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Review

The Challenge of Digitalization in the Steel Sector

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Abstract: Digitalization represents a paramount process started some decades ago, but which received a strong acceleration by Industry 4.0 and now directly impacts all the process and manufacturing sectors. It is expected to allow the European industry to increase its production efficiency and its sustainability. In particular, in the energy-intensive industries, such as the steel industry, digitalization concerns the application of the related technologies to the production processes, focusing on two main often overlapping directions: Advanced tools for the optimization of the production chain and specific technologies for low-carbon and sustainable production. Furthermore, the rapid evolution of the technologies in the steel sector require the continuous update of the skills of the industrial workforce. The present review paper, resulting from a recent study developed inside a Blueprint European project, introduces the context of digitalization and some important definitions in both the European industry and the European iron and steel sector. The current technological transformation is depicted, and the main developments funded by European Research Programs are analyzed. Moreover, the impact of digitalization on the steel industry workforce are considered together with the foreseen economic developments.

Keywords: digitalization; digital technologies; digital transformation; steel industry; digital skills

1. Introduction

Over the last few decades, the European steel sector has undergone relevant transformations. On one hand, this sector has been restructured and consolidated; on the other hand, highly technological production processes and products have been developed. These transformations have considerably impacted the workforce, resulting in numerical reduction and in professional profiles' evolution. In particular, digital transformation and Industry 4.0 contributed to both reducing the need for physical and often cumbersome and repetitive operations and to increasing the demand for highly skilled workforce. In addition, changes in patterns of recruitment as well as in work organization have occurred. In order to be more competitive, the steel sector aims at developing a highly qualified, specialized, and multi-skilled workforce. Nevertheless, due to the skills shortages, recruitment difficulties, and talent management issues, it is important to forecast, identify, and anticipate skill needs.

In order to introduce the current state of this technological transformation, it is important to define the context and to provide some necessary definitions. "Digitization" is defined as "*the action or process of digitizing; the conversion of analogue data (esp. in later use images, video, and text) into digital form*" [1], while the term "Digitalization" refers to the transformation of interactions communications, business functions, and business models into the digital ones. Through the use of "digital technologies" and digitized and natively digital data, digitalization aims at achieving revenue, improving business, replacing/transforming business processes, as well as at creating an environment for digital business. In addition, "digitalization" promotes the integration of digital technologies into areas of a business [2]. On the other hand, "automation" is defined as "*the use or introduction of automatic equipment in a manufacturing or other process or facility*" 1 as well as "*the technology by which a process or procedure is accomplished without human assistance*" [3].

In this context, Industry 4.0 concerns the interoperability, the decentralization of information, the real-time data collection, and the increased flexibility, that represent main aspects of the fourth industrial revolution. This process started with the first industrial revolution, characterized by the mechanization of production performed manually by hand. In this context, steam and water power were used for the mechanization of work [4]. In the second industrial revolution, the introduction of electricity in different processes took place. In particular, in the steel sector, this coincided with the invention of the production area, the improvement of transportation technologies, and the electrification of industrial processes. In addition, the Bessemer process and the open-heart furnace were introduced [5]. The third industrial revolution was characterized by the introduction of Information Technology (IT) and computer technology to automate processes, but still involved human aspects. The use of robots into the processes previously performed by humans and the development of the work based on optimization and the removal of production inefficiencies represent the main aspects [5]. The current industrial revolution, the fourth one, is based on new interconnected technologies in process operations. The term Industry 4.0 was first used in Germany based on initiative of the German Government's High Tech 2020 Strategy [6]. Compared to "Industry 3.0", in Industry 4.0, the machines work autonomously without, or with very limited, human intervention. In particular, the enhancement of automation and connectivity with Cyber Physical Systems (CPS) include smart machines, storage systems, and production facilities capable of autonomously exchanging information, triggering actions, and independently controlling each other. In addition, the Industrial Internet of Things (IIOT) can allow exchange of information provided by sensors that work in real time and transfer data to a local server or a cloud server, where the analysis of the data is performed through the development of predictive models. The final aims can be, for instance, product quality management throughout the entire production chain or early detection and forecasting of anomalies in the processes and prediction of residual lifetime of critical components by means of tools exploiting the data (often Big Data) captured by the sensors (according to the paradigm of Predictive Maintenance).

This review paper derives from an analysis that was performed in the context of a multinational initiative funded by the European Union through the Erasmus Plus framework. This project is devoted to the development of a Blueprint for "New Skills Agenda Steel", is entitled "Industry-driven sustainable European Steel Skills Agenda and Strategy (ESSA)", and has two main aims:

- The proactive identification of skill needs and demands for the construction appropriate training and curricula, including strategizing for the implementation of new vocational education content and pedagogies across the sector, within both companies and education and training institutions;
- The identification, development, and promotion of successful sectoral recruitment and upskilling schemes, and the development of some training tools for efficient management of knowledge fostering talent development and overcoming of recruitment difficulties.

The paper is organized as follows: Section 2 introduces the context of digitalization and provides some important definitions in the European industry and the European iron and steel sector. In Section 3, the main developments achieved within projects that received funding by European Research Programs are analyzed. Section 4 discusses the impact of digitalization on the steel industry workforce and the foreseen future economic developments. Finally, Section 5 provides some concluding remarks.

2. The Framework of the Industrial Digital Transformation

2.1. Digital Transformation in the European Industry

The European industry is deeply committed to integrate the digitalization concept into its production and organization in order to be more competitive in the globalization context. The application of digital technologies allows implementing new processes along the entire value chain, through manufacturing and sales to services. On this subject, digitalization represents a holistic approach covering all areas and functions of a company to exploit digital potentials and analyze each stage of its value chain. For this reason, it is important to underline that digitalization is not a simple transfer from "analogic" to digital data and documents. It is rather the networking between the business processes, the creation of efficient interfaces, and the integrated data exchange and management [7].

The digital transformation is the key aspect of the ongoing industrial revolution [8]. Some new Key Enabling Technologies (KETs) are represented by a. new generation of sensors, Big Data, Machine Learning (ML), Artificial Intelligence (AI), Internet-of-Things (IoT), Internet-of-Services, Mechatronics and Advanced Robotics, Cloud Computing, Cybersecurity, Additive Manufacturing, Digital Twin, and Machine to Machine (M2M) communication. The digital technologies could be ex novo applied to a new plant, or can be adapted to existing plants [9]. In order to achieve industrial production optimization, the application of these technologies aims at developing new skills and new competencies as well as new business models. This will result in the improvement of industrial competitiveness and efficiency, due also to a higher inter-connection and cooperation, sharing resources (e.g., plants, people, and information). On this subject, European industries are committed to addressing some important challenges:

- Ensuring a continuous responsiveness to fulfil the changing future demand and securing the market position;
- Preserving competitiveness with efficient processes, and cost and resources saving;
- Achieving higher product quality;
- Maximizing plant performance, by also minimizing maintenance and low capital lock-up;
- Planning a flexible production by guaranteeing timeliness of delivery [10].

These challenges can be reached through the real-time capability, interoperability, and the horizontal and vertical integration of production systems enabled by Information and Communications Technology (ICT) systems, representing the main features of Industry 4.0 [11]. Furthermore, in order to achieve a flexible production, it is important to also have flexible work, through the self-organization and multi-tasking skills, according to education and lifelong learning initiatives.

Industry 4.0 is based on an intelligent networking of machines, electrical equipment, and modern Information Technology (IT) systems allowing processes optimization and increased productivity of value creation chains [12]. Its strategy is based on intelligent factories exploiting the combination of embedded production system technologies with intelligent production and resulting in a new technological age. In this context, in a recent study, three distinct manufacturing systems in Industry 4.0 have been presented [13]. In the first one, an Intelligent Manufacturing System (IMS), also known as smart manufacturing, the employment of advanced manufacturing technologies, and information enable the optimization of the production process of goods and services. The second manufacturing environment is viewed as IoT-enabled manufacturing, relying on the exploitation of smart manufacturing objects (SMOs); the third major manufacturing is a cloud manufacturing. The intelligent systems involve the development of manufacturing systems that can be organized into a functional network.

Although different possible scenarios have been developed, it has recently estimated that the full shift to Industry 4.0 could need 20 years [14]. This long period can be due to the fact that digital technologies strongly vary with company size. In particular, only 36% of the surveyed European companies with 50–249 employees have implemented industrial robots in their production processes, compared to 74% of European companies with over 1000 employees [15]. However, larger companies have more possibilities to employ some IT/ICT specialists, but Small and Medium-sized Enterprises (SMEs) more intensively use mobile internet and social media (44%) [16].

Although the new digital technologies can make companies more efficient and productive, resulting in opening to new markets, some critical aspects on the future have been recently depicted. According to Pfeiffer [17], Industry 4.0 does not present only positive perspectives, but it can be considered as part of a newly emerging global production regime [18], particularly affecting the low-skilled works and repetitive tasks [19], such as manual operation of specialized machine tools, shot-cycle machine feeding, repetitive packaging tasks, monotonous monitoring tasks, and many warehousing and commissioning functions in logistics [20]. However, even if the digitalization may improve processes, the human experience cannot be replaced. In particular, the mining and metal sector in emerging economies needs to pay gap between highly skilled digital workforce and more traditional workforce [21]. On this subject, evolution in workforce skills are needed, in order to be in line with the industrial requirements. This includes not only attracting and recruiting new talents, but also re-skilling current employees with training programs, which can improve skills in different disciplines, such as science, technology, engineering, and mathematics. In this process, a key aspect is represented by continuous learning, also based on an interdisciplinary perspective. This will produce a future adaptable workforce contributing to increase the competitiveness of the companies as well as their own competitiveness and "appeal" in the work market. Furthermore, re-designing work processes aims at reducing the skill mismatch between jobs and employees and securing their jobs in the future [22].

The implementation of new digital technologies could produce significant improvement in workforce health and safety as well as energy efficiency and CO_2 utilization increase. In addition, innovative and more customized goods and services could be achieved [23]. In the global market and, consequently, in the global competition, the European manufacturing industry will have some market opportunities related to digital technologies. For instance, the 10-year China strategy plan, the *Made in China 2025* [24] strategy, aims at upgrading Chinese industrial base by focusing on 10 key industries. This will offer attractive opportunities for some European businesses in the short and medium term, about critical components, technology, and management skills.

In this context, the European manufacturing industry is leaning towards a greater new production system, increasingly flexible and tailored to the needs of customer. This evolution will preserve its global competitiveness thanks to high-value goods and high-quality products, as well as integration, digitalization, speed, flexibility, quality, efficiency, and security.

2.2. Digitalization in the European Steel Industry

The steel industry is a highly energy intensive industry. However, it is a modern, energy and CO_2 efficient sector, with high value-added production and niche products for the world market, based on an outstanding R&D network [25]. The European steel industry has an annual turnover of EUR 166 billion and it provides the 1.3% of EU GDP. Concerning the workforce, in 2015, it provided 328,000 direct jobs with an even greater number of dependent jobs [26].

The digitalization process in the European steel industry represents a pre-condition for Industry 4.0, as Industry 4.0 is much more than digitalization, but rather a paradigm/philosophy than a technology [27]. The current situation of digitalization in the steel sector is that its workforce is aging. An experienced workforce knows industrial processes very well, but it is less comfortable with digital tools and collaborative work and, sometimes, it is resistant to training and learning activities. For instance, in order to improve the culture of multigenerational digital innovation, the attempt of connection between the workforce under 30 with the older leadership team has been carried out within a Tata Steel site [21]. All over the world, including Europe, innovation, technology, quality, and highly skilled people are the basis for competitiveness [25]. In addition, preserving industrial knowledge and a skilled workforce is an important asset for the iron and steel sector [26]. Nevertheless, also in Europe, the digitalization process lacks uniformity. For instance, in the Czech Republic, the steel industry is still not in line with the other European countries in adopting new technologies and, in particular, in digital transformation, although recent investments have been done for modernizing production and reducing environmental impacts [28].

Due to the complexity of the production processes, the application of new technologies can result in the optimization of the entire steel production. By combining process automation, information technology, and connectivity, the digitalization of the steel production can be beyond a conventional automation of the industrial production. In the future, the intelligent combination of different tools, such as plant and laboratory experiments, physical modelling, and computational modelling will play a significant role in the digitalization process in the steel sector. For instance, recent advances in modeling steel continuous casting have been achieved. As this process involves many interacting phenomena, model verification and validation of model predictions represent the key factors. On this subject, each aspect of models needs to be verified with known solutions and validated with measurements to trust the predictions and improvements arising from modeling studies [29]. The digitalization in the steel production can not only produce quality, flexibility, and productivity, but also ensure the visibility of the real-time operational data and provide insight for a better and faster decision-making along the value chain [30]. Over the last few years, clear implementation of digital technologies has been made in the steel sector. However, the application of a decentralized, unmanned autonomous system, for assembling components, to the continuous process of steel, is difficult and expensive [31]. In addition, the application of digital systems in some production processes, such as Energy management and Water and Wastewater management, aims at achieving continuous improvements in the steel sector regarding quality, costs, energy consumption, and environmental performance. In this context, digital technologies help to adapt and to integrate innovative and emerging techniques to the steel production processes. For instance, novel pollution prevention and control techniques under development and new techniques addressing environmental issues can provide future economic or environmental benefits to this sector [32,33]. In addition, an example on modelling and prediction of the gas consumption to minimize ordered and supplied gas quantity error can be provided. On this subject, a linear regression and the genetic programming approach have been used. The achieved good results can contribute not only to steel production optimization, but they represent a methodological approach, which can be applied to other energy consumption optimizations [34]. Furthermore, as the steel production based on the EAF consumes a large amount of energy, better knowledge of the consumed energy within the EAF operations is fundamental. In a recent study, in order to predict the electric energy consumption during the EAF operation, two models have been considered, one based on linear regression and the second one on genetic programming [35].

The main challenges of the European steel industry on Industry 4.0 are related to legacy equipment, uncertainty about the impact on jobs, and issues of data protection/safety. In addition, results from a recent study [36] showed that the technical barriers are considered less important than the organizational ones. On one hand, internal management represents the driving force for implementing the Industry 4.0 projects, but on the other hand, technology and production are less crucial. Furthermore, the main possible explanations about lack of qualified personnel are the increased use of digital technologies, the lack of suitable educational programs, and the delays in training provision after the introduction of a technological innovation. Nevertheless, one of the main challenges of the European steel industry consists of attracting and retaining qualified personnel [5]. Nevertheless, it is difficult to integrate new technologies and processes among site workers, especially when it comes to older employees. In addition, there is a strong age gap between the workers currently employed and prospective employees creating knowledge transfer issues. Finally, there is a lack of investment in training and education from steelmaking companies and an insufficient amount of in-house training provided by companies.

3. European Research Activities on Digitalization in the Steel Sector

According to [37], the European steel industry faces important challenges due to cost pressure, regulatory requirements, as well as product and service requirements. For this reason, over the last few decades, it has been involved in several policy activities, R&D projects, and patents in the field of digitalization.

Initiatives related to Industry 4.0 also include the Smart Factory Working Group of the ESTEP Platform, founded in 2008 with the former name of "Intelligent Integrated Manufacturing," which published the first edition of a Roadmap for European Steel Manufacturing in 2009 with a vision up to 2020. The ESTEP Working Group covers a broader range of stakeholders and it consists of plant manufacturers and several European Universities and R &D Institutions. In 2018, a workshop on the concept and operational benefits of the Digital Twins in the steel sector was held in Charleroi [38].

3.1. Digitalization & Enabling Technologies

Digital technologies are applied in order to improve the flexibility and the reliability of process and to improve the product quality. In addition, they can be applied for monitoring and assessing the environmental performance of processes, improving control of production and auxiliary processes that have an environmental impact, and providing key performance indicators for resources efficiency [39,40]. Some enabling technologies according to the Use Cases of KETS [41] are:

- Internet of Things (IoT) system: The IoT refers to an inter-networking world where electronic sensors, actuators, or other digital devices are networked and connected with the purpose of collecting and exchanging data [42]. According to [43], the composition of an online monitoring system based on an IoT system architecture can be characterized of four layers: Sensing, network, service resource, and application layers. Such a proposed system has been implemented and demonstrated through a real, continuous steel casting production line and integrated with the TeamCenter platform.
- Big data Analytics and Cloud Computing: In the manufacturing industries, including the steel industry, the conventional database technology can have some difficulties in finishing the capture, storage, management, and analysis of large volumes of structured and unstructured data. Big data analytics is related to algorithms based on historical data identifying quality problems and reducing the product failures. On the steel products, the Big-Data solutions are currently used for quality monitoring and improvement. This technology uses new processing modes in order to obtain significant information from different data types, and, to understand them in-depth, gain insight, and make discoveries for precise decision making. An accurate prediction of surface on steel slab defects can be based on the online collected data from the production line and it is important for adjusting the process online as well as for reducing their occurrence. The main problem is that the samples for normal cases and defects are usually unbalanced. According to [44], a one-class Support Vector Machine (SVM) classifier based on online collected process data and environmental factors for only normal cases was proposed in order to predict the occurrence of defects for steel slabs. ML-based approaches can provide a relevant support in extracting useful information and relevant knowledge from the available data and enabling the development of data-driven models e.g., for a wide variety of applications, such as material properties prediction [45] and product defects detection and identification [46]. Cloud computing gives on-demand computing services with high reliability, scalability, and availability in a distributed environment. Thanks to this technology, everything is treated as a service (i.e., XaaS), e.g., SaaS (Software as a Service), PaaS (Platform as a Service), and IaaS (Infrastructure as a Service) [47].
- Robot-assisted production: This technology is based on the use of humanoid robots in order to perform operations, such as assembly and packaging. Due to an increasing demand for higher quality, faster delivery time, and reduction of cost in the manufacturing industry in the last few decades, automation and robotics have achieved more and more importance. For instance,

if in the steelmaking plant, existing technologies are enhanced with robots and automation, an improvement of surface quality of the steel products could be achieved [48,49].

- Production line simulation: In the steel sector, approaches for the simulation optimization solution have been developed. In particular, investigating potential changes to the designs and operations is the aim of the development of decision support systems [50,51]. Novel numerical techniques, such as meshless methods in the simulation systems of the steel sector, have been also exploited. In [52], a rolling simulation system capable of simulating rolling of slabs and blooms, as well as round or square billets, in different symmetric or asymmetric forms in continuous, reversing, or combined rolling has been elaborated. Vertnik et al. [53] developed a meshless Local Radial Basis Function Collocation Method (LRBFCM) for the solution of three-dimensional (3D) turbulent molten steel flow and solidification under the influence of electromagnetic stirring (EMS) and they demonstrate its application to continuous casting process of steel billets.
- Self-Organizing Production: Such technology involves the automatic coordination of machines, leading to the optimization of their utilization and output. The self-organizing production is related to the decentral instead of central solutions. A new combination of resources, equipment, and personnel, based on a close interaction within them with a master computer, is included and an increase of the automation, leading to the real time control of production networks.
- CPS: Is a system where computation, networking, and physical processes are integrated. The physical processes are monitored and controlled by embedded computers and networks, with feedback loops where they affect computations and vice versa [54].
- Smart supply network: Better supply decisions are possible thanks to the monitoring of the entire supply network. Several factors and objectives have to be taken into consideration in a supply chain of a steel industry. The smart supply networks optimize the steelworks production processes from the beginning to the end of products by using models as part of the integrated supply chain.
- Vertical/Horizontal Integration: Horizontal integration concerns the integration between a resource and an information network within the value chain. Vertical integration is related to networked manufacturing systems within the intelligent factories of the future and personalized customer manufacturing [55].
- Predictive Maintenance: It allows repair prior to breakdown thanks to a remote monitoring of equipment. The combination of equipment monitoring together with intelligent decision methods implement the predictive maintenance techniques. In order to support decision-making and to assist steel companies to improve their competitiveness, ML and Data Mining techniques can be used to draw insights from the data and accurately predict results.
- Cyber Security: Such technology should be taken into consideration, especially for the Internet-based services. A procedural model for a Cyber-Security analysis based on reference architecture model Industry 4.0 and a VDI/VDE guideline 2182 are shown for the use case of a Cloud-based monitoring of the production in [56].
- Augmented Work, Maintenance, and Service: The operating guidance, the remote assistance, and the documentation are favored by applying the fourth dimension, which is the use of the augment reality. This is one of the most interesting enabling technology for companies, especially for improving the maintenance services. For instance, remote maintenance based on remote connection can be carried out by a service technician who is virtually connected. This results in travel costs and time saving, and with quick problem solving.
- Self-driving logistics vehicles: Such technology is based on completely automated transportation systems. The use of intelligent software to support intralogistics operations helps companies to improve processes and to make faster them. In the steelworks, the supply and the disposal of raw materials and the transport of intermediate products as well as the removal of finished products and the handling of by-products, for instance bulk material or slag, are very important. The use of an intelligent transport control system can allow one to plan and control the internal transport orders, resulting in an increase of productivity and service levels, cutting costs.

- Digitalization of knowledge management. Due to an increasing competitive market, the steel sector has been committed to facing significant challenges in the digitalization. Although this process has already started, further improvement can be achieved. On this subject, the knowledge and experience of the technical staff represents the basis of this improvements. The main barriers about the usage of this knowledge and experience are represented by their heterogeneous distribution over the individual staff members, human obliviousness, and knowledge erosion by leaving staff members.

3.2. Past and Ongoing Research Activities Funded by the Research Fund for Coal and Steel

In the European steel sector, the most important funding program for the technology development is the Research Fund for Coal and Steel (RFCS) [57]. This funding program concerns aspects related to the innovation in the digitalization of the steel industry as well.

The most active actors among research institutions and steel companies in such projects are: VDEh Betriebsforschungsinstitut BFI, Swerea MEFOS/KIMAB, RINA Consulting-Centro Sviluppo Materiali, Scuola Superiore Sant'Anna, Centre de Recherches Metallurgiques, ArcelorMittal, ThyssenKrupp, as well as Tata Steel and, to some extent, Gerdau and Voestalpine.

The plant manufacturers such as Primetals and SMS Siemag, followed by Danieli (also with its sister company Danieli Automation) are key players to patents and they are seldom involved in those projects.

This study identified 22 RFCS Projects covering aspects of digitalization in the steel industry starting from 2003, considering projects that are ongoing or completed. Figure 1 depicts the identified projects and the enabling technologies that these projects are developing or have developed: In the x-axis, the projects are reported; in the y-axis, the enabling technologies taken into consideration from the project are expressed in percentage.

Among the ongoing projects dealing with the Internet of Things (IoT) systems technology, TrackOpt aims at implementing an automatic ladle tracking system, in order to ensure the tracking of the product from steelmaking via casting to delivery by using a Multi-Objective Optimization (MOO) Framework and big data analytics as well as innovative acoustic sensors.

Quality4.0, NewTech4Steel, Cyberman4.0, PRESED, and Dromosplan are some examples of RFCS Projects related to the Big Data Analytics and Cloud Computing. An adaptive platform is being developed, allowing online analytics of large data streams to realize decisions on product quality and provide tailored information of high reliability in the running Quality 4.0 project. NewTech4Steel is an ongoing project focused on dedicated use cases in the steel industry exploiting all the technological and scientific possibilities offered by the latest technologies concerning data handling and data analysis. Advanced AI and ML-based analytics, also suitable for big data processing, are exploited for process performance monitoring. Cyberman4.0 and CyberPOS deal with CPS. In Cyberman4.0, big-data tools and techniques are applied to merge process and product data in order to forecast quality downgrading, faults, anomalies, and residual life of critical components in order to timely plan suitable and cost-effective maintenance interventions. Cyberman4.0 is also an important example of a Predictive Maintenance approach applied to the rolling area and aims at developing a so-called Integrated Maintenance Model 4.0 (IMM4.0). CyberPOS introduces simulation and verification tools as well as a new IT framework for establishing the feasibility, safety, and benefits of CPPS (Cyber Physical Production System) in the framework of "Steel Industry 4.0 Automation". Moreover, a CPS-based platform for facilities producing long steel products has been developed [58]. PRESED proposed a solution built around Big Data, Feature Extraction, ML, Analytics Server, and Knowledge Management in order to automatically analyze the sensorial time series data.

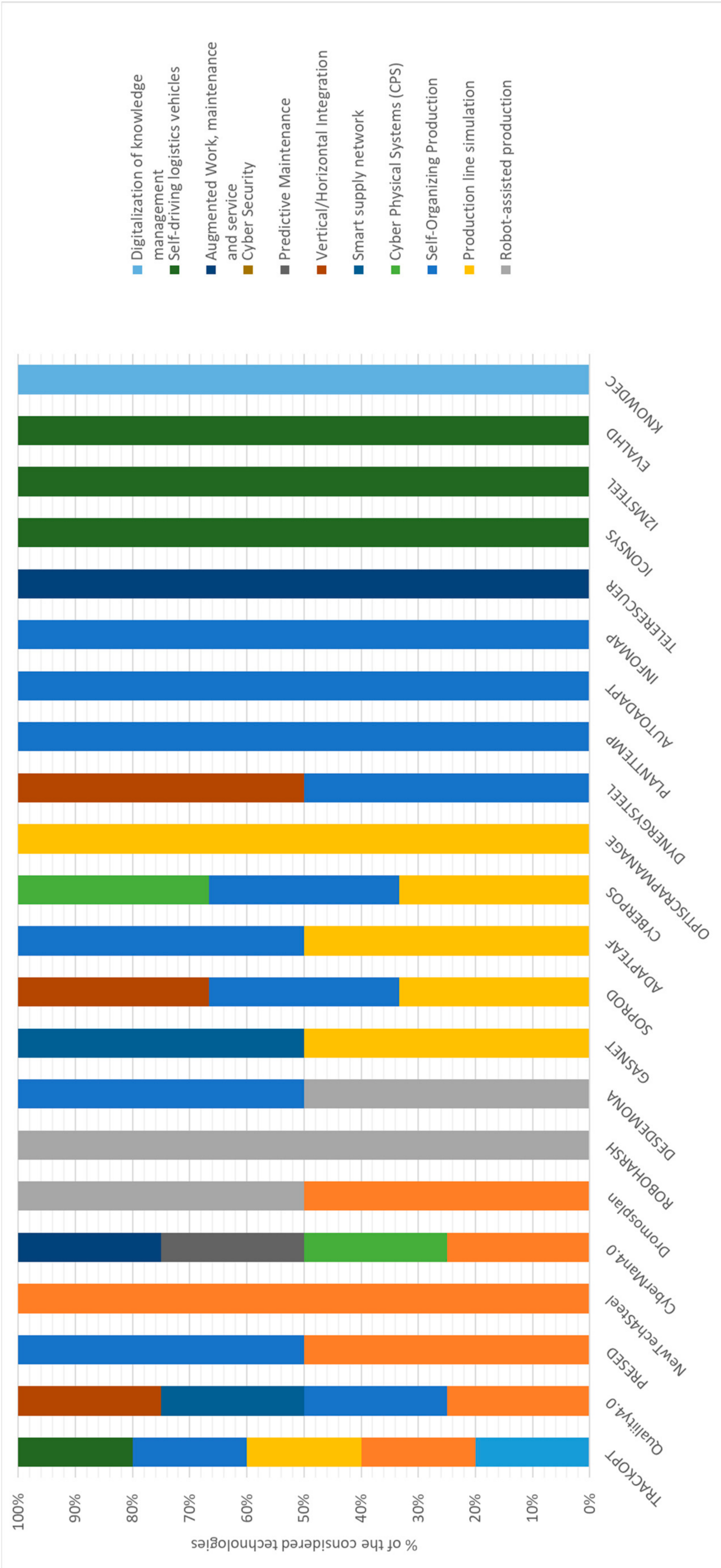

Figure 1. Research Fund for Coal and Steel (RFCS) Projects and the developed enabling technologies.

The projects Dromosplan, RoboHarsh, and Desdemona are related to the robot-assisted production. The ongoing project Dromosplan aims at using Unmanned Aerial Vehicles (UAV) in steel plants in order to replace the human intervention in a number of operations related to the monitoring, maintenance, and safety. New sensor data are being produced in this context in order to prove and evaluate the benefits of UAVs in steelworks [59]. RoboHarsh firstly introduced some concepts of human–robot symbiotic co-operation in the steel industry for the development of a complex maintenance procedure [60,61]. In this project, one of the main results is that the operator role is changing, becoming a supervisor, and, therefore, there is no replacement of the worker but a safer and heavyweight operation reduction. Desdemona is another example of development of procedures for steel defect detection by robotic and automatic systems such as UAVs and ground mobile robots.

In vertical/horizontal integration technology, some examples of RFCS projects are DynergySteel and the abovementioned Quality4.0. In DynergySteel, the simulation, decision support procedures, and control tools have been implemented at several steelmaking plants to improve power management capability and power engagement forecasting [62,63].

Simulation and optimization of the production line is another enabling technology, which handles in several RFCS projects, such as GasNet, SOProd, AdaptEAF, Cyber-POS, as well as OptiScrapManage. GasNet developed a simulation tool of the network of process gas and steam including their generation and flows as well as a multi-level strategy for their optimization. ML-based tools and technologies such as Echo-State and FeedForward Neural Networks, as well as advanced optimization approaches (e.g., Mixed Integer Linear programming) have been used in order to improve energy efficiency and environmental sustainability of the steelmaking processes [64–68]. In SOProd Objected-Oriented Programming (OOP), Python language, LabView, MongoDB, and Optical character recognition are some of the technologies adopted to improve product intelligence and autonomous machine–machine and product–machine communication [69]. In this project, a de-central optimization considering a detailed product and process knowledge facilitates a process self-optimization by using individual product properties and processing information of neighboring processes [58]. Advanced methods for process monitoring and control through multi-criteria approach of performances indicators, together with optimization approaches, have been exploited in OptiScrapManage. Laser scanner and acoustic and hyperspectral sensors are some of the used technologies. By considering the properties of the charged materials, AdaptEAF developed an adaptive online control for the Electric Arc Furnace (EAF), by optimizing the efficiency of the chemical energy input by reducing the total energy consumption and improving the metallic yield.

The project TeleRescuer provides an exemplar application of a special Unmanned Vehicle (UV) within a system for virtual teleportation of rescuers to subterranean areas of coal mines.

A method for the collection, representation, storage, and utilization of the human knowledge to exploit it in computer-based applications has been investigated and implemented by the project "KnowDec". Here, a new approach based on the methodology of knowledge-based decision support system has been developed. The operators of the quality department can capture the experiences concerning the approval of slabs and the collected experiences are stored in the knowledge base, useful for decision support and advices in similar cases.

Most of the abovementioned projects, such as Cyber-POS, TrackOpt, Quality4.0, DynergySteel, AdaptEAF, SOProd, Desdemona, PRESED, InfoMap, PlantTemp, and AutoAdapt deal with the self-organizing production technologies. PlantTemp develops an operator advisory system covering the electric arc furnace and casting processes, meeting the target casting temperature, by saving energy and material consumption. AutoAdapt proposes an expandable system, which aims to apply self-learning methods for adapting such automations to new products and plants. Genetic Algorithms (GA), polynomial models, iterative learning control methods, and feed-forward control are some of the used technologies. In InfoMap, a tool for objective interpretation of maps from different devices along the process route, generating concise data suitable for use within automatic control/advisory systems is developed. Here, Convolutional Neural Networks (CNNs) are applied for flatness defects detection and classification [70] (see also Appendix A).

IConSys implemented an Intelligent Control Station, in order to support decision making in rolling and finishing while the I2MSteel project developed a factory and company-wide automation and information technology for an intelligent and integrated manufacturing steel [71]. EvalHD investigated some aspects related to the implementation of Industry4.0 [72,73].

Figure 2 provides a summary of the abovementioned analysis by showing the number of RFCS Projects for each of the highlighted enabling technology. The identified enabling technologies are inserted in the x-axis and for each technology the number of RFCS projects, which takes into consideration such technologies, is reported in the y-axis.

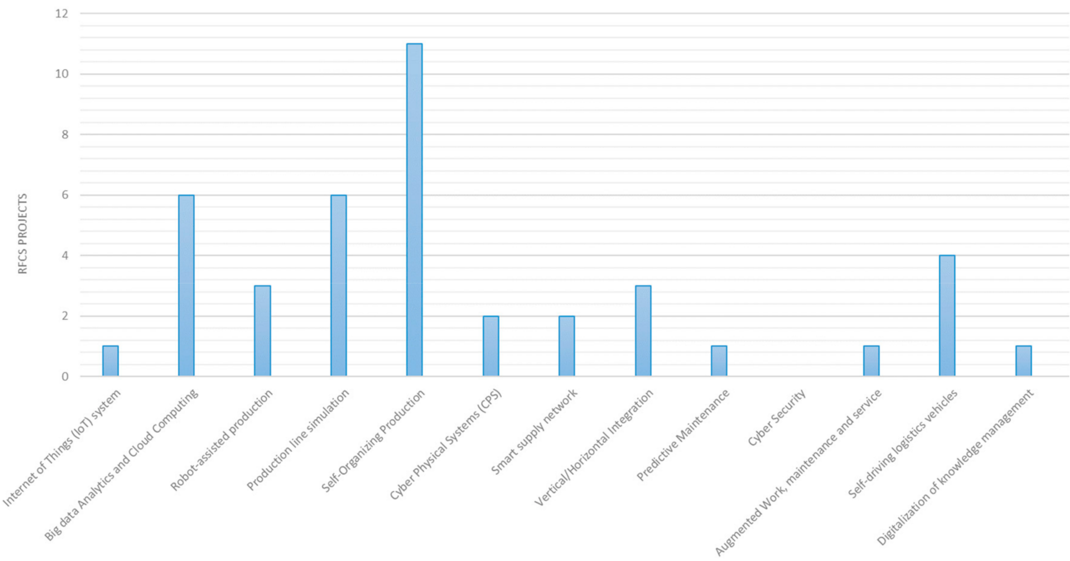

Figure 2. Number of RFCS projects by enabling technologies.

3.3. *Other European Funding Programs for Digitalization and Low Carbon Technologies for the Steel Sector*

Cost pressure, regulatory, and product/service requirements are some of the European steel industry challenges, which the steel industry has to face. The 7th Framework Program (FP7) (2007–2013) and its successor Horizon 2020 (2014–2020) [74] have been included in addition to the RFCS program by the European Union research and innovation funding program. Most of these projects started between 2014 and 2017. Nevertheless, digitalizing the steel industry started before calling these activities Industry 4.0 [75]. On this subject, some projects, starting in the early 1990s and covering some aspect of digitalization of the steel industry, have been identified, for instance BRICK, OREXPRESS, and TAM. All these projects were funded by EUREKA, which is a pan European network for market-oriented, industrial R&D [76].

As far as the FP7 Projects (2007–2013) are concerned, an example is AREUS, which treated integrated technologies for robotic production systems and robotic manufacturing processes optimization environment. WaterWatt and FACTS4WORKERS are some examples of H2020 projects where digitalization is applied in order to remove market barriers for energy efficient solutions and improve the efficiency for managers and workers within Worker-Centric Workplaces for Smart Factories.

The acronym SPIRE stand for "Sustainable Process Industry through Resource and Energy Efficiency" [77] and refers to a Public Private Partnership (PPP) targeting, within the Horizon 2020 program, the European process industries. DISIRE, CoPro, FUDIPO, MORSE, RECOBA, and COCOP are some SPIRE projects facing digital solutions and with specific demonstration in the steel sector.

Concerning other activities, a project on industry 4.0 has been developed at Dillinger. It is a real-time forecasting project for an "adaptive" Basic Oxygen Furnace (BOF), which "learns" and fine-tunes some settings based on the collected process data [78]. Another project has been led by SSAB and has aimed at making available information and instructions relating to any steel item, regardless of where it is produced. Each link of the production chain can use and accumulate information, by creating a basis for both the circular and platform economy [79].

The circular economy concept promotes the reuse, the refurbishment, and the recycling, maximizing the product life and at the same time keeping products and materials at a high level of utility [80] since an important objective defined in EU Masterplan is a competitive and low-carbon European steel industry [81]. Environmental issues such as CO_2 reduction can have several benefits from the KETs application. Advanced process monitoring and increased quality lead to major efficiency. In the field of CO_2 mitigation technologies, the RFCS and H2020 (2014-2020) programs represent the most important instruments for the EU-funded research projects. Low-carbon steel production requires the development of dedicated technologies.

The current pan-European research for the applicable technologies of CO_2 mitigation is focused on three pathways: Carbon Direct Avoidance (CDA), Process Integration (PI), and Carbon Capture, Storage, and Usage (CCU).

According to Figure 3, several EU Projects have been funded in the Process Integration pathway in order to develop technologies for reducing the use of carbon. For instance, ENCOP dealt with the overall energetic optimization of steel plants [33,82,83]. IDEOGAS focused on injection of reducing gas in the Blast Furnace (BF) and top gas recycling. LoCO2Fe developed a low CO_2 iron and steelmaking integrated process route. The identified low-carbon technologies are inserted in the x-axis and for each technology, the number of projects that takes into consideration such technologies is reported in the y-axis.

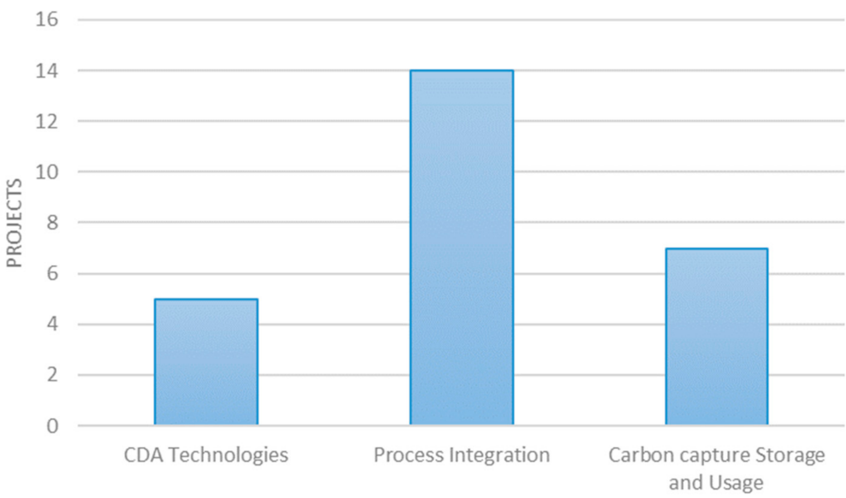

Figure 3. Number of projects related to low-carbon technologies.

CDA technologies mainly consist of iron ore reduction by hydrogen (produced by H_2O electrolysis) and syngas from biomass and Fe reduction by electrolysis. Some examples are HYBRIT, which aims at developing the world's first fossil-free ore-based steel-making technology using hydrogen replacing carbon as reductant, while GrInHy targets the production of a green industrial hydrogen via reversible high-temperature electrolysis designing, manufacturing, and operation of a high-temperature electrolyser.

CCU technologies concern the different methods for carbon capture based on chemical/biological processes of CO_2 conversion and CO_2 capturing by mineral raw materials. Within the CCU technologies, the focus is the conversion of industrial CO_2 into biofuels dealing with the transformation of CO_2 resulting from the iron, steel, cement, and electric power industries into value-added chemicals and plastics. Thanks to the Carbon4PUR project, it has been demonstrated that industrial waste gases such as mixed CO/CO_2 streams can be turned into intermediates for polyurethane plastics useful for rigid foams and coating. It is also possible to recycle carbon into sustainable and advanced bioethanol, as shown in the project Steelanol. FresMe and M4CO2 are other projects dealing with a more efficient CO_2 capture.

4. The Future of Digitalization in the Steel Sector

The steel sector, such as the other European industrial sectors, is committed to understanding the logic of digitalization and, consequently, to implement the digital technologies in its production processes. In the digital transformationm the four levers, resulting from researches carried out on key sectors in German and European economies, which are important for effectively implement the digitalization process, are [84]:

- Digital Data,
- Automation,
- Connectivity,
- Digital Customer Access.

Capturing, processing, and analyzing **digital data** can allow better forecasting of process behavior as well as smarter, easier, and faster decision making. The IoT connects devices equipped with sensors, software, and wireless capabilities, coupled with a growing capacity of data collection and storage. This results in new data sources availability to modern analytical technologies, for pre-processing data faster and in a more detailed way. Concerning the steelmaking processes and products, real-time data allow monitoring both of them. In addition, the use of sensors allows checking a single piece along the production chain: Errors and defects can be easily traced back and eliminated. This can lead to a more efficient production. In addition, data availability and ML, by enabling maintenance work to be anticipated and done before something goes wrong, can produce significant improvements in the equipment maintenance that can be scheduled and remotely checked.

The **automation** concerns the combination of traditional technologies and AI- and ML-based approaches, resulting in systems that work autonomously. In the near future, the automation applications will reduce error rates, increase speed, and cut operating costs. In particular, in the steel sector, the automation of production and consumption will be implemented.

The **connectivity** of separate systems (e.g., interconnecting the entire value chain via mobile or fixed-line high-bandwidth telecom networks) allows overcoming the lack of transparency, resulting in process efficiency improvements. This application in industrial plants is based on the interconnection of production systems facilitated by machine-to-machine (M2M) communications. A better connectivity and data sharing applied to the steelmaking processes aim to reduce some problems linked to remote locations and widespread supply chains. In addition, issues due to market fluctuation and potential hazardous working environments can be overcome.

The **digital customer access** allows the direct access to customers through the mobile internet, providing transparency and new services.

The new reorganization of entire industries and the transformation of business models are enabled through the availability of digital data, automation of production processes, interconnection of value chains, and creation of digital customer interfaces. This can allow steel companies to interact with suppliers and customers in a new and better way.

As far as the implementation of Industry 4.0 in the European steel sector is concerned, some previous and ongoing funded European projects will provide significant results on the digitalization in the near future. Some of them will develop cross-sectorial digital solutions, others are mainly prototype applications and demonstrations. On the other hand, some projects funded by the RFCS can provide further results on the real implementation of the digitalization in the steel sector. On this subject, a work including the publicly funded projects, patent analysis, expert interviews, and a qualitative survey of academics and practitioners related to Industry 4.0 in the steel sector has been performed [36]. Results have shown that transformation of the organizational structure of a company represent the main issues. In addition, Industry 4.0 implementations are required in order to achieve economic benefits to company developments, particularly, improvements in process efficiency and in the development of new business models. Furthermore, Industry 4.0 will improve effectiveness through intelligent support systems for the workforce and the interaction with customers in the organizational domain. In the research approach, the future SPIRE 2050 roadmap, in preparation by the SPIRE Working Group Digital, forecasts an integrated and digital European Process Industry, with new technologies and business models, which will aim to enhance competitiveness and impact for jobs and growth [85]. In the next five years, investments in innovation and digitization will be necessary [37], in order to achieve a level of digitalization to 72% [86]. By providing an example about the future of digitalization in the steel industry, ArcelorMittal group is working in the adoption common platforms and AI algorithms across the whole group and in different business areas [87].

4.1. Digitalization Impact on the Workforce

Significant changes, provided by Industry 4.0 to all aspects of industry structures, also include the workforce dynamics, such as the strategic workforce planning, the right organization structure, developing partnerships, and the technological standardization. The main future directions could be from a human labor-centered production to a fully automated work as well as from monotonous and physical activities to creative ones [88]. Nevertheless, negative changes could also occur, including higher unemployment and widespread workforce de-skilling.

In Germany, in overall sectors, about 23% of the workforce do not have vocational qualifications and in the manufacturing industries, 1.2 million are low-skilled workers. It has been assumed that low-skilled work will be up-skilled, as digitalization will upgrade simple and low-skilled activities and, at the same time, skilled activities will be continuously enhanced [89]. In this context, the industrial low-skilled work will not disappear but rather the level of qualification will steadily rise. It has been foreseen that jobs and skills will be polarized. This thesis consists in the automation of middle-skilled jobs by the use of computers. On the other hand, digitalization increases the productivity of the most skilled jobs, while the low-skilled jobs survive as they cannot be automated. This is because the automated work is concentrated in the middle of the skills distribution [90,91]. In addition, under conditions of digitalization, four development paths for low-skilled work have been identified [90]. The general erosion of low-skilled industrial work and the common idea that simple, routine tasks threatened by the new technologies will probably disappear in the longer term, can be considered only one scenario. In the second path, “upgrading of low-skilled industrial work”, a strategy for improving technological product, is paired off with a highly flexible marketing. The third scenario, characterized as “digitalized low-skilled work”, shows a high-intensity application of digital technologies and new forms of work (e.g., “crowdsourcing” and “crowdworking”) and may also be associated with new forms of low-skilled work. In the fourth scenario, “structurally conservative stabilization of low-skilled work”, there is no discernible change in existing employment and organizational structures. The different scenarios show that the potential job losses due to the implementation of the new technologies is controversial. In addition, the consequences for job activities and qualifications are interpreted as the “upgrading” or “polarization” of skills. Nevertheless, significant changes depend on the kind of technology automation and on its implementation process. Consequently, in the medium term, a limited spread of digital technologies is expected [92].

The progressive process of digitalization and automation produce effects and impacts on the employment in the industrial sectors, included the steel industry. In particular, the application of robotics and computerization will increase the creation of new jobs, particularly in IT and data science [14]. For instance, it has been shown that in Germany, only 12% of jobs are endangered by digital automation [93]. In Europe, over 1.5 million net new jobs have been created in the industrial sectors since 2013, with a growth of labor productivity of 2.7% per year on average since 2009, higher than both the US and Korea (0.7% and 2.3%, respectively) [23]. According to the European Centre for the Development of Vocational Training, between 2016 and 2030, over 151 million job openings are expected, with 91% due to the replacement needs (i.e., retirement, migration, movement into other occupations, or workers temporarily leaving the workplace) and the 9% due to new job openings. In the same period, over 1,750,000 jobs will be opened for ICT professionals [94]. Nevertheless, 2.6 million people worked in skill shortage occupations. During 2013, 47,000 vacancies have been estimated, including 25,600 reported as hard-to-fill by employers and around 23,500 as hard-to-fill, because of the lack of skills required [95]. In this regard, companies should develop their future workforce and adopt new business models and organizational structure, in the perspective of Industry 4.0 [96]. While employees need to be re-skilled, according to the requirements of digital economy, new employees need to be educated, according to the requirements of future jobs and skills. For this reason, the achievement of an up-skilled and re-skilled workforce is possible by implementing training programs, based on digital and business topics. This can be done through a life-long learning approach for addressing digital skills, and continuous training activities represent the key aspects for the companies to achieve a successful future [97]. However, companies also face some issues, such as skill mismatches, that refer to a failure of skill supply to meet skill demand, resulting in stopping the economic growth and in limiting the employment and the income opportunities of individuals [98]. The needs of companies, including the steel sector, are mainly focused on horizontal skillsets instead of high specialized profiles, in order to have a workforce flexible and able to move across multiple tasks. The companies need to have stronger horizontal skillsets rather than highly specialized profiles; in particular, workers with transferable skillsets in order to provide a good level of flexibility and coordination across different departments of their companies. In addition, it becomes increasingly important for companies to have employees who are able to move across multiple tasks and intervene in different areas. In addition, due to current job insecurity, transferable cross-functional skills represent a possibility for a greater security for workers [5]. In the process industries, including the steel industry, although 40,000 jobs have been lost in recent years, due to restructuring [99]; digitalization can provide new flexible skills and a workforce able to fast learn new digital technologies. In this context, cognitive sciences play an important role to provide support, combining awareness and knowledge with advanced control algorithms and optimization [100]. In the Industry 4.0, ICT skills are more important than core skills for employees. In particular, employees should not only have hard-skills, but also soft-skills such as collaboration, communication, and autonomy to perform their jobs in hybrid operating systems. In addition, employees should be able to be adaptable to continuous learning in an interdisciplinary perspective. Concerning engineering, the new education requirements are focused on achieving information and knowledge applicable to the business environment, and different disciplines should be able to work together. Through the design of new integrated engineering programs, the gap between universities and the business environment can be overcome. In addition, working in interdisciplinary teams, realizing interdisciplinary tasks, and providing interdisciplinary thinking represent key aspects for the implementation of Industry 4.0 research areas, such as mechatronic engineering, industrial engineering, and computer science [22].

4.2. Digitalization and Economic Impact

The digital economy can offer new opportunities to companies, including the steel sector. It is important to better understand how digitalization is changing the rules of competition, in order to optimize existing business models and to develop new ones. Due to a growth of the third country imports by 16.3% year-on-year, in the final quarter of 2018, a decrease of the domestic deliveries from EU mills to the EU market compared with the same period of 2017 has been revealed [101]. Economic and steel market outlook 2019-2020 European steel is squeezed between rising import pressure and a depressed home market. The main reason for the weakening of the EU economy in 2018, which will at least persist over the first half of 2019, has been the slowing global economic momentum and the related deteriorating contribution from net trade. A digital economy can be successfully achieved through a pan-European coordination based on a harmonized EU-wide approach. On this subject, different actions have to be implemented and, in particular, it is important to outline common standards at European level as well as to share ideas, knowledge, and experiences. A connected economy needs to rely on a strong infrastructure, in order to connect plant and machinery in an extensive and secure way. The digital transformation of the European manufacturing sector should be quickly achieved, in order to increase competitiveness and limit the new competitor actions. Reduction of energy and raw material consumption, lower OPEX, and reduction of losses as well increase of product qualities and productivity are the most important factors related to the innovative technologies in Industry 4.0 [102]. In [103], the recorded scrap information is transferred to EAF for the calculation of the optimized and best melting condition thanks to the detection and recording of volume and weight for each layer of scrap in the bucket. The raw materials, in fact, are a crucial factor and reducing their cost is more effective than acting on the transformation cost. According to [104], the main implementation areas in manufacturing are real-time supply chain optimization, human robot collaboration, smart energy consumption, digital performance management, and predictive maintenance. Especially the predictive maintenance, according to [104], can help not only increasing revenues, by reducing the maintenance costs from 10% to 40% and by reducing the waste from 10% to 20%, but also optimizing planned downtime, limiting unplanned downtime, and an estimation of a reduction of the operating cost by 2% to 10% is also foreseen. Moreover, digital technologies and ML can be useful in the metals industries in order to avoid unplanned shut down time to repair or replace key components, since such breakages are extremely costly. By using predictive maintenance methods, actuators can be replaced before they break [102]. The advanced analytics techniques like AI and ML can automatically help for the quality issues defining the basic causes, optimizing the optimal recipes for new products/grades, and by reducing the rejection rate [105]. The tools exploited in [106] facilitate the production planning by adopting AI and ML and help to improve due date reliability improving the overall economic success of the steelmaking company.

5. Conclusions

Although the steel production is already partly automated, the application of new technologies can further sustain the optimization of its entire production chain. This will allow the steel industry to become smarter in evolving towards Industry 4.0. The implementation of digital technologies, by continuously adjusting and the optimizing the processes online, contributes to improve the flexibility and the reliability of processes, maximizing the yield, and improving the product quality and the maintenance practices. In addition, they also contribute to increase the energy efficiency as well as to monitor and to control the environmental performance of processes in an integrated way.

The analysis reported in this review paper highlights that the challenge of digitalization consists of the integration of all systems and productions units, through three different dimensions: Vertical Integration (Integration of systems across the classic automation levels from the sensor to the ERP system); Horizontal Integration (Integration of systems along the entire production chain); Life-cycle Integration (Integration along the entire lifecycle of a plant from basic engineering to decommissioning) [30] and the Transversal integration (based on the decisions taken during the steel production chain, taking into account technological, economic, and environmental aspects). The digitalization process also requires jobs based on interdisciplinary teams, tasks, and thinking, to provide interdisciplinary skills. These achievements can be possible by integrating new IT, automation, and optimization technologies. Furthermore, Predictive Maintenance techniques can be implemented by equipment monitoring combined with intelligent decision methods. In this context, the application of Data Mining techniques, also based on ML, can allow anticipating maintenance work and scheduling it. In addition, Knowledge Management is a key factor for achieving improvements in the digitalization process.

The future expectations for the steel industry about digitalization include the optimization and the interactions of the individual production units, within the entire production chain (and beyond). This will allow reaching the highest quality, flexibility, and productivity. Furthermore, the following digitalization applications will represent the most important trends in the future:

Adaptive online control, through-process optimization, through-process synchronization of data, zero-defect manufacturing, traceability, and intelligent and integrated manufacturing.

In the coming years, in order to achieve a successful implementation of digitalization, the steel sector has to afford some important challenges, such as the standardization of systems and protocols, work organization and more skilled workers, investments, and research aiming to adopt appropriate frameworks. The implementation of digitalization is expected to generate productivity effects in the industrial sectors and growth in the economy. Concerning the potential consequences of digitalization for industrial workforce, on one hand, new technologies can cause job losses, but on the other hand, higher qualifications can be achieved. Nevertheless, changes will depend on different factors and they are expected to occur in the medium term, leading to some impacts on the industrial workforce. In addition, the steel sector needs to produce within environmental constraints in order to achieve its sustainability. In particular, the pressure of the environmental constraints represents a challenge for the steel sector to implement digital technologies that can help cope with the increasing trend in energy demand and the requirement of adopting low-carbon energy systems. In the coming years, the steel sector should be able to achieve zero waste, zero climate change emissions, and use half its current resources. On this subject, digital technologies can play an important role to enable improvements in sustainability performance, to plan processes in order to better account for demands and opportunities offered by industrial sustainability, and to enable the experimentation with new business models. The transformation of processes for significantly reducing emissions and improving energy efficiency will lead to the circular economy paradigm achievement and, on the other hand, adopting high-performance components, machines, and robots will optimize the materials and energy consumptions.

However, digital transformation and the full implementation of new digital solutions will only be successful if non-technological aspects are also considered in the technological development and implementation, such as framework conditions at European, national, and regional level, market and consumers, human resources, skills, and labor market. These aspects are integrated in the new SPIRE Roadmap 2050. Here, human resources and new (digital) skills especially will play a crucial role for unfolding the potential of new solutions within the companies.

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Appendix A

Table A1. List of acronyms identified RFCS Projects covering aspects of digitalization in the steel industry.

RFCS Projects				
AdaptEAF	DroMoSPlan	I2MSteel	Plant Temp	Telerescuer
AUTOADAPT	DYNERGYSteel	IConSys	PRESED	TRACKOPT
CYBERMAN4.0	ENCOP	INFOMAP	ROBOHARSH	
Cyber-POS	EvalHD	NEWTECH4STEEL	QUALITY4.0	
DESDEMONA	GASNET	OptiScrapManage	SoProd	

Table A2. List of acronyms of identified other European Funding Projects covering aspects of digitalization in the steel industry.

EUREKA	H2020	SPIRE	FP7
BRICK	WATERWATT	DISIRE	AREUS
OREXPRESS	FACTS4WORKERS	COPRO	
TAM		FUDIPO	
H2PREDICTOR		MORSE	
		RECOBA	
		COCOP	

Table A3. List of acronyms of identified Projects related to the Low Carbon Future Technologies.

CDA	PI	CCU
HYBRIT	IDEOGAS	Biocon-co2
GrInHy	OSMet S2	CarbonNext
H2FUTURE	HISARNA B, C &D	I3UPGRADE
IERO	ACASOS	FresMe
SALCOS	CO2RED	M4CO2
	REGTGF	Carbon4PUR
	RenewableSteelGases	Steelanol
	SHOCOM	
	Torero	
	GREENEAF	
	GREENEAF2	
	ENCOP	
	IDEOGAS	
	LoCO2Fe	
	STEPWISE	

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