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Article

Framework for R&D&I Activities in the Steel Industry in Popularizing the Idea of Industry 4.0

Bożena Gajdzik [1] and Radosław Wolniak [2,*]

[1] Faculty of Materials Engineering, Silesian University of Technology, 44-100 Gliwice, Poland; bozena.gajdzik@polsl.pl
[2] Faculty of Organization and Management, Silesian University of Technology, 44-100 Gliwice, Poland
* Correspondence: radoslaw.wolniak@polsl.pl

Abstract: The research and development activity of a company determines the innovativeness of enterprises and economies. This kind of activity simultaneously influences the pace of their development and the level of competitiveness. With this in mind, the article—against the background of the characteristics of research and development activities—defines a framework for R&D&I activities for the steel industry in the conditions of popularization of the concept of Industry 4.0 and analyzes expenditures on R&D&I activities in Poland in 2010–2019. This topic is important because steel is one of the most important materials for the construction and the manufacture of steel products. It is very important to adjust the steel industry to the new market condition using research and development activities. The analysis was performed on the basis of data on expenditures on R&D&I activities by internal expenditures on R&D, expenditures on product and business process innovations and outlays on fixed assets for environmental protection through investments. The target of the paper is to find response on the three research questions formulated in the paper: what is the dynamics of the changes in the R&D expenditures in the Polish steel industry in 2010–2019 in comparison with the total industry in the country; what is the dynamics of changes in investment expenditures on new products and business process innovations in the Polish steel industry in 2010–2019; what is the level (dynamics) of investment outlays in environmental innovations in the Polish steel industry in 2010–2019? To conduct this analysis, we used the following methods: critical literature analysis, secondary data analysis, statistical methods. Industry 4.0 implementation in the steel industry has a strong, positive influence on the innovativeness of the company and on spending on innovations. On the basis of the data analyzed in the paper we observed that the increase of expenditure on R&D in the Polish steel industry was similar to that of other industries. As a result of the research, it was found that the dynamics of R&D expenditure in the Polish steel industry was consistent with the dynamics of expenditure calculated for the entire Polish Industry. At the same time, the sharp increase in R&D expenditure since 2018 was related to the implementation of the Industry 4.0 concept in the Polish industry. An interesting result of our research is the observed time lag in the form of a postponement of the growth of R&D expenditure after the emergence of the Industry 4.0 concept. We also observed that environmentally fixed capital expenditures may show fluctuating dynamics due to business cycles and legal restrictions to protect the environment. The added value of the publication is the framework of R&D&I activities for the steel industry and an in-depth analysis of R&D&I expenditures on the example of the metal producers in Poland in the last decade of growing interest in the concept of Industry 4.0 (I 4.0).

Keywords: Industry 4.0 (I 4.0); innovativeness; open innovation; business process; sustainable production

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1. Introduction

Development-oriented research is a determinant of the competitiveness of enterprises. Modern business is conducted in a highly dynamic (highly changeable) environment.

The increase in the turbulence of the environment, exemplified among other things by the significant shortening of product and technology life cycles, makes it necessary for enterprises to introduce innovations more quickly. Innovations are the result of defined ideas (ex-ante), which must be used to develop the business. For customers, it is above all innovations that create new product value that are important. The theory of organization and management, and within it the theory of strategic management, strongly emphasizes the theme of research, development and innovation (R&D&I) in the market economy. R&D and innovation activities condition the development of enterprises and economies, simultaneously influencing the pace and level of competitiveness. Many theoretical arguments place planning above other management functions, rightly emphasizing that it is not about predicting but about conscious shaping of the future, which requires R&D&I activity. The shaping of the business future needs to be prescribed in the form of company strategy, in which innovation plays an important role [1–3].

The first attempts to measure R&D activities of industries as a business phenomenon were made in the United States in the 1930s and 1940s. Regular statistical surveys of research and development (R&D) in industry began in 1953 [4]. The end of the last century was characterized by the development of an architecture of reports on R&D in industries of many countries. Starting from the second half of the last century, innovative research carried out in enterprises was presented in statistical reports. In the 1960s, the OECD took on the role of coordinating the standardization of data collection. This organization initiated the development of guides for the measurement and interpretation of data on innovation activity. Measures of innovation, such as the Global Innovation Index (GII), were used to compare the activity levels of industries. In addition, countries and regions have introduced internal measures of R&D activity. Within the EU, the Innovation Union Scoreboard is used (until 2009 known as the European Innovation Scoreboard). Differentiation of measures has also been introduced in individual industries. An example is the Global Competitiveness Report ranking which is published by the World Economic Forum. On the basis of innovation metrics and indices, government, industry or sector organizations produce their own rankings or compilations, which use data on the R&D activities of enterprises. The rankings measure innovation activity at different levels of the economy, from macro to micro. Go-economies, however, are not homogeneous creations: it is usually the case that the development in them does not proceed evenly, and research and development activity is usually concentrated in selected places, e.g., branches of industry. It is interesting to note the dynamics of change in specific industrial sectors, especially in industries that are strategic for the development of economies, such as the steel sector.

Steel is one of the most important materials for construction and the manufacture of steel products. Increasing consumer demand has led to an increase in global steel production. In the last decade, global steel production has increased from 1,435,254 thousand tones (2010) to 1,875,155 thousand tones (2019) [5]. Additionally, the increasing demand for steel in terms of quality makes the market very competitive. Large steel corporations (strong equity groups in the global steel market) have established research and development (R&D) infrastructures to innovate steel production processes and meet quality requirements [6]. Large steel companies have their own R&D centers with strong laboratory facilities. The first mention of R&D activity in the steel sector appeared in the first half of the last century. In 1936 at Tata Iron & Steel Company (TISCO) the first R&D Laboratory was set up, in 1916 in Nippon Steel Corporation. In this company the Research Section was initiated in the government-managed Yahata Steel Works [7,8]. R&D activity in the steel companies evolves with the dynamics of the business environment. Innovation results in new products and technologies and more efficient business processes. Since 2011, the German Industry 4.0 strategy, which has quickly become very popular in many developed countries around the world, has initiated a new research area abbreviated as “smart” or “smart manufacturing”. This new area of R&D activity is based on the key technologies (pillars) of Industry 4.0 that enable steel mills to build competitive advantage through smarter manufacturing [9,10].

In the new reality—the strong popularization of the Industry 4.0 concept—a research gap has appeared related to the analysis of R&D&I activities of the industry in conditions of strong promotion of the Industry 4.0 idea: "manufacturing of basic metals". For the purposes of the research, the R&D&I activities framework for the contemporary steel industry was determined on the basis of a literature review. Literature studies provided a basis for determining the scope of analysis of R&D&I activities on the basis of data from the Organization of Statistics Poland. The research objective was to determine the dynamics of R&D&I activities on the basis of an analysis of expenditures on R&D&I in the Polish steel sector.

In the presented analysis we answer the following questions:

- What is the dynamics of changes in R&D expenditures of the Polish steel industry in 2010–2019 in comparison with the total industry in the country?
- What is the dynamics of changes in new product investments and business process innovations in the Polish steel industry in 2010–2019?
- What is the level (dynamics) of investment outlays in environmental innovations in the Polish steel industry in 2010–2019?

The paper consists of the theoretical and analytical parts. The first part of the presented paper was based on a literature study and resulted in the R&D&I framework for the steel industry in the Industry 4.0. The second part of the paper concerned the dynamics of R&D&I expenditures in the sector of metal producers in Poland in the last decade. The analysis covered the segment of metal producers—the manufacture of basic metals—in which steel producers are located. The analysis of the dynamics of R&D&I expenditures should be treated as a case study. In Poland the average annual production of steel is ca. 9 mln tons. The given amount is an averaged production of the last decade. The scenario for the coming years is moderately optimistic, the production will remain at an average level with a slight upward or downward trend. Poland is ranked on 19th place in the top list of world steel producers (2019) [11].

The analysis of R&D activities of the Polish metal producers was made on the basis of data from Statistics Office in Poland. This organization (in Polish: GUS) prepares industrial reports in Poland. The analysis period covered the years 2010–2019. The choice of the analysis period was dictated by the purpose of the research, which was to determine the dynamics of R&D&I activities in a period of strong popularization of the idea of Industry 4.0. The analysis did not cover the years 2020–2021, due to the pandemic period. This was a period with many restrictions on the mobility of society and business (lock-down). During the pandemic period, the steel sector in Poland experienced a decline in steel production [12]. In 2020, steel mills were strongly affected by problems related to: ensuring continuity of raw material supplies, rapid growth in prices of raw materials and energy, and falling demand for steel products, especially in the second quarter of 2020 due to a decline in production of cars.

Today very interesting and useful approach to innovation is that based on open innovation [13,14]. Open innovation approach is a new model of knowledge management which should involve innovation processes which are open towards outside world. It is different approach comparing to traditional attitude to innovativeness which is the basis approach use in companies nowadays [15–18]. The conception of open innovation was born in 2003 in USA [19,20]. The attitude towards innovations in Open Innovation vary and is based on collaboration with external research [21–23]. In Open Innovation logic organization should not do all the innovation alone but be based on collaboration with other entities and use the whole potential of innovation [24].

The open innovation approach is also known as crowdsourcing, community-based innovation, open-source innovation or user innovation. This approach can be helpful to improve the outcomes of the company [25]. The international researchers have found that open innovation approach is use rather by big companies not small enterprises. Larger companies are more involved in the open innovation activities. They try to develop mutually beneficial collaboration with knowledge institutions, startups or consulting firms.

Small and middle enterprises rather try to collaborate with strategic partners in the case of market related activities [26–28]. Because in the steel industry the big companies prevails it is important to analyze the potential of using the open innovation approach in this industry.

2. Theoretical Approach for Sectoral Analysis

The increasing activity of enterprises in the markets and the progressive importance of knowledge-based economies, as well as the fourth industrial revolution taking place, forced radical changes both on the enterprises themselves and on their environment. The research and development activity of enterprises determines the development of business and industry. According to the OECD organization "research and development", abbreviated to "R&D", includes activities connected with creative work that is undertaken on a systematic basis. The scope of this activity is connected with the increase of the stock of knowledge. This knowledge could include knowledge of culture and society, man, and the use of the stock of knowledge to create new potential applications [29]. Many countries, including Poland, have adopted this OECD definition for R&D activity. In Poland, for reporting purposes, R&D activity includes three types of research: (i) basic research; (ii) industrial (applied) research; (iii) development work (http://stat.gov.pl/bdl; http://stat.gov.pl/metainformacje, accessed on 20 April 2022). The area (ii) includes the internal R&D expenditures of enterprises, which was one of the analysis segments for the topic of this publication (Figure 1).

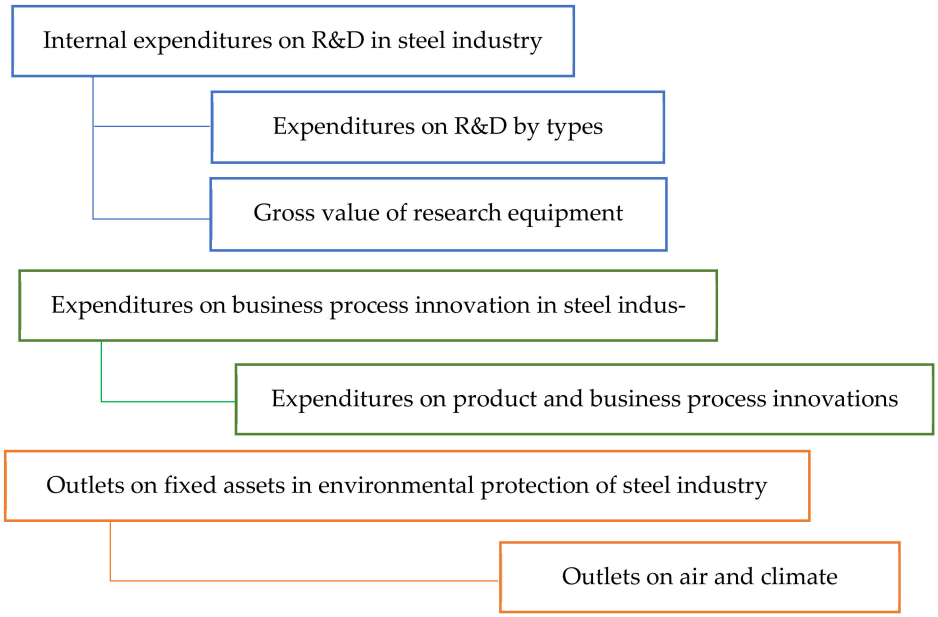


Figure 1. R&D&I activities in the analysis. Source: own elaboration.

R&D is creative work, carried out in a methodical way. In enterprises, R&D activities are realized by departments (organizational units) for research and innovation in cooperation with internal and external laboratories, scientific institutes and universities, as well as other organizations. Statistics in Poland (GUS) on expenditures on R&D activities present internal expenditures; for example, we can include here the value of research and development work in the case of a given unit which is performed by its own research activities to facilitate its usage. It should be performed regardless of the sources of the financing of a particular activity, including both investment expenditures related to R&D activity and also current expenditures. The depreciation of fixed assets is not included. On the other hand, some data connected with R&D expenditures include additional external expenditures of the company on broad innovative activity. This could be defined as the value of research and development works in the case of a given unit. The mentioned unit could be purchased from other units (foreign or domestic). Data about problems connected

with internal expenditures on research activities can be aggregated according to the amount of expenditure compiled by units on particular types of economic activities (in Polish: PKD). PKD section 24—the manufacture of basic metals in Poland (category of economic entitles: manufacture of basic metals)—was used for the analysis. The research on R&D outlays is based on the classification of sources of funds for outlays proposed in the Frascati Manual (OECD, 2002) [29]. The typology of these outlays is presented in Table 1.

Table 1. Typology of R&D expenditures in the Polish industrial statistical reporting.

1. Government budget for R&D activities of industry	The amount of expenditures allocated by the government to R&D within the country, budgeted as all items related to R&D and then estimated in terms of financial resources.
2. Internal expenditures on R&D activities	Expenditures incurred during the reporting year on R&D work carried out in the reporting unit, regardless of the source of funds; this includes current expenditure as well as capital expenditure on fixed assets related to R&D activities, but excludes the depreciation of the company assets.
(a) Current outlays on R&D activities	Personnel expenses, non-durable objects and energy, costs of consumption of materials, costs of business trip, costs of external services (other than on R&D activities), other current costs connected with R&D excluding the depreciation of fixed assets and VAT taxes.
- expenditures on staff	Gross salaries with wage surcharges.
(b) Investment outlays on R&D activities	Expenditure on new fixed assets used in R&D activity, including purchase of used fixed assets and purchasing of investment equipment.
3. Gross value of scientific and research equipment	Value of research equipment: measuring or laboratory equipment.

Source: based on OECD [29].

The scope of analysis, in this article, within segment 1 (Figure 1) of the analysis of R&D input dynamics in 2010 includes: (i) internal expenditures (item 2 in Table 1); (ii) capital expenditures (item "b" in Table 1); and (iii) gross value of R&D equipment (item 3 in Table 1). Segment 2 consists of an analysis of business innovation: product innovations and business process innovation (expenditures and dynamics compared 2010). The last segment (3) is about outlets on environmental protection including outlets on air and climate. All segments were presented for the Polish steel industry—the manufacture of basic metals with a comparison to the total industry in Poland.

A broader concept than R&D is R&D&I or Research and Development and Innovation. In definition of innovation, researchers rely on publications by Schumpeter [30] and Drucker [31]. In 1934, Schumpeter has formulated a definition of "innovation," or "development". He has defined this concept as "a new combinations" of new or existing knowledge, equipment, resources, or other factors. According to Schumpeter [30], innovation is: (i) the introduction of new products or services to the market—they are also changes in existing products that increase their quality and usefulness; (ii) the conduct of new production methods; (iii) the application of new ways of selling; (iv) the application of new methods of purchasing; (v) finding and opening new markets; and (vi) the introduction of new forms of organization of economic processes. A significant development of the science of business innovation occurred in the second half of the 20th century. A significant contribution to the development of the science of innovation was made by P. Drucker who formulated the term systematic innovation—a purposeful and organized action to change the value delivered to the customer [32]. In his opinion, innovation in a dynamic environment must be based primarily on the search for new values and new ways of satisfying needs [32]. In contemporary business, quoting Ch. Freemann, not innovating means dying [33]. A company that does not innovate inevitably grows old [32]. Peter Drucker has described his

"innovation" definition in 1985 in the book *Innovation and Entrepreneurship*. He has defined the innovation concept as the specific tool of entrepreneurs and also the means by which entrepreneurs can exploit change as an opportunity in the case of a different business or a different service [32]. W. Chan Kim and R. Maunborgne [34] urge companies to look for a "blue rating" and value innovation.

Contemporary innovation activity includes all developmental, commercial or financial and activities undertaken by a company with innovation as its intended goal. Innovations occur in all phases of a company's activities, from design, products, marketing activities, customer service, management, pricing and control [35]. Innovations are tools, which not only improve the processes of adapting business to changes, but which also allow us to anticipate them and to prepare actively for them. The innovative activity consists of the process of the improvement of the quality of products and services, the application of various concepts in the enterprise management, but also in overlooking the possibilities of satisfying the future needs of customers or even creating them. Innovations can be classified in many ways. One of them is the division into product and process innovations. Research and development work aims at the production of technologically advanced products and processes. A significant degree of technological advancement of economies results from a high level of innovativeness ensured by research and development, which in turn results in the application of new techniques in the production process and an increasing share of new products on the market [36].

R&D activities carried out by companies are almost always innovative activities. Therefore, it assumes that innovation and R&D activities are to some extent terms with synonymous meaning [37]. In fact, the largest part of innovation expenditure in many industries consists precisely of R&D expenditures [38]. Expenditure on innovation activities includes: (i) expenditures on research and development (R&D); (ii) expenditures on own personnel working on innovations; (iii) purchase of materials and external services for the implementation of innovation activities; (iv) capital expenditures on fixed assets; (v) intangible assets (including purchase and development of software and intellectual property); (vi) other expenditures (including product design, definition of service delivery, preparation of production and distribution for innovation implementation, training and professional development of personnel, marketing) [39].

Statistical statements present data on innovation activities in industry and concern the introduction of new or improved products and their development. It is also connected with services put to the market and the introduction of totally new or improved business processes in a particular enterprise. Product innovations are new or improved products, significantly different from those previously offered to customers by the enterprise. Business process innovations refer to the introduction of new or improved business processes in the enterprise, within one or more business functions, which significantly change the previously used business processes [39]. A new or improved product can be defined as a product or service that differs significantly from the company's previous products. This difference should contain one or more features or technical parameters. These changes include the addition of new, or the improvement of existing, functions or usability. Relevant functional features include technical performance, quality, reliability, durability, convenience, efficiency in use, affordability, ease of use and usability [39]. In our research we referred to product and business process innovations in the Polish steel industry according to the Polish Classification of Activities; the sector is analyzed as the manufacturing of basic metals. The analysis took into account the inputs of enterprises according to the classification in Table 2.

Table 2. Typology of expenditures on product and business process innovations in the Polish industrial statistical report.

1. Expenditures on innovative activities	Amount of expenditures (from various sources) on innovative work, i.e., on product and business process innovations in the reporting year.
(a) expenditures on R &D activities	R&D expenditure (value/amount) in the reporting year.
(b) on purchase of knowledge	Amount of expenditures on the purchase of knowledge from external sources and computer software in the reporting year.
(c) on investment (capital expenditure)	Amount of expenditures on buildings, land, technical equipment, machinery, and tools and transport in the reporting year.
(d) on staff and marketing	Expenditures on staff training and expenditures on marketing activities related to new products in the reporting year.

Source: based on the [40].

In the conditions of strong popularization of sustainability, investments in environmental protection (environmental investments) are important in the category of expenditures. In the Polish reporting system, the outlays on fixed assets dedicated to the reduction of the negative impact of production (industry) on the environment through investments are reported. The structure of the expenditures on fixed assets for environmental protection is presented in Table 3. The research analyzed item 1 from Table 3 and 1a from Table 3.

Table 3. Typology of expenditures on environmental fixed assets in the Polish industrial statistical report.

1. Expenditures on fixed assets for environmental protection	Amount of expenditure on fixed assets which can be used for the protection of all environmental components in the reporting year.
(a) expenditures on air protection	Amount of expenditure on fixed measures to protect air and climate in the reporting year.
- of which: purchase	types of modern fuel combustion technologies
(b) expenditures on water and wastewater management	waste water management and protection of waters of which outlays on municipal wastewater treatment, sewage system for the transport of wastewater and precipitation water, rotary system of water supply.
(c) expenditures on waste management, groundwater, surface water and protection of soils,	Amount of expenditures on fixed assets for waste management, soil and water protection the reporting year.
(d) expenditures on noise and vibration reduction	Amount of expenditures on fixed assets for the noise and vibration reduction in the reporting year.

Source: based on the description [40].

Data connected with outlays on fixed assets and other types of tangible effects of investments in water management and environmental protection are presented in accordance with the data from the Polish Statistical Classification of Environmental Protection and Facilities. This document was introduced on the basis of the Regulation prepared by the Council of Ministers of 2 March 1999 [41]. Presented classification was compiled by ECE/UN Single European Standard Statistical Classification of Environmental Protection Activities and Facilities and also by European System for the Collection of Economic Information on the Environment (SERIEE). The document was implemented by the European Union.

The last piece of information that requires explanation to understand the essence of the analysis of R&D&I data is the classification of industry in Poland. According to the Polish Classification of Activities PKD, dating back to 2007, which was compiled on the basis of the document prepared by the Statistical Classification of Economic Activities in the

European Community—NACE Rev. 2 The PKD classification was introduced on 1 January 2008 by the Regulation of the Council of Ministers. It dates back to 24 December 2007 [42]. Especially important from the paper point of view are sections connected with "Industry", including sections "Manufacturing", "Mining and quarrying", "Electricity, gas, steam and air conditioning supply" and also problems connected with "Water supply; sewerage, waste management and remediation activities". In the section "Manufacturing" is the "manufacturing of basic metals". The structure of the analyzed sector of the manufacture of basic metals is presented in Table 4. In the analyses, position 1 was used according to Table 4.

Table 4. Sector of manufacture of basic metals in Poland—statistics data.

Filed in Business Activity	Economic Entities in 2020
1. Manufacture of basic metals	176
(a) iron, steel and ferroalloys	16
(b) manufacture of tubes, hollow profiles, pipes, and related fittings of steel	26
(c) manufacture of other products produced by first processing of steel	28
(d) manufacture of basic precious materials and other non-ferrous metals	34
(e) casting of metals	73

Source: based on [40].

Research limitations concerning the steel segment in Poland: annual reports on industrial activity in Poland do not provide data on activity classes (for "a", "b", etc. from Table 4), therefore the total production of metal products was analyzed (item 1 from Table 4). In Polish industrial reporting there is no data on expenditures on individual information and computer technologies. The Statistical Yearbook of Industry—Poland prepared by Statistics Poland—GUS (Warsow) contains data on expenditure on high, medium–high, medium–low and low technologies (according to the OECD classification of technology levels). These expenditures were analyzed, but for the reporting period 2013–2019 (no data for previous years) and only for the manufacturing sector, in which steel production plants are registered (no data on expenditures in the sector: manufacture of basic metals.

3. R&D&I Framework for the Steel Sector in Industry 4.0 in Literature

Business activities in the last decade have focused on the idea of Industry 4.0. The concept of Industry 4.0 first has appeared at the Hannover Fair in Germany in 2011. It was a proposal for the development of high technology for industry. This new concept is a long-term process of developing companies with radical technological changes that can create cyber-physical systems both within companies and in entire supply chains [43]. The key technologies of Industry 4.0 introduced in companies are a set of innovative solutions, which consists of: the Internet, IIoT, big data, blockchain, cloud computing, human–machine interactions, robotics, open source software and artificial intelligence [44]. Companies are building cyber-physical production systems as forms of integrating information technology and operational technology [45,46]. Cyber-physical systems are evolving as technology advances and over time will form smart factory systems [47]. Investment in new solutions based on Industry 4.0 technologies in companies is referred to as smart manufacturing (SM). According to Kan et al. (2016) [48], "Smart Manufacturing, is the concept connected with fourth revolution in the manufacturing industry. It can be developed as a new paradigm. We can think about this concept as the collection of cutting-edge technologies which can be used to support accurate and effective engineering decision-making

processes in real time. It can be achieved through the introduction of ICT technologies and also the useful approach it the convergence with the existing in the industry manufacturing technologies". Changes in enterprises start from single workstations equipped with the latest technologies, through smart production lines and technologic nests, to smart factory systems in business network structures. According to Lu and Ju [49] future manufacturing can be considered "smart" when it is capable of agilely adapting to a wide variety of changing conditions in Industry 4.0. Industry 4.0 is a combination of organizational, technological, process, product and marketing innovations. The level of development of a given company is a result of changes in all these areas. However, the needs of the market must not be forgotten. If companies are able to implement innovations related to Industry 4.0 and read market signals well, they will have a chance to function in global value chains.

Contemporary value chains rely on digitalization and artificial intelligence. According to Zhong et al. "digitalization of the production process which the usage of artificial intelligence can determine the directions of the process of implementing contemporary industrial development processes and are placing it in the architecture of a new market economy" [50]. According to Lu and Ju, this "requires logistic systems, production plants and supply chains to achieve the enough level of flexibility in design and reconfigurable of the production processes to respond quickly to changing customer needs, market changes and production uncertainties" [49]. Research and development in Industry 4.0 must be directed towards the production of highly technologically advanced products that will have a strong impact on the competitive conditions in the global market. The increasing availability of new technologies is an incentive to develop and improve production systems and leads to potential economy-wide benefits. It can be concluded that a significant degree of technological advancement of economies results from a high level of innovativeness ensured by research and development work carried out in enterprises and their environment, which consequently results in the application of new techniques in the production process and an increasing share of new smart products on the market [51]. Research and development works are included in the company's intangible assets and as an individual, unique activity aimed at obtaining better results as a result of their implementation they are the company's own product. Intangible assets, and thus R&D, are seen as core competencies of the company [52]. Innovations in Industry 4.0 are realized ideas concerning primarily intangibles, which were created on the basis of technological possibilities of the Fourth Industrial Revolution and the concept of Industry 4.0 development popularized in developed countries.

The implementation of Industry 4.0 concept have positive effect on boosting innovations and innovative approach in business. Implementing of Industry 4.0 related cutting-edge technologies can enable organization effective and precise management in real time of all production processes especially because of innovative information and communication technology usage. This technology is an important part of every industry 4.0 related system. New, innovative solution can enable organization to link digital technologies with operation and manufacturing innovative solutions. This approach should lead to the vertical integration of intraorganizational production systems and the horizontal integration of intraorganizational production systems [53,54]. The lack of innovative solution implementation in times of Industry 4.0 can lead to decreasing in the supply chain flexibility and many problems with suppling [55]. Using of innovative, Industry 4.0 related technologies have potential positive effect on increase of organization innovativeness and competitive growth [56]. This can also lead to enhancement of the sustainability of existing industrial systems [57]. This is especially important in the steel production industry because of strong effects of the production processes in this industry on the natural environment and the importance of the environmental issues on the European Union level.

The implementation of Industry 4.0 related solution in business can have a positive effect on many technological solutions and relations between technologies and social performances. The Chen point out that the main contribution of Industry 4.0 implementation is connected with improvement of the ergonomics and safety, collaborations within the

organization between people and machines and between organization and surroundings; interactions within the range of digital environment, increase of the role of human rights and development of the community [58,59].

The implementation of Industry 4.0 is also related with the implementation of open innovations. The open innovation approach is especially useful in the implementation of green technologies in Industry 4.0 condition [60]. The importance of this statement is connected with the importance of environmental issue for the steel industry we have mentioned earlier in the paper. In many papers we can observe the analysis of the role of open innovation approach in Industry 4.0 organizations [61,62]. The open innovation approach is connected with promotion of suitable innovations especially in the case of organizations implementing Industry 4.0 approach [63,64]. The open innovation can be defined as a model that enable business to build a strong, structured, innovative ecosystem that uses network of external patterns and because of that is focused on developing core internal competences [65]. Open innovations in Industry 4.0 conditions boost inside-out and outside-in innovation processes. Using this approach organization can replace traditional rivalry among firms in industry instead of it introducing coopetition, collaboration and cooperation [66]. The implementation of open innovation concept in industry need mutual collaboration. This collaboration should be with external stakeholders and because of it we can improve the innovativeness level by utilizing outside knowledge which can bring many benefits in the process of developing mutual competences [67]. When organization use the open innovation approach the innovative process can become more sustainable and they can reduce extra innovation-based behaviors among employees and investment [68]. The employees' behaviors are boosted by collaboration and many interactions with outside partners. When steel industry organizations focus on enhancing an ecofriendly approach to innovation they can improve and promote sustainable, green products and green processes [69].

The innovative activity of industry requires the definition of a framework to be created in view of the opportunities and threats to the development of smart manufacturing. To realize this objective, the authors performed an in-depth literature study for the steel sector, which was a segment of the study. According to the global policy, the global industry has to comply with the requirements of the environmental law. In highly developed countries, the industry and its individual sectors are adopting and pursuing sustainable development goals. Sustainability is a corporate strategy that evolves with technological progress. In the concept of Industry 4.0, the promoted manufacturing technologies and value-added chains are built on the assumptions of sustainability. Industry 4.0 cannot develop without sustainable development. The idea of Industry 4.0 over the years is increasingly linked to the principles of sustainability, and the implemented technologies of the fourth industrial revolution are to help companies save resources (raw materials) and energy. The steel industry is one of the most energy-intensive sectors, so steel companies have a strong interest in innovations that save energy. As technological investments increase, energy and raw materials are being diminished in the steel sector under study [70,71]. Energy efficiency is embedded in the industrial development strategies of developed countries around the world. Global efforts on renewable energy. One of the EU policy objectives is to develop applicable technologies to improve energy and resource efficiency (SCU—Process Integration, according to a document from The Clean Steel Partnership) [72]. The EU Commission has announced on 12 December 2019, in its new prepared strategy the conception of The European Green Deal. This concept is connected with the Industrial Emissions Directive. Is shall be revised carefully to make it consistent with energy, climate, and circular Economy policies [73].

A significant challenge for innovation in the steel industry and for R&D activity is the reduction of CO_2 emissions. The Clean Steel Partnership in UE (Brussels, 2021) [74] proposes a three-stage R&D&I conception about how to accelerate carbon mitigation in the described in this paper case of steel industry: (i) focuses on those projects that may not be implemented immediately in the company, but allow for a quick evolution towards

possibility of improvement of processes; (ii) targets projects that generate quick CO_2 reduction opportunities; (iii) looks at specific projects in which implementation can lead to 'revolutionization' of the whole steel industry through innovative breakthrough development solutions, and beside require capital investment to implement new processes. The Clean Steel Partnership (CSP) promotes clear technologies and also cutting CO_2 emissions from burning fossil fuels (e.g., coal) in the steel production. Innovations focuses on the steelmaking process. Innovative clean steel technologies are already contributing to the production of climate-neutral steel. Decarbonizing the steel sector is important for achieving a sustainable, thriving, and circular EU economy [75,76]. In reality, there is no one single solution to decarbonize the whole steel sector. It can be performed by implementation of many different technological pathways which should be followed by companies to achieve climate neutrality. Additionally, combining different innovative technologies it has to be proven how to generate more CO_2 reduction than in the case of the separate deployment of similar technologies. The whole steel sector made a strong contribution to reduce its emissions and because of that contributing to achieve the EU energy and climate targets. Additionally, in terms of the reduction level of CO_2 and potential energy saving, European policy is important in increasing the recycling of steel scrap and also residual material. This leads to the improvement of smart resources usage and can generate further supporting activities in a circular economy model in the EU (see CSP, 2021, and The European Green Deal, 2019) [72]. Modern technological innovation is based on BAT according to IDEAS/RePEcIndustrial Emissions Directive 2010/75/EU [77]. In our modern times, the emphasis of governments on the sustainability of the steel industry is much stronger than in the 1990s [76–78]. The development of the steel industry must be in line with the goals of the 2030 Agenda for Sustainable Development [79]. Technological innovation in the EU steel industry is in line with the European Green Policy, the UN 2030 Sustainable Development Goals [80].

Sustainable steel is a material enabling the deployment of green technologies. Finally, the steel used in this process is infinitely recyclable, and because of that its residues and waste energies can become very valuable resources [81]. Increasing the recycling of steel is a target of innovation processes [82]. Moreover, steel is considered a very important mitigation enabler. Because of its strength and durability, this material enables savings in other industries.

The R&D activity of steel companies is strongly linked to the participants in the supply chain. We must not forget that steelmakers participate in wider value chains including sectors which are crucial for the EU competitiveness, like construction, mobility, automotive, energy generation and networks, mechanical engineering, and defense [83]. The liaison of many function within the EU countries are necessary to implement the Clean Steel Partnership. This partnership can play a crucial role in bringing together, identifying, enabling and coordinating many important breakthrough technologies with their high innovation potential. The mentioned Partnership could engage all relevant stakeholders especially including industrial players, academia, the research community, civil society organizations and Member States to ensure that any kind of R&D&I initiatives could lead to improvement of the positive impacts within and beyond the whole steel sector.

In addition to many environmental aspects, innovative activity in the steel industry is changing the quality of steel products. Competition in the steel market focuses on ensuring high functional and marketing quality. Innovation research carried out in companies is integrated into the improvement of steel product quality. Quality in the steel sector is closely related to the continuous adaptation of the product to the needs of customers, especially the automotive and construction sectors [84]. Laboratories investigate the ideal shapes and functions of structural members and materials. They also develop new products that could be environmentally friendly and put significant contribution to the society They can also establish the technologies required to manufacture innovative products [85]. R&D with innovation helps companies increase their competitive advantages in higher value segments of the steel market [86].

Over the centuries, steel production technologies have been improved to produce better and better steel products [87]. The current steel production process in the world is carried out using two key technologies: EAF AND BOF. Embryonic and innovative technologies include: DRI and HBI [88]. The future of innovation and thus the R&D activity of companies will be related to the development of these technologies, classified as green innovation. In Industry 4.0 these technologies receive strong support from digitalization [89]. ICTs have been developed in the steel industry since the late 1990s. IT/computer solutions, including steel process control and steering systems, in the conditions of Industry 4.0 are enriched with the possibilities of IoT and cloud computing [90–92]. Innovation and investment in the described in the paper steel sector can lead to the production of a better, cleaner, high quality steel. This type of the steel can in turn stimulate the production of goods with lower impacts of their lifecycle [93]. Technological innovations introduced in production companies were and are opportunities to improve the productivity of industrial processes, which in the conditions of strong dynamics of technological progress is very broad, because it concerns many areas of business activity [94]. R&D team starts being responsible for plant engineering/technology and also other equipment maintenance in plant relating to steelmaking, ironmaking, energy and rolling, as and also many supporting fields such as for example: refractories, factory automation, mechatronics, civil engineering, architecture, system control technology, and water supply technologies. Total Productive Maintenance in the steel industry was and is one of the key pillars of World Class Manufacturing. In Industry 4.0, the opportunities for innovation in the maintenance field are even greater, due to the collaboration of machines and their increasing AI, as well as IoT and IoS services. A strongly developed area of the maintenance of predictive maintenance (PdM), which increases the chances of the reliability of machines in the process plants [94]. Another challenge for R&D and Innovation in Industry 4.0 is Lean activities, i.e., searching for and eliminating all waste using the technologies of the fourth industrial revolution [95].

In summary, the R&D framework in the steel industry is evolving with the dynamics of the business environment [96,97]. The attempt made to outline them, is an open-ended activity, just like innovation itself. With certainty, however, it can be said that an important place in the steel industry's R&D&I activity is occupied by green innovations (see the report of EU, 2021) [98] and the UN's Sustainable Development Goals [99]. Research, development and innovation (RD&I) can be considered key drivers and also critical success factors to achieving a process of rapid transition of the company and the whole industry to sustainability to innovate in the case of the Fourth Industrial Revolution. The Agenda for Sustainable Development linked with the EU growth strategy can be explicitly use to the increase of transformative role that the process of RD&I could play in the pursuit of sustainable competitiveness. The UN SDGs should be considered both challenges and opportunities connected with the process of developing business-led solutions and technologies with the potential to contribute to green and social transformations as well as to assure a sustainable recovery for the EU countries in the next decades [82]. According to the challenges the sustainability was locked in the center of the frameworks of R&D&I activity in the steel industry (Figure 2). Surrounding green innovation are digital innovation (digitization) and smart solutions of the Fourth Industrial Revolution. Synergy effects between technologies, projects, and sectors could create the dynamics needed to drive low-carbon industrial production. This is useful to implement the new steel products and innovational manufacturing processes. These synergies will help open up new markets and cooperation in the circular economy with key enabling technologies (KETs) of Industry 4.0.

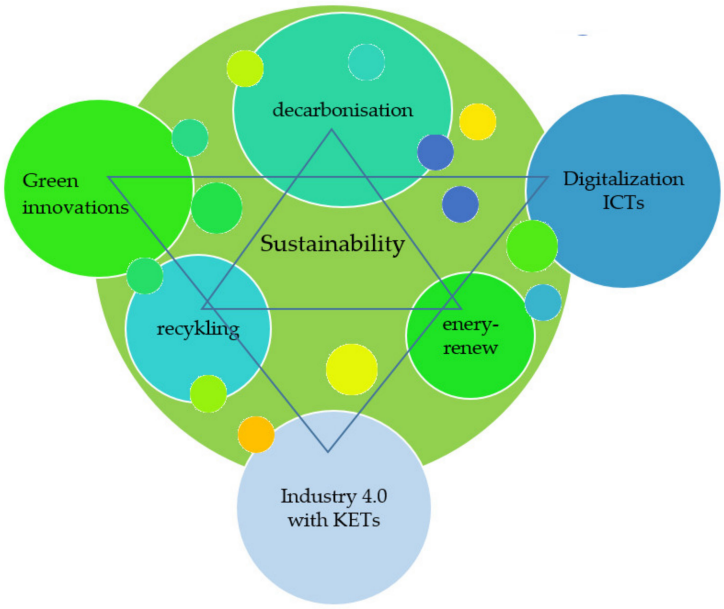


Figure 2. The frameworks for R&D&I in the steel industry. Source: adapted with permission from Ref. [100].

4. Industrial Analyses of R&D&I Activity in the Polish Steel Industry

The analysis was based on data collected and made publicly available by Statistics Poland (www.stat.gov.pl/, accessed on 20 April 2022). The analysis took into account expenditures on research and innovation activities. The sector of metal producers was analyzed (steel producers in Poland are classified in this sector). The sectoral analysis performed was compared with industry dynamics. In the sectoral analysis—the manufacture of basic metals—2010 was considered the base year for comparison, as a year before the presentation of the Industry 4.0 strategy by the German government. The analysis was terminated in 2019 due to the pandemic crises, which caused a decrease in R&D expenditures in the Polish steel sector.

The following hypotheses were adopted in the study:

Hypothesis 1 (H1). *The idea of Industry 4.0 popularized since 2011, in developed countries, is evident in the increasing dynamics of R&D expenditures in industry, including the steel sector under study in Poland.*

Hypothesis 2 (H2). *In the steel sector in Poland—the manufacture of basic metals—there was a time lag in the form of a time lag in the growth dynamics of R&D expenditures compared to the growth dynamics in the total industry in Poland.*

Hypothesis 3 (H3). *The increasing dynamics of R&D expenditures should translate into an increase in product and process innovation in the sector of metal manufacturers.*

Hypothesis 4 (H4). *Expenditures on fixed assets for environmental protection may show fluctuating dynamics due to business cycles and increasing legal regulations aimed at environmental protection.*

4.1. R&D Expenditure Dynamics of the Steel Industry in Poland

The first stage of the analysis was R&D expenditures in the steel sector in Poland and its comparison with expenditures in the total industry in Poland. Figure 3 presents R&D expenditures in the section of the Polish Classification of Activity called: the manufacture of basic metals.

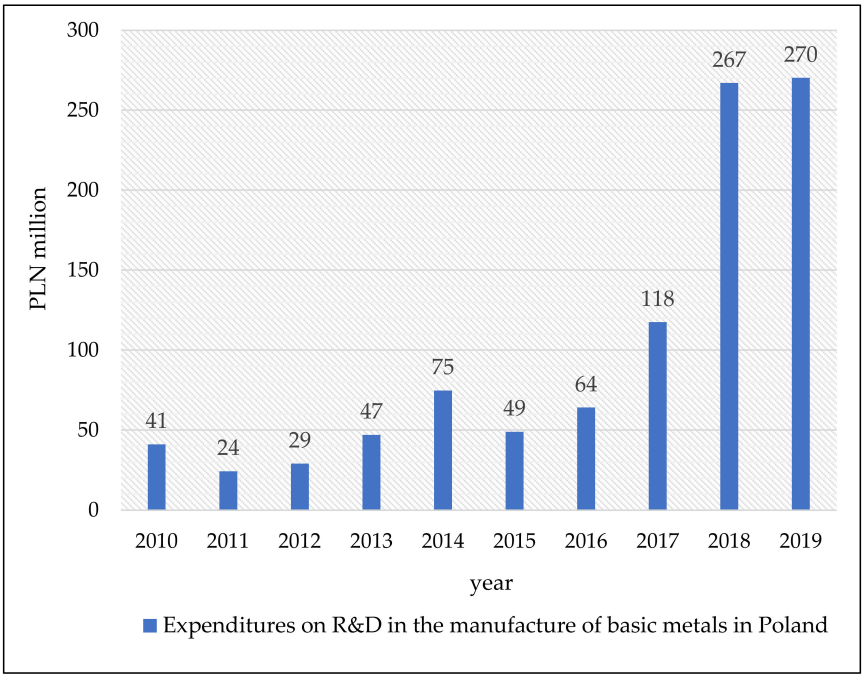


Figure 3. Expenditures on R&D in the manufacture of basic metals in Poland. Source: adapted with permission from Refs. [101–109].

Based on the data, it was found that in 2017, for the first time in Poland, metal producers spent more than PLN 100 million. In the following two years, these expenditures exceeded the level of PLN 250 million per year (in 2018, enterprises spent PLN 267 million on R&D, and in 2019 even more by 3 million, PLN 270 million). The share of metal producers' expenditure in the total industry expenditure on R&D does not exceed 4%. In the last two years analyzed (2018–2019), the share of R&D expenditure in industry R&D expenditure was above 3.5% (Figure 4).

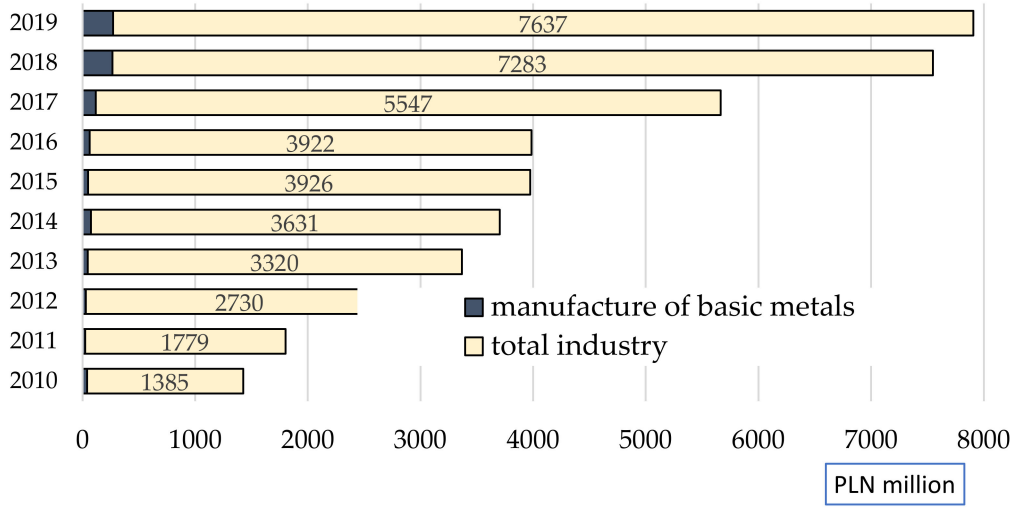


Figure 4. Expenditures on R&D in the manufacture of basic metals and in the total industry in Poland. Source: adapted with permission from Refs. [101–109].

Based on the data (Figure 4), it was found that the only year in which there was a decrease in R&D expenditures in the total industry in Poland was 2016 (4 million PLN less was spent compared to the previous year). Figure 5 compares the dynamics of expenditure in the manufacture of basic metals with expenditures in the total industry in Poland. For

the comparison, the figure with two Y axes (Y1, Y2) was used, where on the Y1 axis are the expenditures of the metal sector and on Y2 the expenditures of the total industry in Poland.

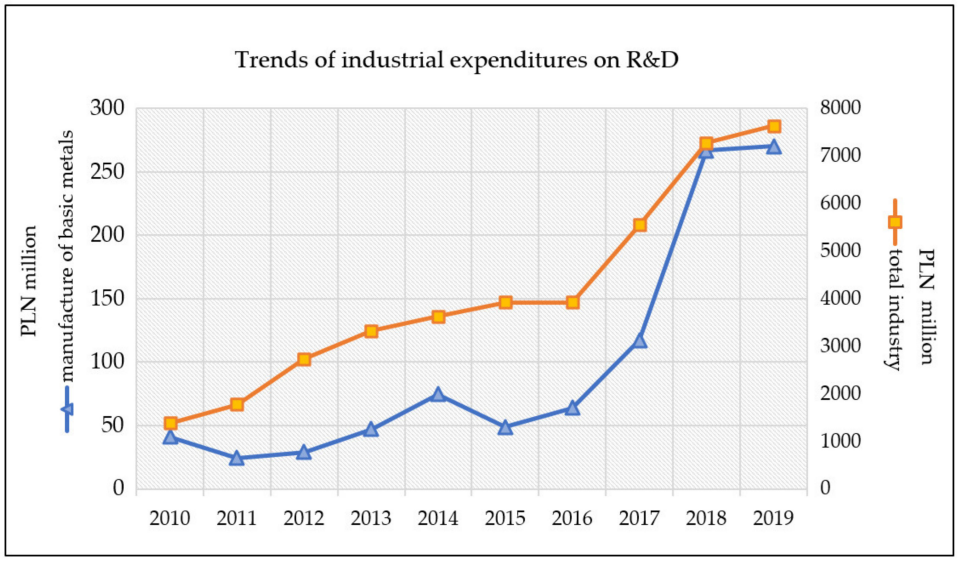


Figure 5. Comparison of expenditures on R&D for the manufacture of basic metals and total industry in Poland. Source: adapted with permission from Refs. [101–109].

On the basis of the comparison of expenditures, a conclusion was drawn that in the sector of metal producers in Poland the trend of the dynamics of expenditures was consistent with the dynamics of expenditures in the industry as a whole. An upward trend was recorded in the last three years (from 2017 to 2019, in previous years there were slight fluctuations in the course of the trend: decreases or increases. The sharp increase in spending by the metal producing sector, including steel, in the last three years was a result of the development of R&D departments in companies (Figure 6).

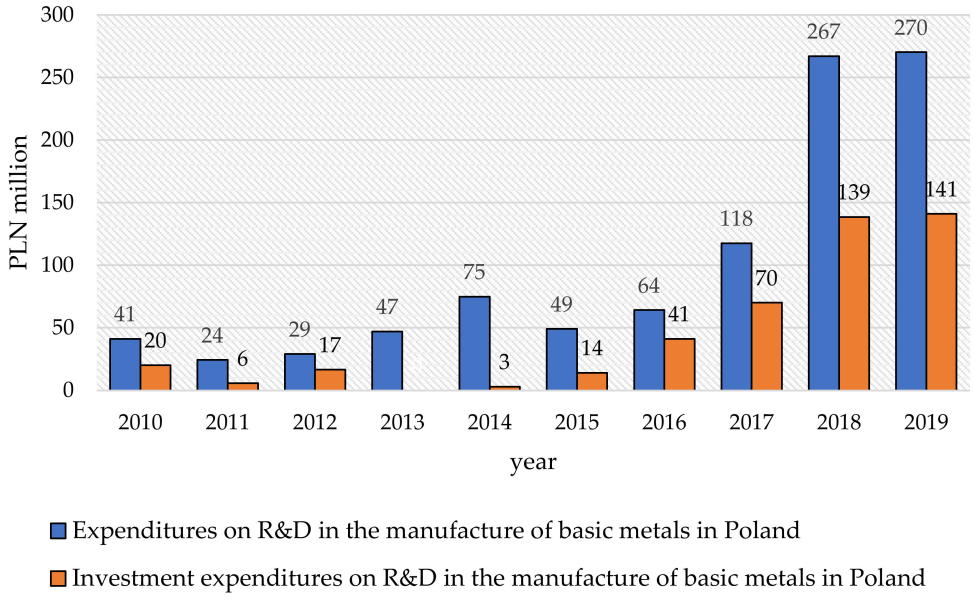


Figure 6. Investment expenditures on R&D in the manufacture of basic metals in Poland. Source: adapted with permission from Refs. [101–109].

Based on the data presented in Figure 6, we can see a trend of increasing expenditure on internal R&D investments starting from 2014. In 2016–2019, the shares of expenditure

on internal R&D support investments accounted for more than 50% of total expenditure (64.12% in 2016, 59.57% in 2017, 51.87% in 2018, 52.18% in 2019). The dynamics of the share of expenditures on internal investments for the development of research activity and innovation in enterprises in the steel sector (metal producers) was higher than the dynamics of the share of internal investments in total R&D expenditures for the total industry in Poland (there the share was below 50%)—Figure 7. Additional information for Figure 7: no data in statistical report for 2013 for the manufacture of basic metals.

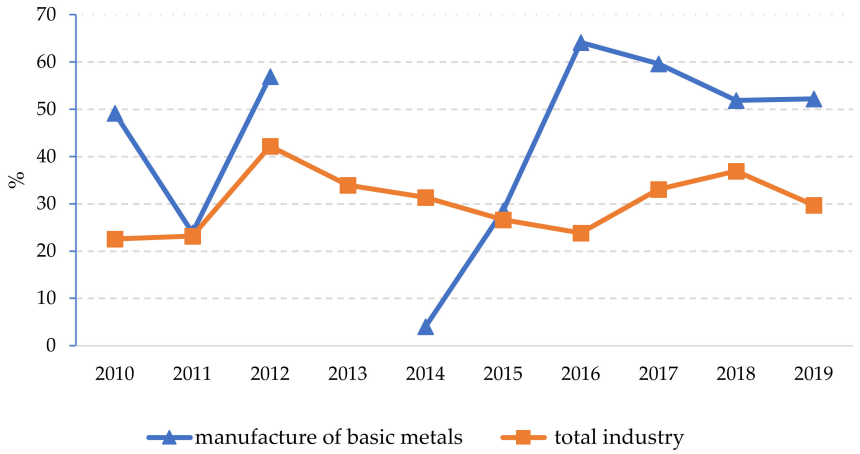


Figure 7. Shares of investment expenditure on R&D in total expenditures in the manufacture of basic metals compared with expenditures in the total industry in Poland. Source: adapted with permission from Refs. [101–109].

The gross value of research equipment in the laboratories of the sector of metal producers in Poland has increased significantly in recent years. Trends in the gross value of equipment in both the metal producing sector and the total industry in Poland have been increasing, with the exception of 2019 for both surveyed segments, and 2017 for total industry (Figure 8). After 2012, a significant increase in the value of equipment was recorded in both segments under study. The share of the value of purchased apparatus in the total expenditures of Polish industry exceeded 3% in 2019. After 2016, the share of expenditures on the purchase of research equipment in the sector of metal producers in Poland showed an upward trend, up to 3.28% in 2019 (Figure 9). Additional information for Figure 8: no data for the manufacture of basic metals in 2010–2012.

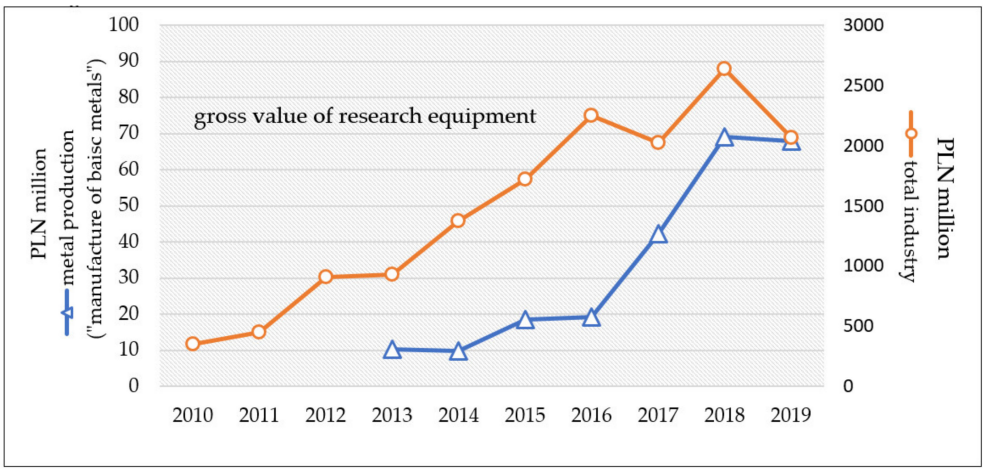


Figure 8. Trends of shares of expenditure on the gross value of research equipment in the manufacture of basic metals and in the total industry in Poland. Source: adapted with permission from Refs. [101–109].

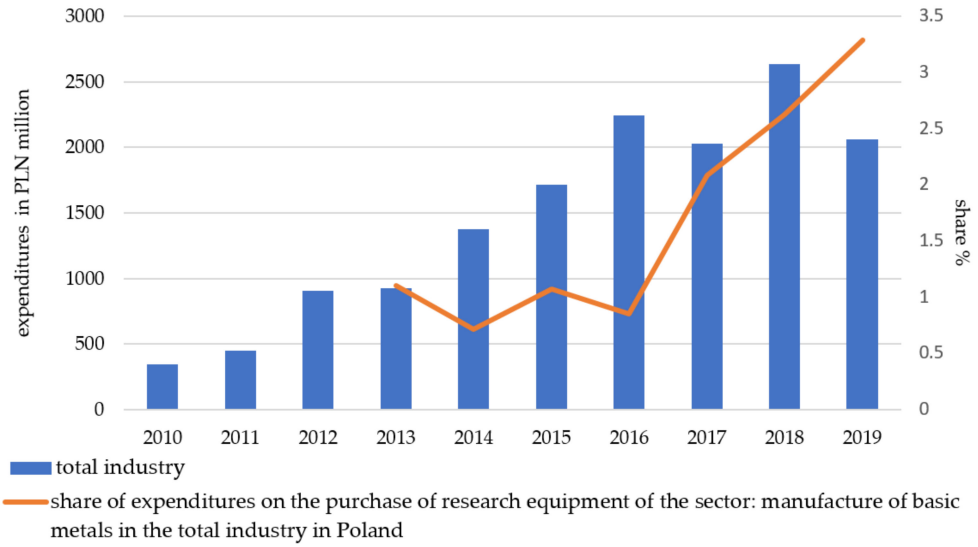


Figure 9. Shares of investment expenditure on R&D in the total expenditure in the manufacture of basic metals and in the total industry in Poland. Source: adapted with permission from Refs. [101–109].

At the end of the analysis, a comparison of expenditure dynamics was made for the base year 2010, i.e., before the initiation of the Industry 4.0 concept. The results of the analysis are presented in Table 5.

The dynamics of changes analyzed categories (Table 5) were calculated according to the formula:

$$D_{R\&D} = \left(\frac{E_{R\&D\ (t)}}{E_{R\&D\ (t=2010)}} - 1 \right) \times 100 \quad (1)$$

where:

$D_{R\&D}$—the indicator of the dynamics of the position $E_{R\&D}$
$E_{R\&D\ (t)}$—the value in the current year (t)
$E_{R\&D(t=2010)}$—the value in the base year (t = 2010)

Analysis of the data included in Table 5 indicates a strong increase in the dynamics in 2017–2019 R&D industrial activities in relation to the base year 2010, i.e., before the announcement of the new industrial development strategy Industry 4.0 in Germany. In total industry in Poland in the period under study there was no declining dynamics, but only an increasing one, while in the metal producers there was negative dynamics for total R&D expenditures in 2011–2012 and for internal investment expenditures in R&D in 2011–2015. It can be assumed that the sector of manufacture of basic metals in Poland reacted with a delay to the idea of Industry 4.0 (hypothesis: H2 was confirmed). On the basis of the analysis performed, it was found that since 2016 a strong upward dynamic in the growth of internal expenditure on R&D, including investment and purchase of research equipment, has become apparent (hypothesis H1 was confirmed).

Table 5. R&D from 2010 to 2019—analysis of expenditures and dynamics for basic year 2010.

	Manufacture of Basic Metals		Total Industry		Manufacture of Basic Metals		Total Industry		Manufacture of Basic Metals	Total Industry	
Year	**PLN mln**	**%**	**PLN mln**	**%**	**PLN mln**	**%**	**PLN mln**	**%**	**PLN mln**	**PLN mln**	**%**
	Internal Expenditure on R&D	**Dynamics**	**Internal Expenditure on R&D**	**Dynamics**	**Internal Investment Expenditures on R&D**	**Dynamics**	**Internal Investment Expenditures on R&D**	**Dynamics**	**Research Equipment ***	**Research Equipment**	**Dynamics**
2010	41.1	base year	1385	base year	20.2	base year	312.5	base year	no data	346.9	base year
2011	24.3	−40.88	1779	28.45	5.8	−71.29	412.2	31.90	no data	448.6	29.32
2012	29	−29.44	2729.7	97.09	16.5	−18.32	1151.7	268.54	no data	910.7	162.53
2013	47.1	14.60	3319.9	139.70	0	−100.00	1125.7	260.22	10.3	929.7	168.00
2014	74.8	82.00	3630.5	162.13	3	−85.15	1137.4	263.97	9.9	1375.8	296.60
2015	49	19.22	3926.1	183.47	14	−30.69	1044.5	234.24	18.5	1719.3	395.62
2016	64.1	55.96	3921.8	183.16	41.1	103.47	935	199.20	19.2	2246	547.45
2017	117.5	185.89	5546.6	300.48	70	246.53	1832	486.24	42.3	2026.3	484.12
2018	267	549.64	7282.9	425.84	138.5	585.64	2686.2	759.58	69.2	2634	659.30
2019	270.2	557.42	7637.1	451.42	141	598.02	2269.8	626.34	67.8	2064.2	495.04

* according to Formula (1). Source: adapted with permission from Refs. [101–109].

4.2. Dynamics of Expenditures on New Products and Business Process Innovations in the Steel Industry in Poland

The effect of research activities of the steel industry in Poland should be an increase in expenditures on product and business process innovations (such an assumption was made in hypothesis: H3). Expenditures on product and business process innovations in the section "manufacture of basic metals" of Polish Classification of Activities, starting from 2016 were at a level above the average value of expenditures for the period from 2010 to 2019 (Figure 10), and expenditures for the total industry only in the period of three years (from 2015 to 2017) were above the average value (Figure 11).

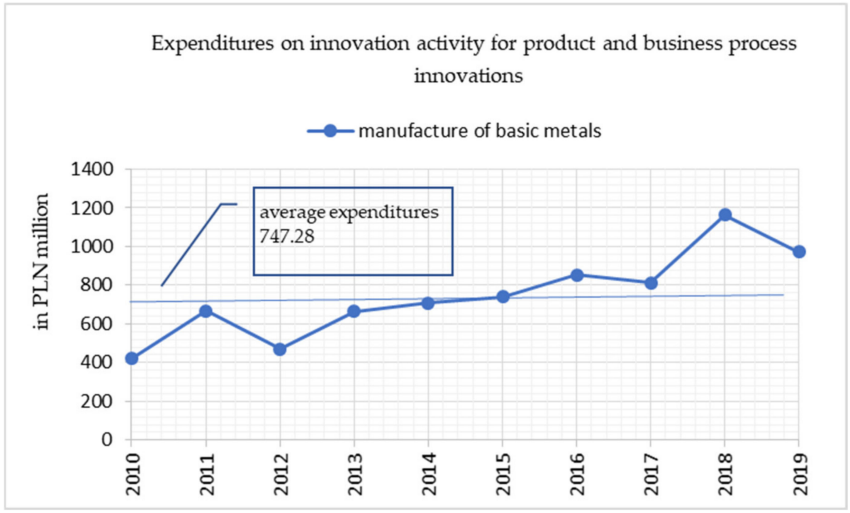


Figure 10. The amount of spending on innovation activity for product and business process innovations in the manufacture of basic metals in Poland. Source: adapted with permission from Refs. [101–109].

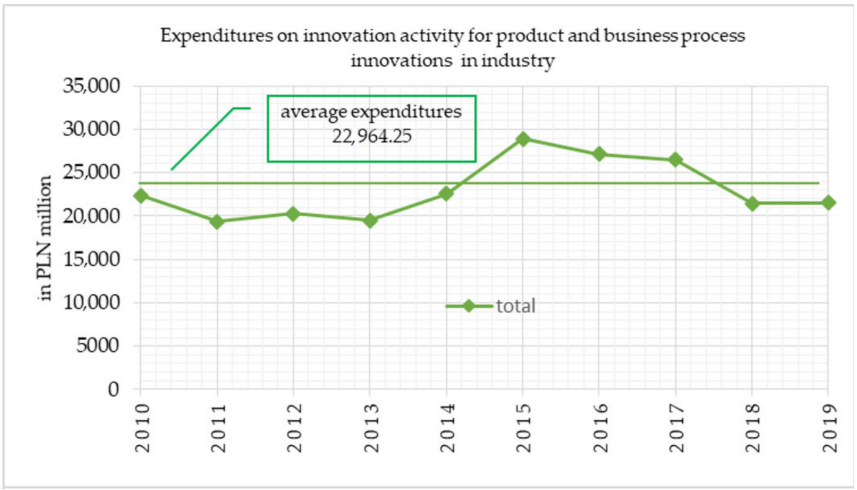


Figure 11. The amount of spending on innovation activity for product and business process innovations in the industry total in Poland. Source: adapted with permission from Refs. [101–109].

Relating expenditures on product and process innovations in the steel sector to the dynamics of changes in R&D expenditures (Table 5) we obtain a confirmation of a strong impact of the popularized concept of Industry 4.0 on the dynamics of expenditures, which increased starting from 2016. In the category of technology investment expenditures by level of technology (Figure 12), the highest growth was observed in 2017, with strong growth dynamics of medium–high technology in the industrial processing "manufacturing" sector in Poland (Figure 12), with declining dynamics of low technology.

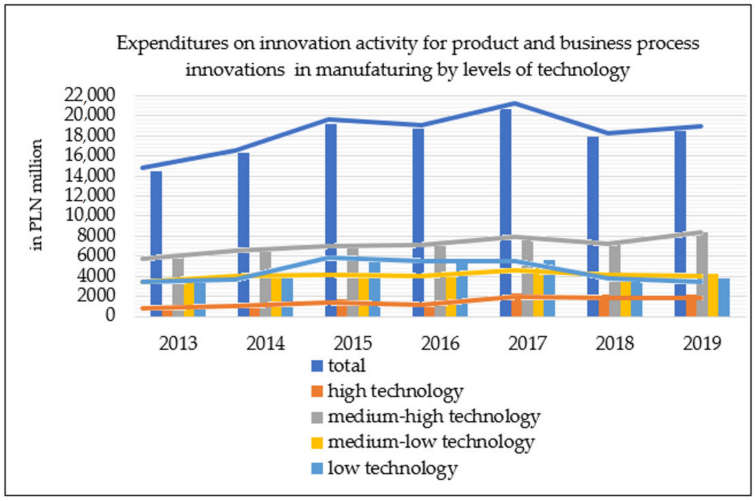


Figure 12. The amount of spending on innovation activity for product and business process innovations according to the levels of technology in manufacturing in Poland. Source: adapted with permission from Refs. [101–109].

The summary of this part of the analysis is a comparison of the dynamics of expenditures on product and business process innovations in relation to the base year 2010 (year 0 = 2010), i.e., to the year before the initiation of the concept of industrial development referred to as Industry 4.0. The results of the analysis are presented in Table 6. On the basis of the data, it was determined that in the metal manufacturing sector the dynamics of expenditure on product and business process innovations starting from 2016 were very high. The results of the analysis confirm the next hypothesis adopted for the purposes of the study (H3).

Table 6. Innovation from 2010 to 2019—expenditures and dynamics for basic year 2010.

		Year									
		2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
manufacture of basic metals	PLN mln	420.8	666.8	471.7	663.4	709.6	740.9	852.6	812.5	1162.4	972.1
dynamics *	%	basic year	58.46	12.10	57.65	68.63	76.07	102.61	93.08	176.24	131.01
total industry	PLN mln	22,379	19,376.5	20,293.2	19,520.7	22,544.3	28,920.7	27,157.5	26,464.3	21,463.7	21,523.6
dynamics *	%	basic year	−13.42	−9.32	−12.77	0.74	29.23	21.35	18.26	−4.09	−3.82

* according to Formula (1). Source: adapted with permission from Refs. [101–109].

4.3. Dynamics of Investment Expenditures on Environmental Protection in the Steel Industry in Poland

Analyzing the last part of the data, it was found that outlays on environmental protection fixed assets in the metal producer industry were the highest in 2016–2018 (Figure 13), while in the industry analyzed as a total, the highest outlays were in 2014–2015. According to the fourth hypothesis (H4), we see that trends have cycles of high growth dynamics of change, in 2016–2018 for the manufacture of basic metals and in 2014–2015 for the total industry in Poland. Trends in environmental investment outlays are strongly correlated with climate protection expenditures in both the research areas (Figures 13 and 14). Data used for the analysis and dynamics of outlays on fixed assets in environmental protection in analyzed sectors are presented in Table 7.

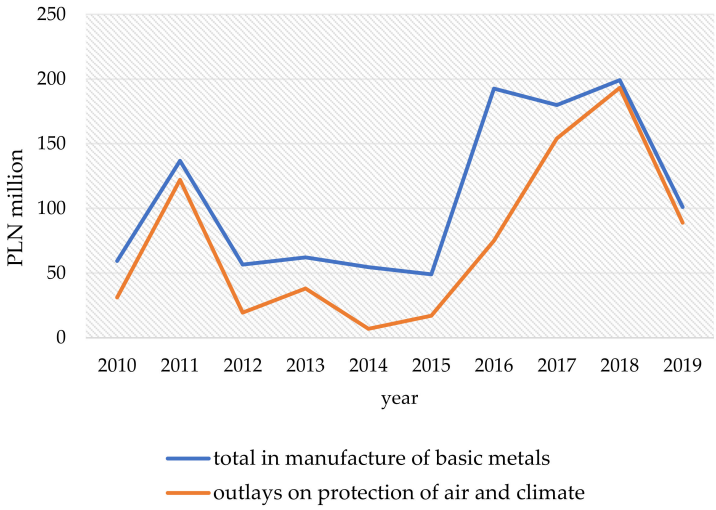


Figure 13. Amount of fixed assets in environmental protection in manufacture of basic metals by investment in Poland. Source: adapted with permission from Refs. [101–109].

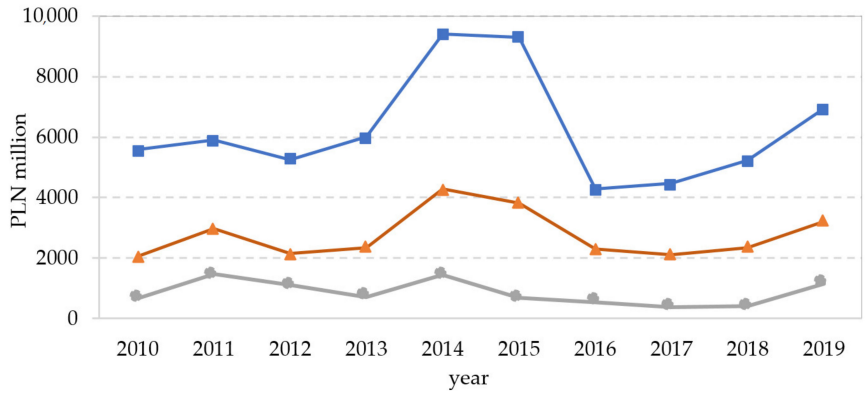


Figure 14. Amount of fixed assets in environmental protection in industry by investment in Poland. Source: adapted with permission from Refs. [101–109].

Table 7. Dynamics of amounts of fixed assets in environmental protection for basic year 2010.

	Manufacture of Basic Metals				Industry Total			
	on Environmental Protection	Dynamics *	on Climate Protection	Dynamics *	on Environmental Protection	Dynamics *	on Climate Protection	Dynamics *
Year	PLN mln	%	PLN mln	%	PLN mln	%	PLN mln	%
2010	59.17	basic year	31.05	basic year	5586.40	basic year	2063.11	basic year
2011	136.80	131.19	122.10	293.19	5897.13	5.56	2970.25	43.97
2012	56.41	−4.66	19.40	−37.52	5258.09	−5.88	2157.04	4.55
2013	61.98	4.75	37.96	22.25	6003.68	7.47	2339.64	13.40
2014	54.41	−8.05	7.00	−77.47	9417.31	68.58	4291.12	107.99
2015	49.03	−17.15	16.92	−45.52	9299.46	66.47	3813.13	84.82
2016	192.47	225.27	74.86	141.07	4290.58	−23.20	2308.00	11.87
2017	179.76	203.80	154.09	396.23	4476.25	−19.87	2107.58	2.16
2018	199.11	236.50	193.27	522.37	5242.15	−6.16	2338.25	13.34
2019	100.95	70.60	88.85	186.11	6940.99	24.25	3211.39	55.66

* according to Formula (1). Source: adapted with permission from Refs. [101–109].

Again, based on the analysis of the dynamics, this time of environmental investment outlays in the sector of metal producers, it was determined that in 2016–2019 there was a strong increase in dynamics compared to environmental investment outlays in 2010.

Final conclusion from the research: on the basis of the performed detailed analysis of data on steel industry activities in R&D&I in Poland, it was established that the sector of metal producers in Poland, including the sector of steel producers, experienced an increase in expenditures in particular segments of R&D&I activities in the second half of the past decade, i.e., five years after the German government initiated the Industry 4.0 strategy. The following final conclusion can be drawn that there was a time lag of steel enterprises' R&D&I activities under the conditions of Industry 4.0. Based on the analysis of data on expenditures on R&D activities and on product and process innovations and fixed assets for environmental protection, including climate protection in particular, an upward dynamic was recorded from 2016, and the year 2011 was taken as the beginning of the Industry 40 concept (presentation of the Industry 4.0 strategy in German government).

5. Discussion

In the publication there is a presentation of the results about R&D&I contribution in polish steel sector. Similar analyses about R&D&I in steel industries were presented by other researchers in leading journals [110–114], and reports [73,115–118] concentrated mainly on selected aspects of R&D&I activities in that industry not on the holistic view of the contribution of this sector and the comparison to the industry as a whole in each particular country.

The analysis of the literature about topic presented in the paper allows us to conclude that the concept of analyzing R&D&I activities as one concept is increasing. It is connected with the EU documents which are use those concept especially when they describe the sustainable strategy of organization. The interesting papers written by Zsolt et al. [119] present an insight into how to analyze the effects of various initiatives for R&D&I projects in European Union countries. This is a very important problem because the proper approach to dealing with problems in the innovation development and application—which we will describe in following part of the discussion—is the key to the successful implementation of innovative solutions in the steel industry.

Similar to our research, other scholars think that the problem of R&D&I in the steel sector is very important and the number of organizations making an effort in this area is increasing in recent years. A very interesting report was prepared by the Clean Steel Partnership. According to their research, a very important part of the R&D&I activities in the steel industry should be concentrating on issues connected with decoupling the electricity usage and the reduction of CO_2 emissions. To achieve a significant level of reduction of emissions of CO_2 in the steel industry, organizations can implement the following innovative solutions: implement innovative technologies to avoid carbon emissions during the steelmaking process; improvement of the usage of carbon from steel production processes, for example utilization, carbon capture, storage, applications and process integration [75].

In Poland, the increasing amount of money spent on R&D&I in the steel industry also suggests that problems connected with carbon dioxide emissions should be a very important part of the new innovations and investments in this sector. Polish steel industry organizations should concentrate on efforts connected with carbon direct avoidance and also smart carbon usage in steel production processes. Under the framework Horizon Europe there are three main types of partnership which can be proposed to support the R&D&I framework [115,116,118]. An effective partnership should concentrate on the coordination of R&D&I efforts in order to build systems that can better address global challenges. The coordination process could be achieved by specified roadmaps and objectives— the initiatives connected with finding R&D&I activities should concentrate on the effectiveness of pro-ecological efforts [116].

The effective usage of money spent on pro-ecological R&D&I should be built upon a series of existing cooperation frameworks. In this case, Public-Private Partnerships and

also other efforts should be used to increase the commitment of all parties involved in the steel production process [115]. This approach can increase the fruitfulness of the conducted innovative initiatives. Because Polish steel industry organizations are increasing the amount of money spent on R&D&I they should take into account that to achieve the money from Horizon program they should concentrate on areas covered by the research Fund for Coal and Steel program. It is worth mentioning that proper application and increasing the amount of innovative pro-ecological solutions should be based on overcoming the main barriers to R&D&I. Steel industry organizations should also ensure that proper available technological solutions are deployed. Implementing innovative solutions in the steel production industry we should take into account that the investment cycle in this industry is relatively long one and takes between 20 and 30 years [117].

The main problem with the R&D&I in the steel industry is because many research organizations do not have the scale which is enough to fully shoulder the cost of deployment of innovative solutions. It is also worth mentioning that many parts of the commercial steel industry organizations do not have enough money to bear high economic and technological risk. It give the probability to stack into the so called valley of death. To avoid this problem steel industry innovative organizations should concentrate on avoiding major challenges in the innovation development and implementation process.

The first challenge is connected with the problem with adoption gap. This is a problem with diffusion of steel industry innovative technologies that already have been developed on industrial scale. Sometimes organization can have very promising innovative solution but the funding adoption gap can deter organization from implementing it on industrial scale. The second challenge is connected with possibility of integration new innovative steel industry technology to the existing production system. In many situation it can be a challenge.

The problems of sustainable steel production are mainly connected with the R&D&I activities in the steel industry. The analyses carried out in the publication showed that the introduction of the Industry 4.0 concept in the steel industry is related with an increase in expenditure on innovative technologies. In particular, according to the agendas of the European Commission [116,117], these investments should be oriented towards Sustainability. In the literature we can spot some papers how organization should deal with the R&D&I funding to achieve successful innovation implementation.

An interesting approach based on an example of a Spanish organization was described by Salaz-Ruiz [120]. His results are similar to the challenges described in this paper. He also pointed out the problem of financing and integrating projects in the industry to achieve a sufficient level of innovativeness. Other scholars have achieved similar results [121–124].

In the steel industry, it is also very important to use an open innovation approach. Whenever it is possible, especially in digitalization processes, organizations should be based on existing open innovation solutions and should use and develop them.

The research shows that the dynamics of pro-ecological investments in Poland's steel industry is increasing. This allows us to be optimistic about overcoming the main barrier to the involvement of the steel industry in the development of new pro-ecological technologies, which is access to adequate financial resources. The most significant challenge for the steel industry is to prevent the climate change. The steel industry in this case is fully committed to dealing with the mitigation of greenhouse gas emissions [82,125–127]. These activities should have a positive effect on meeting the objectives of the Paris Agreement and should help steel industry organizations meet the EU target to reduce domestic CO_2 emissions by 80% to 2050. The implementation of this approach needs a long term strategy to develop steel industry low carbon technologies.

A comparison of our research with the analysis conducted by Daroń and Górska is very interesting [128]. They analyzed some aspects of innovative activities in the Polish steel industry during the years 2011–2017. Similar to our research, they point out the increasing amount of innovativeness measured as the introduction of new or significantly improved products in the steel industry organization in the years 2015–2016 compared to earlier

years. They also observe a strong emphasis on product and processes innovation in the steel industry. On the basis of our research, we observed that the financing is an important part of conducting innovations in the steel sector. The mentioned authors [128] observed that the metal sector, besides its own sources of financing, tries to acquire additional funds using foreign capital investment and bank loans. Other authors point out the importance of European Union funds in the financing of steel industry innovations [128–130].

The proper usage of money spent on R&D&I in the Polish steel industry needs in-depth knowledge about the way new technological solutions are developed in the steel industry and what their impact is on the modernization of the technological base. Historically, according to an analysis by De Paula [127], steel companies dedicated an increasing share of R&D&I spending to new products. They relegated the issues connected with innovative equipment and processes for engineering companies and equipment manufacturers. In those times the amount of spending on R&D&I in the steel industry was relatively low. This low amount of spending on innovations in the steel industry in comparison to the average in industry before 2010 was pointed out by Silva and Carvalho [93]. This was the case in countries such as Sweden and Germany. The same results were achieved be Lee and Ki with the example of South Korea [131] and Nakamura and Ohashi [132] with the example of Japan.

The situation started to change especially because of implementing various aspects of Industry 4.0 in the steel industry. As we presented in the paper from 2010, we can observe the increasing amount of spending on R&D&I in the steel industry. This was because of the change in approach to innovation—now steel industry organizations are implementing new innovative solutions by themselves or are using an open innovation approach. Muscio and Ciffolilli [133] have found that Industry 4.0 was a gamechanger and after implementation of this concept, industry organizations are implementing new innovative solutions more rapidly. According to Mozart [134] and Pinkham [135], many technologies connected with Industry 4.0 are innovative and because of this the implementation of the Industry 4.0 concept is strictly connected to the widespread innovation and increase of spending on R&D&I. The new steel mills' innovative specific solution allows them to function as digitized factories—this is connected to increasing the amount of money spent on the development of innovative and open innovation based solutions.

The results presented in this paper have value from a broader economy and government policy formulating point of view. On the basis of the results obtained in this paper a framework of R&D&I activities for the steel industry and an in-depth analysis of R&D&I expenditures on the example of the metal producers in Poland in the last decade of growing interest in the concept of Industry 4.0 (I 4.0) can be formulated. The implementation of the new conception of Industry 4.0 which can bring many benefits to the whole society need an increase of R&D activities to be implemented correctly and have results such as an increase of product and process innovation in the industry [136,137]. To be beneficial for the whole of society, the government needs to boost innovativeness in industry. This could be achieved using various types of investment incentives, including tax incentives to increase the level of innovativeness of the industry.

The good policy of research and development spending to boost innovativeness is important because of a time lag that is observed between the growth dynamics of research and development expenditures and the growth dynamic of the industry. To achieve in the future the economic development based on Industry 4.0 implementation in industry we must increase the expenditure on research and development. It gives the industry the possibility to increase the number of product and process innovations and could lead to technological progress and better economic results.

In today's economy, we can observe an increasing role of environmental issues which are especially important from a global warming point of view [138–142]. We think that our analysis about expenditures on environmental protection in the steel industry may contribute to the field. On the basis of the conducted analysis, we observe the fluctuating nature of research and development spending in the case of environmental protection

(Figures 13 and 14). To achieve enough potential of environmental innovativeness and to adjust the steel industry to changing environmental requirements we need to stabilize those spending at a high level. It also needs careful planning of environmental innovation investment policy on industry and government levels.

Our research was conducted on the basis of the steel industry but we think that the results could be similar in other heavy industries. There, the government should also increase its activity towards preparing good policies to increase the innovativeness. It is a key to success and it can have positive effects on technological progress and economic development.

We think that to boost innovativeness in the steel sector it would be useful to implement the open innovation approach. The innovation process in steel industry must be realized according to sustainable goals. The sector has many environmental aspects [143]. The traditional approach towards innovation does not allow their full potential to be realized because the organization is based only on its own resources and research and development potential [144–147]. Using an open innovation attitude to the innovation of a particular organization can include collaboration with others, external research centers and, importantly, the active involvement of suppliers and customers in the process of innovation creation [148]. The transfer of those external researchers and the process of linking them with internal innovative solutions can be very beneficial to the whole steel industry and can increase the number of innovative solutions in the sector. Organizations from the sector can also try to transform their solutions into open source solutions and increase the level of mutual collaboration. The innovation process is moving faster in large companies in the global steel market. Combined capitals have greater capabilities. In the global steel industry, key strategic fusions took place in the first decade of this century [149].

Summarizing the discussion, the authors emphasize that the process of analyzing R&D&I activity in the Polish steel industry was based on the assumption that, after 2011, with the popularization of the I 4.0 concept, companies should become more active in the field of innovation. In order to confirm the thesis in an objective manner, the authors used mass data reported by the main statistical office in Poland—GUS. In future research, the authors will present the analyzed expenditures in international currency (dollars or euros according to the bank exchange rates of these currencies in Poland in a given year) and compare them with the R&D&I expenditures of other EU countries.

6. Conclusions

On the basis of our research, we can conclude that the amount of spending on R&D&I in the Polish steel industry is increasing. In our analysis we observed the increase in expenditures on R&D in the steel industry from 2010 to 2019. An especially strong increase was found in the years 2018–2019, which can be linked to the implementation of Industry 4.0 based solutions in the Polish steel industry. Industry 4.0 implementation in the industry, as is pointed out in the literature, has a strong, positive influence on the innovativeness of the company and the spending on innovations [45–49]. In the analyzed data we observed that the increase of expenditure on R&D in the Polish steel industry was similar to that in other industries. As a result of the research, it was found that the dynamics of changes in R&D expenditures in the Polish steel industry was consistent with the dynamics of expenditure calculated for the entire Polish industry. At the same time, the sharp increase in R&D expenditure since 2018 was related to the implementation of the Industry 4.0 concept in the Polish industry. The results presented in the paper support hypothesis H1, that the idea of Industry 4.0, popularized since 2011 in developed countries, is reflected in the increasing dynamics of R&D expenditure in industry, including in the steel sector under study. According to the research, the increase in the dynamics of expenditure on R&D&I began in 2018, i.e., several years after the emergence of the Industry 4.0 concept in the world. This was related to the delayed implementation of these solutions by the Polish steel industry. The results support the H2 hypothesis that in the surveyed Polish steel sector—metal producers—there was a time lag in the form of a postponement of the

growth dynamics of R&D expenditure, after the emergence of the new concept of Industry 4.0 for developed countries in Europe and the world.

It is worth mentioning that the gross value of research apparatus used by steel producers has increased in recent years. This is related to the trend discussed in the publication, observed in the metallurgical industry, of a shift from outsourcing research and innovation to creating them within the organization. This results from the digitalization of processes, the introduction of the Internet of Things and the implementation of the smart factory concept in the Polish steel production industry.

The presented results were confirmed by the analysis of expenditure on product and process innovation in the Polish steel industry. These analyses also allowed us to conclude that, since 2017, we have observed the strong growth of medium–high technology in the Polish industry including the steel industry. The strong increase in the dynamics of the implementation of product and process innovations in the Polish steel industry started during times of the implementation of the Industry 4.0 concept and was directly related to it. The need to implement new technologies and new process solutions related to the implementation of Industry 4.0 had an impact on the discussed dynamics of product and process innovation. The obtained results support the H2 hypothesis that the increasing dynamics of R&D expenditures should translate into an increase in product and process innovation, which was proved on the basis of the metal producer sector.

On the basis of the analysis conducted in the paper, we can say that the effects of the research and development activities of the steel industry in Poland can be connected with an increase in expenditure in the case of innovations (process innovations and product innovations) in this industry. We can observe that the level of expenditures on product and process innovations in the case of the manufacturing of basic metals in the Polish classification of Activities from the year 2016 was above average values in the period 2010–2019. The expenditures for the whole steel industry were above average compared with data from all Polish industries. The results of our analysis support hypothesis H3.

Environmental innovations have a special role in the implementation of the Industry 4.0 concept in the steel industry. This is directly related to the need to reduce carbon dioxide emissions and the introduction of new ecofriendly technologies in the Polish steel production industry. In this case, we observe cyclical fluctuations in expenditures, which were highest in 2016–2018 to decrease slightly in 2019. In particular, attention should be paid to the possibility of using the open innovation approach in the process of the implementation of green innovation in the steel industry. The results support hypothesis H4, that environmental fixed capital expenditures may show fluctuating dynamics due to business cycles and legal restrictions to protect the environment but should show high dynamics.

We think that the added value of the publication is the framework of R&D&I activities for the steel industry and an in-depth analysis of R&D&I expenditures with the example of metal producers in Poland over the last decade of growing interest in the concept of Industry 4.0 (I 4.0). We think that this framework and the concept of the relationship between innovation and development activities and innovation in the steel industry are the main theoretical contributions of our study. We also think that the very valuable findings are connected with the analysis of the expenditure of fixed assets for environmental protection in this industry and the findings about the fluctuating dynamics of this expenditure. Those results can be useful in the process of planning environmental policy at the industry and governmental levels.

Future research should focus on an analysis of the following years, in particular 2020–2022 and beyond. At present, there is not yet access to full data on this subject. This kind of analysis will allow us to determine whether the observed increase in spending on R&D&I in the Polish steel industry is a permanent trend or just a temporary phenomenon related to the implementation of Industry 4.0 solutions and the energy transformation of the economy. This is certainly a prospective research question, which will need to be answered in the future.

The main limitation of the paper is connected to the data we used to conduct our analysis. The analysis was performed on the basis of the Polish steel market. It is the main analysis—if someone could try the dynamics of R&D&I expenditure in relation to the steel industry in Industry 4.0 idea implementation, the results could be slightly different. Our analysis is also based on secondary sources and we could not guarantee that all the data collected in the sources we used were fully corrected. Our analysis ends at 2019 because we do not have full data about the analyzed problem from the years 2020–2022.

In addition, this was during a period of business constraints related to the COVID-19 pandemic, which translated into an economic crisis that also affected the steel sector in Poland. A very important limitation of the paper is connected with the area of research—we analyzed only the Polish steel industry and because of that, it is not possible to present a conclusion about the world's steel industry based on our paper. In the future it would possibly be interesting to analyze the situation in other countries.

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Institutional Review Board Statement: According to our University Ethical Statement following the following shall be regarded as research requiring a favourable opinion from the Ethic Commission in the case of human research (based on document in polish: https://prawo.polsl.pl/Lists/Monitor/Attachments/7291/M.2021.501.Z.107.pdf, accessed on 15 July 2022): research in which persons with limited capacity to give informed or research on persons whose capacity to give informed or free consent to participate in research and who have a limited ability to refuse research before or during their implementation, in particular: children and adolescents under 12 years of age, persons with intellectual disabilities persons whose consent to participate in the research may not be fully voluntary prisoners, soldiers, police officers, employees of companies (when the survey is conducted at their workplace), persons who agree to participate in the research on the basis of false information about the purpose and course of the research (masking instruction, i.e., deception) or do not know at all that they are subjects (in so-called natural experiments); research in which persons particularly susceptible to psychological trauma and mental health disorders are to participate mental health, in particular: mentally ill persons, victims of disasters, war trauma, etc., patients receiving treatment for psychotic disorders, family members of terminally or chronically ill patients; research involving active interference with human behaviour aimed at changing it research involving active intervention in human behaviour aimed at changing that behaviour without direct intervention in the functioning of the brain, e.g., cognitive training, psychotherapy psychocorrection, etc. (this also applies if the intended intervention is intended to benefit (this also applies when the intended intervention is to benefit the subject, e.g., to improve his/her memory); research concerning controversial issues (e.g., abortion, in vitro fertilization, death penalty) or requiring particular delicacy and caution (e.g., concerning religious beliefs or attitudes towards minority groups) minority groups); research that is prolonged, tiring, physically or mentally exhausting. Our research is not done on people meeting the mentioned condition. Any of the researched people: any of them had limited capacity to be informed, any of them had been susceptible to psychological trauma and mental health disorders, the research had not concerned mentioned above controversial issues, the research had not been prolonged, tiring, physically or mentally exhausting.

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