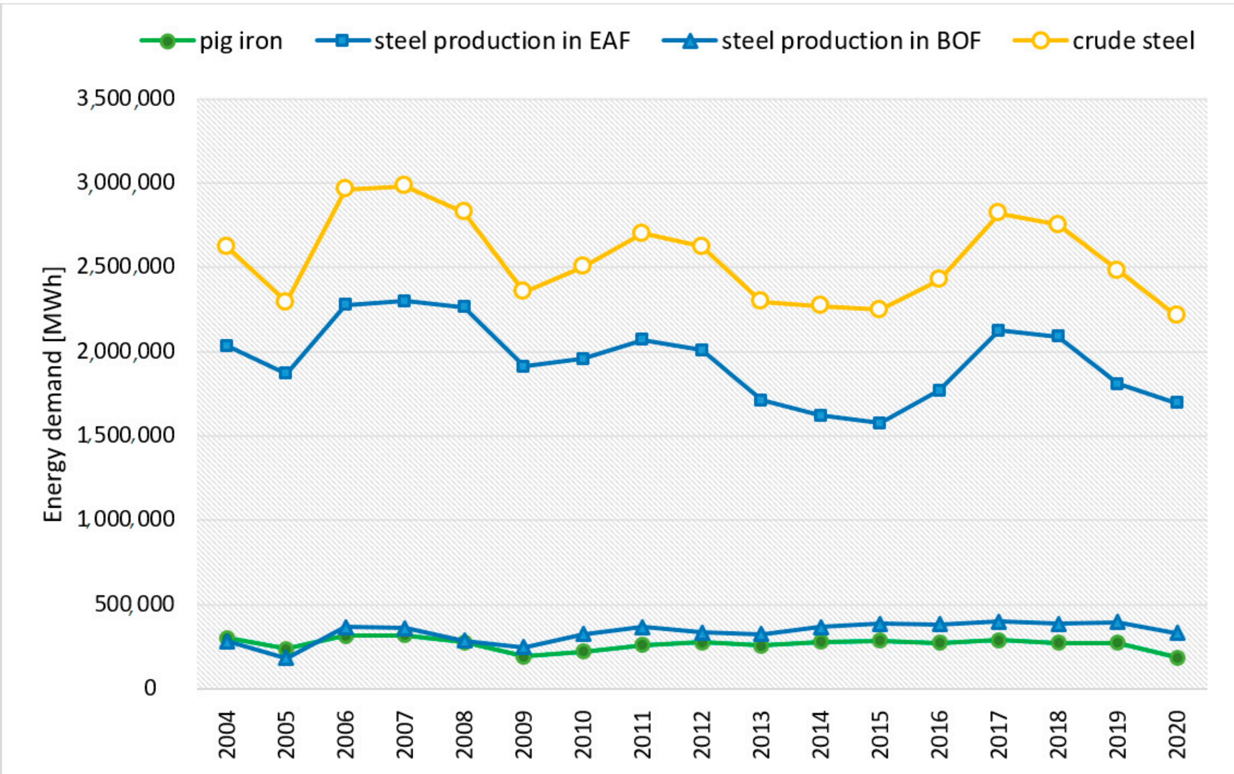


**Figure 13.** Total energy demand in all metallurgical processes in Poland from 2004 to 2020. Source: Own elaboration. Total energy intensity for the category: crude steel is the sum of energy intensity for production of pig iron with BOF and EAF.

## 5. Heat and Energy Consumption in Forecasting Analysis

The previous chapter presented data on heat and energy consumption in steel production processes in Poland from 2004 to 2020. We will now analyse the results from the point of view of environmental innovation in the Polish steel industry.

Before forecasting heat and energy demand and intensity in the Polish steel sector, the authors determined steel production forecasts.

### *5.1. Forecasts of Steel Production*

Steel production forecasts were determined based on annual steel production volumes. The actual data are summarised in Table 1, and the time series of the data distribution is shown in Figure 14. Table 1 summarises the data used for forecasting and the results. Calculations were performed in an Excel spreadsheet for a simple moving average model for a series formed around a constant (average) value for $k = 3$, where $k$ is the starting point.

**Table 1.** Forecasts of steel production in Poland.

| T | Year | Steel Production Million Tonnes | $y_t^*$ | $\frac{\lvert y_t - y_t^* \rvert}{y_t}$ | $(y_t - y_t^*)^2$ |
|---|---|---|---|---|---|
| 1 | 2004 | 10.583 | | | |
| 2 | 2005 | 8.336 | | | |
| 3 | 2006 | 10.008 | | | |
| 4 | 2007 | 10.631 | 9.642 | 0.093 | 0.977 |
| 5 | 2008 | 9.728 | 9.658 | 0.007 | 0.005 |
| 6 | 2009 | 7.128 | 10.122 | 0.420 | 8.963 |
| 7 | 2010 | 7.993 | 9.162 | 0.146 | 1.367 |
| 8 | 2011 | 8.776 | 8.283 | 0.056 | 0.243 |
| 9 | 2012 | 8.358 | 7.966 | 0.047 | 0.154 |
| 10 | 2013 | 7.950 | 8.376 | 0.054 | 0.181 |
| 11 | 2014 | 8.558 | 8.362 | 0.023 | 0.039 |
| 12 | 2015 | 8.813 | 8.289 | 0.059 | 0.275 |
| 13 | 2016 | 9.198 | 8.441 | 0.082 | 0.574 |
| 14 | 2017 | 10.330 | 8.856 | 0.143 | 2.171 |
| 15 | 2018 | 10.157 | 9.447 | 0.070 | 0.504 |
| 16 | 2019 | 8.997 | 9.895 | 0.100 | 0.806 |
| 17 | 2020 | 7.856 | 9.828 | 0.251 | 3.889 |
| 18 | 2021 | 8.454 | 8.436 | 0.002 | 0.000 |
| 19 | 2022 | 8.436 | 8.436 | 0.104 | 1.159 |
| 20 | 2023 | 8.445 | 8.445 | Ψ | *RMSE* |
| 21 | 2024 | 8.440 | 8.440 | | |
| 22 | 2025 | 8.440 | 8.440 | | |

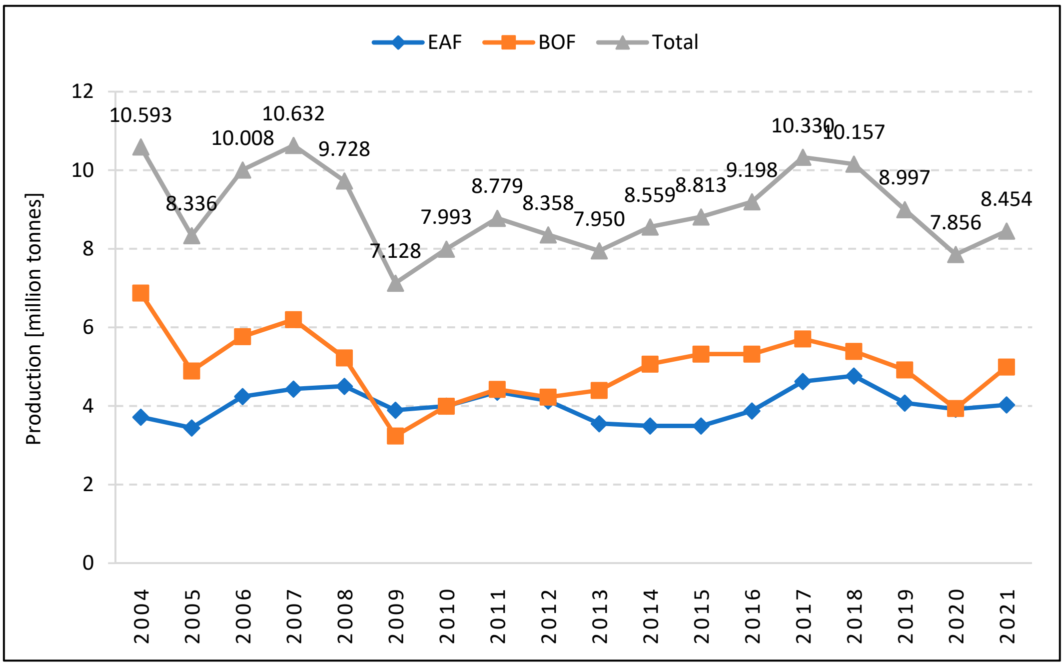


**Figure 14.** Steel production in Poland in the period: 2004–2021.

On the basis of actual data, it was determined that steel production in Poland in 2021 was 8.454 million tonnes (Figure 14). Furthermore, having the steel production volume for 9 months of 2022 Q1 = 2098 thousand tonnes; Q2 = 2075 thousand tonnes, Q3 = 1831 thousand tonnes (data from Polish Steel Association), the authors assume that steel production in Poland for the full year will be less than 8 million tonnes of steel at the end of 2022 (if the steel production in Q4 will be 1500 tonnes, so the total steel production will be 7.5 million tonnes). The forecast of steel production in 2022 is (Table 1) 8.436 million tonnes, which confirms the conjecture that Poland's steel production in 2022 may be slightly above 8 million tonnes or will fall if there are situations that exacerbate the crisis in the industry. The forecasts show that the average steel production will be below 8.5 million tonnes. It is not a good scenario for the Polish steel mills, but. in comparison to real data about steel production in quarters (Q) of 2022, we can say that the scenario with an average annual steel production of 8.440 million tonnes (Table 2) is quite good in times of crisis.

**Table 2.** Estimated energy and heat demand for forecasts of steel in 2022–2025 (variant 1A).

| Year | Forecast of Steel Production [Thousand Tonnes] | Estimated Energy Demand [MWh] | Estimated Heat Demand [GJ] |
|---|---|---|---|
| 2022 | 8436 | 2,395,668 | 6,224,840 |
| 2023 | 8445 | 2,399,225 | 6,231,481 |
| 2024 | 8440 | 2,397,804 | 6,227,791 |
| 2025 | 8440 | 2,397,804 | 6,227,791 |
| average per annum | 8440 | 2,397,875 | 6,227,976 |

In Poland, in previous years, almost 50% of steel was produced using blast furnaces (BOF technology) and slightly less using electric furnaces (EAF technology)—Figure 14. With only one blast furnace in operation in the Polish steel industry (in steel mills), more steel will need to be produced in electric furnaces, and as the analysis shows, the electric process needs more energy than the converter process. Figure 15 shows the forecasts of volume of steel production for Poland.

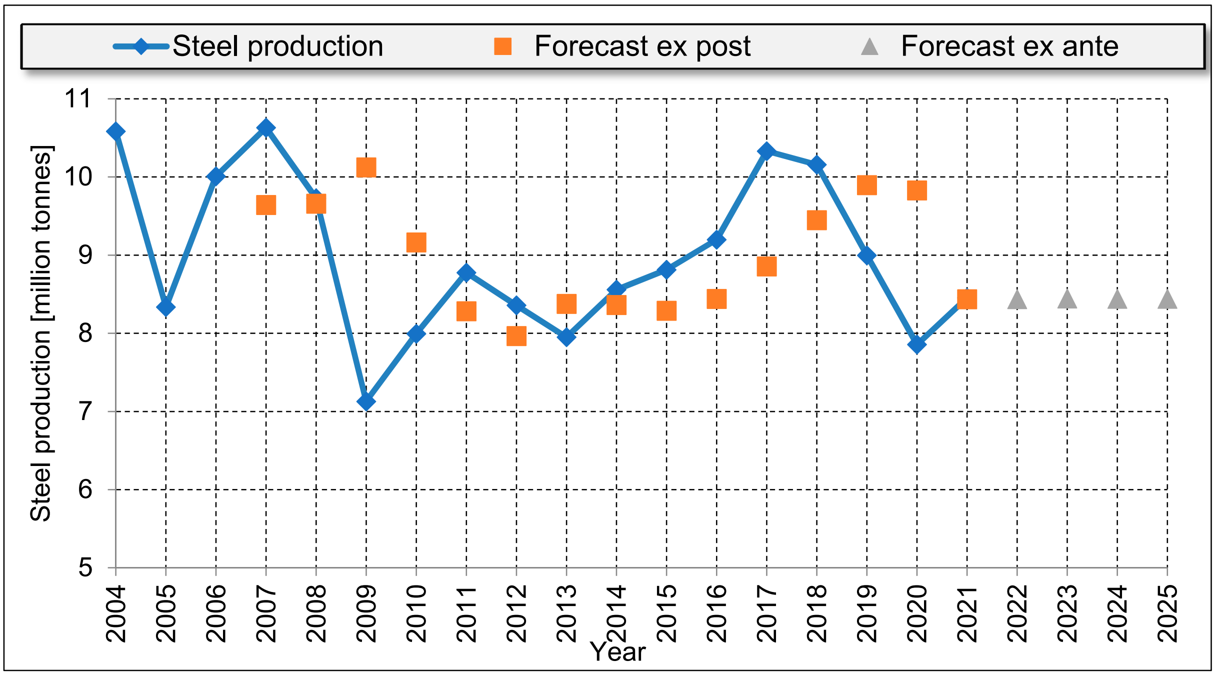


**Figure 15.** Forecasts of steel production in Poland in the period: 2022–2025.

The forecasts presented are not high, due to unfavourable changes in the environment (the effects of the post-COVID-19 crisis, the war in Ukraine, the energy crisis). A weakly optimistic approach is conditioned by Worldsteel's forecast for 2023; this organisation predicts that global steel demand will increase by only 1%, with a decline in demand in the countries involved in the war (−7%) and in the EU (−1%).

*5.2. Forecasts of Heat and Energy Consumption*

Based on the unit (per tonne of steel) average annual energy and heat intensity calculated on the basis of historical data for the period from 2004 to 2020, which was 737.891 MJ/t for heat (Figure 4) and 284.145 kWh/t for energy (Figure 10), and the forecasts of steel production in the period 2022–2025 (Table 2), future demand was estimated. The estimated energy and heat demand are shown in Table 2.

If one uses the estimated energy and heat demand from Table 2 (a line in the table described as "average", which was 2,397,875 MWh for energy and 6,227,976 GJ for heat, respectively, and relates them back to the determined steel production forecasts per tonne in 2022–2025, the estimated energy and heat intensity could be determined—the results are shown in Table 3.

**Table 3.** Estimated energy and heat intensity for forecasts of steel in 2022–2025 (variant 1B).

| Year | Forecast of Steel Production [Thousand Tonnes] | Estimated Energy Intensity [kWh/t] | Estimated Heat Intensity [MJ/t] |
|---|---|---|---|
| 2022 | 8436 | 284.243 | 738.261 |
| 2023 | 8445 | 283.940 | 737.475 |
| 2024 | 8440 | 284.108 | 737.912 |
| 2025 | 8440 | 284.108 | 737.912 |
| average per annum | 8440 | 284.100 | 737.890 |

When a moving average model, such as that used to determine steel forecasts, was used, variant no. 2 forecasts were obtained (Table 4). The results of the forecasting are shown in Figures 16 and 17. If one uses the forecasted energy and heat demand from Table 4, the heat and energy intensity (per tonne of steel) is as follows (Table 5).

**Table 4.** Forecasts of energy and heat demand based on forecasting model used to determine the forecasts of steel production in 2022–2025 (variant 2A).

| Year | Forecast of Steel Production [Thousand Tonnes] | Forecast of Energy Demnad [MWh] | Forecast of Heat Demand [GJ] |
|---|---|---|---|
| 2022 | 8436 | 2,302,627 | 5,170,798 |
| 2023 | 8445 | 2,243,207 | 4,749,042 |
| 2024 | 8440 | 2,253,110 | 4,861,510 |
| 2025 | 8440 | 2,266,314 | 4,758,415 |
| average per annum | 8440 | 2,266,314 | 4,861,510 |

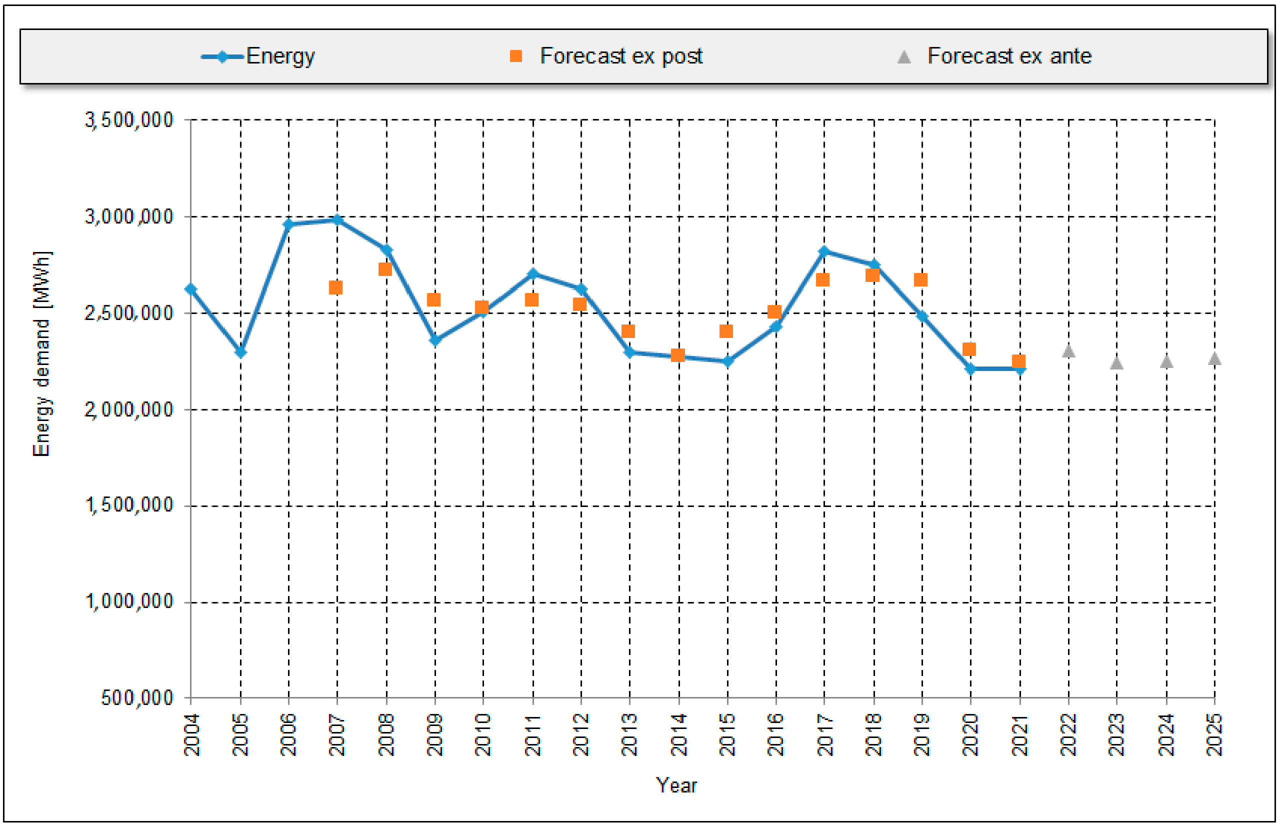


**Figure 16.** Forecasts of energy demand in steel industry in Poland.

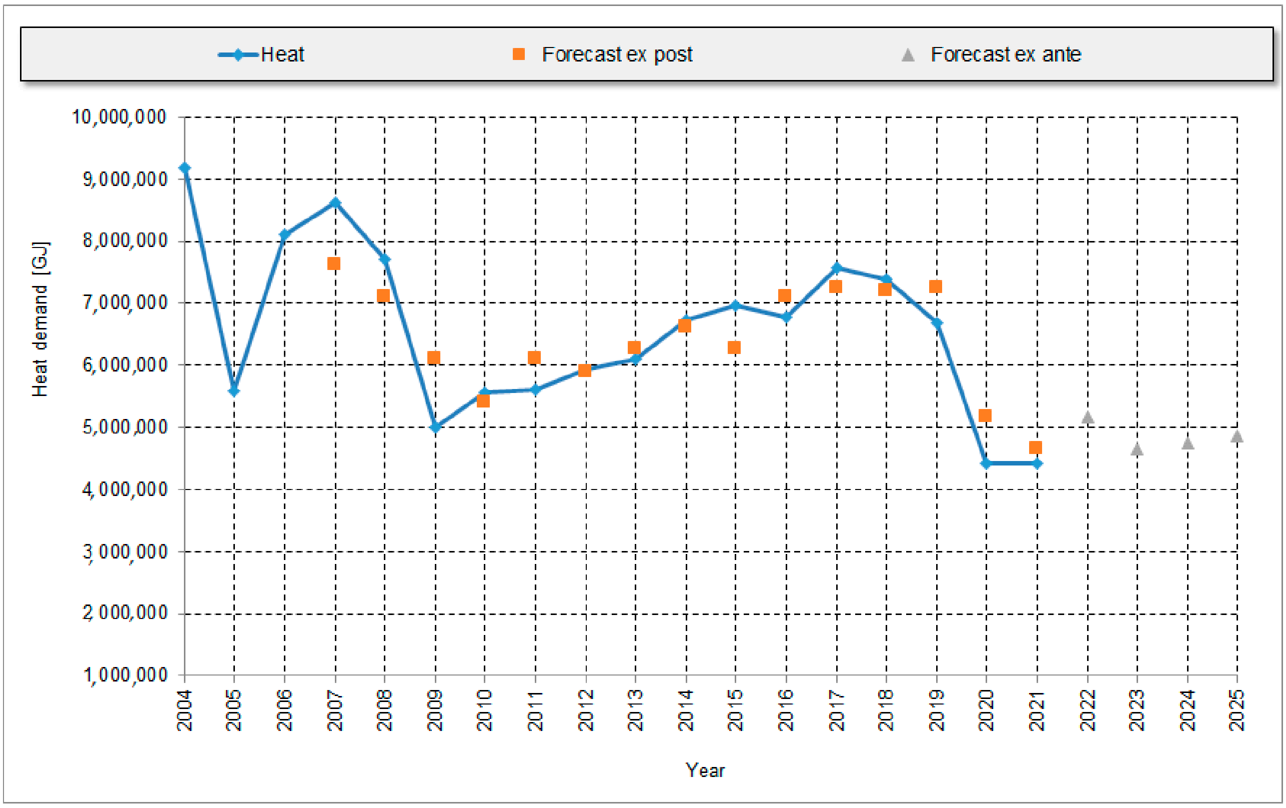


**Figure 17.** Forecasts of heat demand in steel industry in Poland.

**Table 5.** Forecasts of energy and heat intensity based on forecasting model used to determine the forecasts of steel production in 2022–2025 (variant 2B).

| Year | Forecast of Steel Production [Thousand Tonnes] | Estimated Energy Intensity [kWh/t] | Estimated Heat Intensity [MJ/t] |
|---|---|---|---|
| 2022 | 8436 | 272.953 | 612.944 |
| 2023 | 8445 | 265.626 | 562.350 |
| 2024 | 8440 | 266.956 | 576.008 |
| 2025 | 8440 | 268.521 | 563.793 |
| average per annum | 8440 | 268.514 | 578.774 |

The authors do not undertake to decide which of the energy and heat consumption forecasts (projections) is the best because several scenarios have to be taken into account in planning, and each of the variants has to be taken into account in future investment planning. In Table 6, obtained results were presented.

**Table 6.** Summary of estimated energy and heat consumption for the Polish steel industry.

| | | Variant 1A | | Variant 1B | | Variant 2A | | Variant 2B | |
|---|---|---|---|---|---|---|---|---|---|
| | Steel | Energy | Heat | Energy | Heat | Energy | Heat | Energy | Heat |
| Year | Thousand Tonnes | MWh | GJ | kWh/t | MJ/t | MWh | GJ | kWh/t | MJ/t |
| 2022 | 8436 | 2,395,668 | 6,224,840 | 284.243 | 738.261 | 2,302,627 | 5,170,798 | 272.953 | 612.944 |
| 2023 | 8445 | 2,399,225 | 6,231,481 | 283.940 | 737.475 | 2,243,207 | 4,749,042 | 265.626 | 562.350 |
| 2024 | 8440 | 2,397,804 | 6,227,791 | 284.108 | 737.912 | 2,253,110 | 4,861,510 | 266.956 | 576.008 |
| 2025 | 8440 | 2,397,804 | 6,227,791 | 284.108 | 737.912 | 2,266,314 | 4,758,415 | 268.521 | 563.793 |
| average per annum | 8440 | 2,397,875 | 6,227,976 | 284.100 | 737.890 | 2,266,314 | 4,861,510 | 268.514 | 578.774 |

Considering heat intensity in technological processes, significant differences can be seen between two production processes: BOF and EAF. The amount of heat consumed per tonne in Poland was much higher for BOF processes compared to EAF processes. For BOF processes, it was 961 MJ/t, while, for EAF technologies, it was 66.38 MJ/t. It is worth noting that a decrease in heat intensity with BOF technology has been observed in recent years—from 2010 until now, small decreases in energy intensity have been observed every year due to the use of new innovative technologies.

When BOF technology is used, there is an opportunity to implement technological innovations to reduce the heat intensity of processes. An especially useful solution to decrease the heat intensity in BOF technology is to conduct careful LCA analysis which is widely applied in the steel industry [92]. For example, Olmez used the LCA analysis to BOF technology and found that there is a large number of solid wastes and also energy wastes in the production process [93]. Dealing with dose problems can be very beneficial for heat intensity in BOF production processes.

In particular, technologies described in international literature such as furnace design and equipment change to decrease the amount of heat usage are used. When we want to evaluate innovative solutions connected with EAF technology it is important to take into account the thermal effects connected with exothermic reactions of oxidation of iron, carbon and its alloys. This effect is strongly connected with the temperature of the substances and also with the chemical reactions. Currently, most innovations connected with EAF technology are based on the development of means and methods how to provide better intensification of the process of liquid bath heating and solid charge melting [94].

In the case of EAF production, technology represents about 28% of world production and 16% of production in the European Union [95]. From this point of view, it is a very important technology. The study shows that a decrease in heat intensity can also be observed in the production of a tonne of pig iron and crude steel. In the case of EAF technology, only a very slight decrease in heat intensity was observed between 2018 and 2020 due to the introduction of new innovative solutions. However, it is worth bearing in mind that EAF technology is the least heat-intensive of all those analysed.

In the case of the analysis of energy consumption in technological processes in steel industry, a significant improvement in electricity was observed over the analysed period 2004–2020. Throughout the whole analysed period, as a result of the application of innovative technologies in the case of steel production in EAF technology, energy intensity decreased annually from the level of 547.8 kWh/t in 2005 to the level of 432.5 kWh/t in the case of 2020. Comparing the data with the data on energy intensity of the global steel industry, it can be concluded that the energy intensity of this industry in Poland is at a good level. According to international data, the average electric energy intensity of EAF processes is 100 to 500 kWh of energy per production on one tonne of steel [96,97]. Taking this into account, it can be seen that, between 2004 and 2007, the Polish steel industry was clearly more energy-intensive than the world average, as its energy intensity exceeded 500 kWh/t. Since 2008, as a result of investments in technological innovation, it started to perform at the world average level. As of 2017, the electricity of Polish EAF metallurgy reached below 450 kWh/t, which is below the world average.

Studies have shown that investments in green energy and new technologies have allowed Polish steel mills to significantly reduce their energy intensity, which allows them to produce in a more sustainable manner, in line with the pro-environmental guidelines of European Union countries. Nowadays, as confirmed by global studies carried out for example by Logar and Skjanc, innovative solutions can reduce the energy intensity of steel production, in particular in the case of EAF technologies [96]. Particularly relevant technologies in this respect include solutions such as: CO post-combustion [98]; off gas slag heat recovery, oxy-fuel burners [99], high power transformers [100], oxygen addition or bottom stirring [101]. The new innovative solution can have positive impact not only on the electricity and sustainability of production technology, but also their usage can lower the costs of production of steel in EAF technology [102]. The EAF technology when we used innovative methods to decrease the amount of energy used in production can be in accordance with sustainability and circular economy. Because of this, today, electric steel production factories want to focus their activities on new, innovative solutions to improve their energy efficiently in production processes due to optimal exploitation of the energy and also due to minimization of wastes and various types of emissions [103–105]. There are many technologies which can be useful in steel production to recover the energy and utilize in a way which can bring the organisation economic benefits [106,107]. For example, Amado used interesting data-mining innovative algorithm in order to achieve ranking list of variables which most influence on the energy intensity when using EAF technology [108,109].

It is worth noting that, for the EAF and BOF technologies analysed, the EAF technology is always more energy intensive and the BOF technology more heat intensive [110]. For this reason, pro-environmental innovations in the steel industry should first aim to reduce the energy intensity of EAF technology and the heat intensity of BOF technology. The analysis of data for Poland for the period 2004–2020 shows that both cases occur. The study shows that the heat intensity of BOF technologies has been steadily decreasing since 2010, and the energy intensity of EAF technologies has been decreasing throughout the period under review. In the coming years, steel production in Poland will not be high. According to the forecasts set out, it will oscillate around 8.4 million tonnes of steel produced annually. For such estimations, average energy consumption may range from 2,266,314 MWh (Variant 2A in the last line in Table 6) to 2,397,875 MWh (Variant 1A in the last line in Table 6), and heat consumption from 4,861,510 GJ (Variant 2A) to 6,227,976 GJ (Variant 1A), and per tonne of steel from 268.514 kWh/t (Variant 2B) to 284.100 kWh/t energy consumption (Variant 1B), and from 578.774 MJ/t (Variant 2B) to 737.980 MJ/t heat consumption (Variant 1B).

It can be concluded from this that the Polish steel industry is adapting to pro-ecological requirements and, thanks to the introduction of technological innovations, is moving towards the concept of sustainable metallurgy operating according to green steel principles and the principles of circular economy in the EU [111]. Investment in steel mill technology translates into TPM. Maintenance is the basic functionality of the devices and decrease the number of failures in order to reach improvement of production efficiency [112]. Steel producers need to take into account situations of crises, e.g., after COVID-19. Crises have always had a downward effect on steel production [113].

## 6. Conclusions

The analyses carried out in the publication allowed the objective of the work to be achieved and the research questions to be answered. The research shows that the Polish steel industry in Industry 4.0 conditions reduces electricity and heat consumption between 2004 and 2020 as a result of investments in new sustainable, environmentally friendly technologies. Considering two typical steel production technologies BOF and EAF, there is always a higher heat intensity in the case of BOF technology, while in the case of EAF technology, there is a higher electric energy intensity. An analysis of the heat intensity of the technologies studied showed that, from 2010 onwards, a slow annual decrease in the heat intensity of the BOF technology can be observed, resulting from technological investments, while the heat intensity of the EAF technology remains unchanged. The opposite situation is the case with energy consumption by technologies. In this case, there is a clear decrease in electricity for EAF technologies each year throughout the study period, while there is little change for BOF technologies. The observed improvement in the electricity of EAF technology in Polish mills as a result of investments in new technologies allowed the current level of 432.5 kWh/t to be reached for 2020, which is a good result in comparison with the electric energy consumption of steel production worldwide, clearly below the average of about 450 kWh/t.

The decrease in the electricity of steel produced in Industry 4.0 conditions using EAF technology is an important issue, as the high energy intensity of EAF processes affects the overall energy consumption for crude steel production processes in Poland. In the future, the use of new innovative technological solutions, including solutions based on Industry 4.0 principles related solutions, should help the Polish steel industry to further reduce the level of energy and heat intensity. Such activities will enable the achievement of sustainable steel production and product in accordance with the green steel concept. Actually, the real problem is the analysis of the two routes: BF/BOF and DRI/EAF. The BF/BOF route consumes much more energy [5,7].

The method presented in the paper gives us the possibility to forecast the energy intensity usage in the future. On the basis of the conducted analysis, it can be stated that, in the next years, the energy consumption may range from 2,266,314 MWh to 2,397,875 MWh.

The main problem with the presented forecasts lay in a fast changing environment, which is connected especially with the war in Ukraine and climatic changes. We prepare three variants of steel production, energy intensity usage and heat intensity forecasts. The first is based on the unit average annual energy and heat intensity calculated on the historical data, in the second, we use the forecasted average energy and heat intensity for annual steel production and, in the third, we used a moving average model. It is not possible to decide which presented models are the best suited to the prediction of energy and heat consumption by steel industry. In the future, it will be worth analysing the adjustment of the prediction to real data.

We think that the results obtained from the paper can be useful for industry and government planning purposes, especially in the process of strategy planning for steel industry in Industry 4.0 conditions and adjusting this industry to environmental changes and European union restriction connected with decarbonisation policy. On the basis of our analysis, government and steel organizations can prepare their policy for the future functioning. The whole steel industry should concentrate on new Industry 4.0 connected solution targeted at the decrease of energy demand in the steel production processes. It can be achieved by promoting ecological, low energy technologies. In particular, the steel industry should concentrate on steel mill technology which can translate the organization into TPM. In addition, it is very important to concentrate on the analysis of wastes. It could lead to decreasing the number of failures and the increasing of production efficiency.

The presented paper has some limitations. The first limitation is connected with the range of data analysed in the paper. Our analysis was conducted on the example of Poland and, maybe in other countries, the resolute and trends could be slightly different. However, the method of the prognosis of future demand is universal and could be used for the data about the steel industry in another country. The second limitation can be connected with the data accuracy. We used in the paper as an input raw data from secondary sources collected by Polish steel organizations. However, the data accuracy is based on methods of collection. We do not have control of it, and we can not be sure that all steel industry organizations send all proper data for statistical purposes. In addition, we should mention that all prediction methods are prepared on the basis of past data, and the results of forecasting are proper in stable environments. Very big changes in the world economic conditions can have an impact on production level and can lead to a gap between our prognosis and reality.

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