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Sustainability of the Steel Industry: A Systematic Review

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Abstract: The concern for environmental sustainability focused on the decarbonization of industrial processes is becoming increasingly important, especially in the steel and iron industries, which are strong candidates for reducing emissions of harmful gases such as ammonia, benzene, carbon monoxide, hydrogen chloride, hydrogen sulfide, hydrogen cyanide, nitric oxide, nitrogen dioxide, and sulfur dioxide. The potential application of hydrogen as a renewable fuel alternative to petroleum derivates is encouraged. A systematic review of the literature was performed on a ScienceDirect basis. The results indicate the sector's main trends, opportunities, and challenges. Most current research points out the necessity of actions in artificial intelligence, Industry 4.0, energy, decarbonization, supply chain, and strategic planning. This study presents concepts regarding technological updating toward environmental sustainability in the iron and steel industry.

Keywords: carbon neutrality; hydrogen; environmental safety; green environment; process engineering; technological update; renewable energy.

1. Introduction

As a result of world population growth, the consumption of energy and materials is increasing, leading to environmental consequences. Some of these consequences include increased production of solid waste, increased air pollution caused by vehicles and industrial plants, and contamination of surface and groundwater [1].

According to the World Steel Association, the industry accounts for 7–9% of total global carbon emissions—second only to power generation as a source of CO_2, and most of that CO2 comes from coal-powered production methods [2].

So, eco-friendly industrial production is essential to save our environment. Carbon sequestration techniques can efficiently reduce carbon dioxide emissions from the steel sector. Steel by-products can be converted into raw materials for producing paints, cement fertilizers, and other goods. The major challenge in cement production is the higher input of raw materials and fuel in clinker production. These problems can be rectified by adopting a suitable co-processing method. Blended cement with highly efficient clinker coolers, dryers, separators, calciners, pre-calciners, and waste heat recovery systems can reduce energy requirements [3].

The search and exploitation of renewable clean energy sources have become crucial because of the developing day-by-day interest in clean water and energy affected by the improvement of the economy, population, industrialization, urbanization, insufficient energy, climate abnormalities, and environmental pollution. The major cause of the emissions of harmful gases into the environment is the high utilization of petroleum derivatives [4,5].

Nowadays, there is a huge demand for electricity around the globe. Due to the diminishing and polluting nature of fossil fuels, renewable energy sources have gained a huge attraction [6].

Simulations, integrated modeling, and gradient methods have optimized production processes, saved time, assisted decision-making, and contributed to materials and emissions control [7,8].

The future of the iron and steel industry has been modeled and analyzed in light of various market penetration scenarios for the best available and innovative technologies, as well as the International Energy Agency's climate change mitigation targets for keeping global warming below 2 degrees Celsius. Plausible modernization pathways have been studied, revealing a possibility of achieving levels of CO_2 emissions consistent with the climate targets by 2030–2040. However, meeting the 2050 targets will necessitate disruptive innovations in tandem with carbon capture and storage/utilization, improved material efficiency, and a greater share of recycled steel production [9].

In this context, the present systematic literature review focuses on the sustainable production of steel. Research articles published in peer-reviewed journals on this topic were searched in the database 'ScienceDirect'. This study presents concepts regarding technological updating aimed at the environmental sustainability of the iron and steel industry.

2. Materials and Methods

The systematic review developed in this work was based on the study of Pagani *et al*. (2015) [10]. The methodology has a basic nature and a qualitative approach, and in terms of objectives, it is classified as exploratory. A systematic review enables the researcher to conduct a thorough and reliable analysis of research on a specific topic. This can still be designated as a form of research based on literature as a source of data, thus presenting similar or conflicting results and providing a basis for future investigations [11].

As a research procedure, the following keywords were searched in the ScienceDirect database: "Environmental safety", "Technological update", "Technological obsolescence", "Green Sustainability", "Decarbonization" and "Iron and Steel industry". Initially, in the first reading, we sought studies published from 2019 to the present, chosen according to the title, and (when reading the abstract) those who did not fit the theme were excluded from the bibliographic portfolio of this systematic review.

3. Results and Discussion

Altogether, 219 articles were found in the ScienceDirect database. Subsequently, a new filtering was carried out aiming at publications focused on the theme, thus eliminating 170 articles. Of the remaining 49 articles, 40 were characterized as most relevant to composing the bibliographic portfolio and feeding the discussion on the topic. This survey was carried out in September 2022. Table 1 shows the types of publications identified in ScienceDirect and published between 2019 and 2022 related to the theme.

Table 1. Types of published documents.

Document Type	Record count	% of 219
Article	185	84.47
Proceedings Paper	6	2.73
Review	24	10.95
Book Chapter	2	0.91
Technical note	2	0.91

It is observed that the number of articles is higher than the other types of documents. Within the research universe surveyed, taking into account the 40 publications selected for the final portfolio, it is possible to quantify the publications of the most relevant authors on the subject studied. Table 2 presents the number of publications by the authors selected for the final bibliographical portfolio:

Table 2. A number of publications by the authors selected for the final portfolio.

Authors	Record count	% of 219
John et al., [12]	1	0.45
Wang et al., [13]	2	0.91
Swennenhuis et al., [14]	1	0.45
Mohammadi et al., [15]	2	0.91
Pourmehdi et al., [16]	3	1.36
Mehmanpazir et al., [17]	1	0.45
Conejo et al., [18]	2	0.91
Skoczkowski et al., [19]	1	0.45
Zhu & He [20]	2	0.91
Javad et al., [21]	1	0.45
Hallin et al., [22]	1	0.45
Kolagar et al., [23]	1	0.45
Na et al., [24]	1	0.45
Kim et al., [25]	1	0.45
Xue et al., [26]	3	1.36
Huang et al., [27]	2	0.91
Nkonyana et al., [28]	1	0.45
Giri et al., [29]	1	0.45
Ianinno et al., [30]	1	0.45
Sun et al,. [31]	1	0.45
Depczyński [32]	1	0.45
Liu et al., [33]	2	0.91
Zhang et al., [34]	2	0.91
Nwachukwu et al., [35]	2	0.91
De Souza & Pacca [36]	1	0.45
Guo & Tang [37]	1	0.45
Han et al., [38]	1	0.45
Beham et al., [39]	1	0.45
Goshin et al., [40]	1	0.45

The articles were also classified according to the year of publication, according to ScienceDirect data in 2022, as shown in Table 3:

Table 3. Number of publications per year 2019-2020.

Year of publication	Record count	% of 219
2019	40	18.26
2020	55	25.11
2021	68	31.05
2022	56	25.57

From Table 3, it is possible to verify that the number of publications has increased over the period. Table 4 shows the most relevant research areas, taking into account the articles identified in this survey:

Table 4. Publications by research area.

Area	Record count	% of 219
Engineering	74	33.78
Energy and Decarbonization	62	28.31
Supply chain	27	12.32
Strategic planning	34	15.52
Industry 4.0	12	5.47
Artificial intelligence	10	4.56

Table 5 shows the 40 most relevant articles found in this study.

Table 5. Most relevant articles on the topic found in the literature review.

Title	Author	Year
How key-enabling technologies' regimes influence sociotechnical transitions: The impact of artificial intelligence on decarbonization in the steel industry	[12]	2022
An integrated analysis of China's iron and steel industry towards carbon neutrality	[13]	2022
Towards a CO2-neutral steel industry: Justice aspects of CO2 capture and storage, biomass- and green hydrogen-based emission reductions	[14]	2022
A systems dynamics simulation model of a steel supply chain-case study	[15]	2022
Analysis and evaluation of challenges in the integration of Industry 4.0 and sustainable steel reverse logistics network	[16]	2022
Dynamic strategic planning: A hybrid approach based on logarithmic regression, system dynamics, Game Theory and Fuzzy Inference System (Case study Steel Industry)	[17]	2022
A review of the current environmental challenges of the steel industry and its value chain	[18]	2020
Technology innovation system analysis of decarbonisation options in the EU steel industry	[19]	2020
A Multi-stage Malmquist-Luenberger Index to Measure Environmental Productivity in China's Iron and Steel Industry	[20]	2022
Green supplier selection for the steel industry using BWM and fuzzy TOPSIS: A case study of Khouzestan steel company	[21]	2020
Digital transformation and power relations. Interpretative repertoires of digitalization in the Swedish steel industry	[22]	2022
Evaluation of long-term steel demand in developing countries- Case study: Iran	[23]	2022
A novel evaluation method for energy efficiency of process industry — A case study of typical iron and steel manufacturing process	[24]	2021
Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options	[25]	2022
Evaluation of symbiotic technology-based energy conservation and emission reduction benefits in iron and steel industry: Case study of Henan, China	[26]	2022
Biased technical change and its influencing factors of iron and steel industry: Evidence from provincial panel data in China	[27]	2021
Performance Evaluation of Data Mining Techniques in Steel Manufacturing Industry	[28]	2019
Understanding the performance measurement of Indian steel Industry: A DEA approach	[29]	2022
An Application-Oriented Cyber-Physical Production Optimisation System Architecture for the Steel Industry	[30]	2022
Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives	[31]	2020
MCDA based approach to supplier evaluation – steel industry enterprise case study	[32]	2021
The production and application of hydrogen in steel industry	[33]	2021
A carbon flow tracing and carbon accounting method for exploring CO2 emissions of the iron and steel industry: An integrated material–energy–carbon hub	[34]	2022
Exploring the role of forest biomass in abating fossil CO2 emissions in the iron and steel industry – The case of Sweden	[35]	2021
Carbon reduction potential and costs through circular bioeconomy in the Brazilian steel industry	[36]	2021
Modelling and discrete differential evolution algorithm for order rescheduling problem in steel industry	[37]	2019
A hybrid granular-evolutionary computing method for cooperative scheduling optimization on integrated energy system in steel industry	[38]	2022
Performance, Quality, and Control in Steel Logistics 4.0	[39]	2020
Energy Technologies For Decarbonizing The Steel Processing Industry – A Numerical Study	[40]	2022

As can be seen, several authors point out trends, opportunities, and challenges for the current scene. The next sections present the main results of the works selected in this systematic literature review, pointing out a synthesis from the authors' discussion on the topic.

3.1. Carbon neutrality.

Wang *et al*. (2022) state that technological diffusion is necessary to develop an optimal cost model for carbon neutrality in the iron and steel industry, and promoting energy-saving technologies is the most effective strategy to reduce carbon neutrality in the iron and steel industry [13].

In the same context, Swennnenhuis *et al*. (2022) point out that a rapid transition to a CO_2-neutral steel industry is necessary to limit climate change. Such a transition raises questions of justice, as it entails positive and negative impacts unevenly distributed among social actors [14].

To Skoczkowski *et al*. (2020), the decarbonization of the iron and steel industry is crucial in efforts to meet the EU's GHG emission reduction targets in 2030–2050. Promoting decarbonization in this sector will necessarily require the identification, development, and diffusion of innovative technologies for the production of I&S. The authors use an approach inspired by the Technological Innovation System (TIS) to analyze the development of technology in the EU I&S industry and identify possible paths for its decarbonization. When analyzing the functioning of these elements and their interactions in a more general context of innovation dynamics and policy design, risks and uncertainties were also discussed [19].

According to Zhang *et al*. (2022), accurate carbon accounting is critical for energy-intensive industries such as iron and steel. Finding carbon emission reduction potential in the production of local iron and steel, however, is impossible due to the crudeness of methods based on black box models and the uncertainty surrounding the effects of changes in a given material and energy flow on the complex production process' carbon flows. To solve this problem, the concept of "hub" is innovatively used for carbon flow tracking and carbon accounting. The conventional power hub is extended to a material flow-based power hub in this work, and an integrated material-energy-carbon hub is proposed. Based on the integrated carbon hub, the interconnection between carbon, material, and energy flows and the impacts of different materials and energy flows on the variation of CO_2 emissions from iron and steel production processes are explored in a case study. The results show that the steel mill contributes the most to the CO_2 emissions of the entire site, and the impacts of material and energy flow on the carbon flow of the entire site are significant. Investigated are the impacts of injection of pulverized coal, imported coke, ore mix, ore grade, and scrap content. The findings showed that the suggested carbon hub is a useful instrument for precise carbon accounting and carbon flow tracking and contributes to iron and steel sector low carbon transition pathways [34].

To Nwachukwu *et al*. (2021), the use of forest biomass in the manufacture of iron and steel focuses on providing a variety of available raw biomass, biomass conversion technologies, and distribution of biomass-based products to reduce fossil fuel CO_2 emissions. Biomass-based products are produced by converting biomass varieties from forestry operations and forestry industries through slow pyrolysis and gasification technologies. Using a spatially explicit cost optimization model, the supply of biomass is optimized to meet the corresponding demand for energy and material substitution, and the extent to which biomass can be a tool in CO_2 reduction is explored. Study results show that maximum use of biomass-based products results in a 43% reduction in CO_2 emissions across all existing steelmaking technologies. The results also show that increasing the biomass utilization rate through substitution targets is more effective than using a carbon pricing policy, as maximum CO_2 reduction is not achieved even with very low CO_2 prices. In the analysis of the scenario, it appears that the low prices of fossil fuels constitute a barrier to adopting biomass as an alternative to fossil fuels. Compared to the usual case, a maximum increase of 27% in energy-related costs for the industry was calculated [35].

According to De Souza & Paca (2021), although steel recycling is a recognized circular economy strategy, domestic scrap stock can be a constraint to reducing carbon emissions from the steel industry. In Brazil, the production of charcoal can be a complementary alternative for mitigating climate change to recycling. This study evaluated the potential and costs of CO_2 reduction in a low carbon (LC) scenario for the Brazilian steel industry based on two circular options based on bioeconomy. To this end, Brazilian steel production was forecast until 2050 through an econometric model. The technical amount of scrap and the economic viability of charcoal were estimated to determine the penetration of LC strategies. In addition, an uncertainty analysis was performed using the Monte Carlo method. For the median value in the simulation, we find that crude steel production will emit 64 $MtCO_2$ in 2050. A recycling share of 36% of total steel production could reduce these emissions by 20%, and 86% of the remaining blast furnace production could be based on charcoal, improving the reduction by 65%. The weighted average cost of the LC scenario is -$1/$tCO_2$ for the median value in the simulation, but positive values were found in 45% of the simulations. Charcoal has higher abatement costs but less uncertainty than recycling. Such strategies can significantly reduce emissions from the Brazilian steel industry, putting off other emerging or more expensive alternatives. However, economic policies are needed due to the additional cost of charcoal, in conjunction with law enforcement to ensure sustainable coal production, and regulations are needed to improve logistics and scrap market disparities [36].

Goshin *et al*., (2022) analyzed approaches to decarbonize the energy supply of the secondary steel processing industry. Real data from a secondary steel production company was used in combination with state-of-the-art low-carbon energy supply technologies. In addition, the use of waste heat from a pusher furnace for process integration is being considered. The time process model developed allows the holistic optimization and expansion of the steel process system in relation to technical-economic criteria. As we have shown, the implementation of the annual heat demand of a municipality shows that an almost 100% self-sufficient heat supply is possible [40].

3.2. Energy options.

Na *et al*. (2021) show that energy efficiency is an important indicator for exploring energy conservation and consumption reduction. Traditional energy efficiency assessment methods for the process industry lack in-depth thinking about the energy usage of the entire system. This article established an energy efficiency assessment method based on the proposed energy requirements for the process industry. When establishing material and energy flow networks, the energy efficiency of the typical iron and steel manufacturing process (ISMP) is analyzed, and its influencing factors are discussed. The results found that the energy required for coking, sintering, pelletizing, blast furnace iron production, basic oxygen furnace steel production, and steel rolling is 2626.2 MJ/t-coke, 1122.9 MJ/t-sinter, 992.3 MJ/t-pellet, 9781.5 MJ/t-hot metal, 393.95 MJ/t-molten steel, and 445.3 MJ/t-steel of products, respectively. Typical ISMP energy efficiency is 66.9%. ISMP energy efficiency can be effectively improved by adjusting the steel ratio, recovering waste heat and waste energy, and developing interface technologies [24].

According to Kim et al. (2022), the steel industry consumes the most coal and produces greenhouse gases. It uses about 7% of the world's energy resources, and according to conservative estimates, it contributes between 9% and 10% of the world's greenhouse gas emissions. Decarbonizing the steel industry is vital to meeting climate change mitigation targets and achieving a sustainable future for the industry. This article presents a comprehensive and systematic review that considered over 1.6 million pieces of literature and took an in-depth look at a shortlist of 271 studies on the decarbonization of the steel industry.

The review determines the climate footprint of the iron and steel sector by using a sociotechnical lens to examine raw materials, iron and steel manufacturing processes, manufacturing and usage of steel products, waste, and recycling. The review evaluates 86 potentially game-changing technologies while evaluating established and new decarbonization strategies. Decarbonizing the iron and steel sector will positively affect the environment, public health, and energy and carbon emissions reduction. Components of the financial, organizational, and behavioral aspects of decarbonization barriers are taken into account. The analysis also goes over various financial and policy options that can be used to get around obstacles. Research gaps are then discussed [25].

Conejo *et al*. (2020) highlight that the steel industry is the largest energy consumer in the world among industrial sectors. It is generally recognized that energy and the environment are closely related. Steel production is an energy-intensive process that has a significant environmental impact. The report examines the improvements made in the steel industry's global energy, carbon dioxide emissions, and water use. Pressure on companies, particularly the steel industry, to minimize pollution in general and, more specifically, their carbon and water footprints has intensified due to the depletion of freshwater supplies and the effects of climate change and global warming. The implications of these effects on the value chain are discussed in this review. The contribution of new emerging steelmaking technologies is also reviewed. Finally, important issues that contribute to defining a sustainable industrial activity, such as the recycling of steel and the by-products of steel production, are studied. The history of the steel industry is full of lessons, one of which is the need to keep dreams alive. In fact, there are expectations to solve problems caused by technological progress [18].

Xue *et al*. (2022) showed that the steel industry (ISI) has been facing great pressure for energy conservation and emission reduction (ECER), and industrial symbiosis (IS) is expected to be a promising way to carry out ECER in ISI. This study systematically identified material and energy flows in the ISI using the material flow analysis method to collect the symbiotic technology in the first place. Then, a comprehensive assessment framework based on the life cycle assessment and conservation supply curve was established to quantify and select symbiotic technologies. Based on this, the ECER potential brought about by promoting the technologies selected for Henan ISI was assessed by scenario analysis. The findings indicate that: (1) the 35 technologies gathered have remarkable effects in reducing the environmental impacts of Human Toxicity Potential, Primary Energy Demand, and Global Warming Potential, and 18 of the best available technologies were selected after a comprehensive evaluation. (2) Promoting the best available technologies could bring great ECER potential to the Henan ISI, with energy savings of 1.24 Mtce, CO_2 emission reduction of 4.64 Mt, SO_2 of 6.97 kt, NOx of 4.00 kt, and 2.16 kt PM for the Henan ISI in 2030 compared to 2017, and the ECER rate reached 9%, 13%, 26%, 7%, and 3.5%, respectively. (3) Coking, steel and steelmaking processes have contributed most to the potential of ECER, while energy exchange technologies of electricity generation using coke sensible heat (E1), recycling of sensible heat from coke (E2), electricity generation from the saturated steam converter (E12), and blast furnace slag material substitution technologies instead of cement doping to produce concrete (MS7), and steel slag instead of doping of cement to produce concrete (MS10), had a significant ECER effect. In addition, specific policy recommendations were proposed for promoting symbiotic technology in the ISI. This study is useful for improving the method of evaluating symbiotic technology at a technical level, enriching IS research at an industrial level, and providing a reference for a follow-up study in the field of IS [26].

Huang *et al*. (2021) point out that the impact of technical change on economic growth is closely related to the structure of input factors, and guiding technical change toward energy saving can achieve economic growth and energy conservation goals. Based on provincial panel data from 2006–2016, this article first uses the slack-based measurement model and bootstrap data engagement analysis (bootstrap-DEA) to calculate the Biased Technical Change Index (BTC) and its bias iron and steel factor (ISI). Next, BTC influencing factors are examined using panel regression analysis. The bootstrap-DEA-corrected results show that the ISI BTC level in China is 1.0110, with a contribution rate of 20.75% to the total green factor productivity. In addition, China's ISI experienced a technical shift in labor-saving, energy-saving, and capital usage during 2006–2016. In two-factor comparisons, the technical change tended to save labor in capital labor and energy labor and energy in capital energy. According to the findings of the regression study, boosting urbanization, increasing production scale, and upgrading industrial structure are all good ways to support BTC. The major strategy is to increase energy efficiency. However, there is a strong negative association between excessive capital deepening and BTC. This article offers policy proposals for the green growth of ISI based on these findings [27].

Liu *et al*. (2021) point out that the steel industry faces unprecedented pressure to reduce CO2 emissions and achieve sustainable energy development due to increasingly serious environmental issues and the continuous depletion of fossil resources. Hydrogen is considered the most promising clean energy source of the 21st century due to its diverse sources, high calorific value, good thermal conductivity, and high reaction rate, making hydrogen have great potential for application in the steel industry. In this review, different hydrogen production technologies are described that have the potential to supply hydrogen or hydrogen-rich gas to meet the high demand of steel mills. The applications of hydrogen in the blast furnace (BF) production process, direct iron reduction (DRI) process, and iron reduction smelting process are summarized. In addition, the functions of hydrogen or hydrogen-rich gases as fuels are also discussed. In addition, some suggestions and perspectives for the future development of the steel industry in China are provided [33].

3.3. Supply chain and strategic planning.

Mohammadi *et al*. (2022) showed that among the interactions and dynamics that permeate the supply chain (SC), computer modeling and simulation promote the determination of system behavior and decision-making. The authors showed that using Causal Loop Diagrams (CLD) and Inventory Flow Diagrams (SFD) promoted economic advances in the steel industry, especially with regard to an increase of approximately 4% in iron ore content. The cost of steel production fell by 2.4% [15].

Mehmanpazir *et al*. (2022) proposed a hybrid approach to dynamic strategic planning in the steel industry. Assuming demand, supply, and price as the main subsystems, the interactions between the subsystems were analyzed using multiple logarithmic regression analyses supported by a historical database. We used three static and four dynamic scenarios using the leader-follower paradigm and coalition game theory to simulate using system dynamics. The generated simulated data, i.e., the initial parameters as inputs and independent variables as outputs, were used to mine the fuzzy rules of a fuzzy inference system (FIS) to estimate the system's future behavior. FIS was used to conduct the most probable cases on the market. The most likely strategy based on the long-term behavior of the market, i.e., the average case, is determined. Implementing the average strategy that comes from the dynamic nature of parameters, variables, random loops, system dynamics, game theory, and long-term fuzzy inference systems is reliable. Short-term noise cannot significantly impact the results, as they are all considered in the proposed dynamic strategic planning procedure. The entire framework was applied in a real-case study in the steel market [17].

Pourhmedi *et al*. (2020) point out that many organizations are trying to balance their supply chains' social, environmental, and economic aspects to gain competitive advantages over their rivals and have a sustainable supply chain. Steel is one of the most critical raw materials used in virtually every aspect of our lives, directly or indirectly influencing a country's industry and economy. The end products of the steel industry can be reused at the end of their life cycle, making the principles of reverse logistics applicable in the supply chain and transforming it into a closed-loop supply chain. This research developed a multiobjective linear mathematical model under uncertainty to optimize a sustainable closed-loop steel supply chain. The existing uncertainty is modeled through a method based on scenarios in the stochastic environment, and the proposed multiobjective model is developed following a fuzzy goal programming approach. A real-life case study was conducted in one of Iran's active steel supply chains to validate the model. The model optimizes total profit, energy and water consumption, CO2 emissions, job opportunities created, and lost workdays by determining optimal production technology, whether retailers move to hybrid centers, and the flow of materials and products. The final results show that reducing just 1% in profit can alleviate harmful environmental effects by 5%. Finally, various managerial implications derived from the end results and sensitivity analysis are discussed to provide insights for industry leaders who want to increase their profits in relation to environmental and social effects [16].

Zhu & He (2022) present a multi-stage model of the Malmquist-Luenberger index (MLPI), considering the joint production of desirable and undesirable products in multiple production processes. The proposed approach not only assesses the growth in total environmental factors productivity (ETFP) of the entire system but also investigates the progress and regression of each sub-process, i.e., the iron-making sub-process and the steelmaking sub-process. The drivers of ETFP change are identified through the multi-stage MLPI decomposition. The validity of the proposed model was demonstrated with the application of the model to 48 iron and steel companies in China during the period 2009–2013. In addition, this study explores the analysis of regional system differences and multi-stage ETFP among 31 provinces in the eastern, central, and western regions. The results show that the ETFP of the system, steelmaking subprocess, and steelmaking subprocess experienced an annual increase. The most important finding is that increasing environmental efficiency is the most critical determining factor in promoting the growth of ETFP. The technical regression of the steelmaking sub-process is the main source of constraint on the growth of the system's ETFP. Furthermore, the ETFP system change varies greatly in different regions, being greater in the east region and less in the western region. Compared with conventional single-stage MLPI, multi-stage MLPI is smaller and has greater discriminatory power [20].

Javad *et al*. (2020) point out that green supply chain management has increasingly emerged as an essential approach for many companies and organizations to become environmentally sustainable. Suppliers play an important role in creating a sustainable supply chain. This study aims to select Khouzestan Steel Company (KSC) suppliers based on their green innovation capability. In this survey, the company's alternative suppliers are identified, and the most effective criteria for supplier selection are determined based on the supplier's green innovation skills. The Best-Worst Method is used to rank the various green supplier selection criteria in the multicriteria decision-making problem. Then, the Fuzzy TOPSIS (Order of Preference by Similarity to the Ideal Solution Technique) is used to classify the various suppliers based on weighted criteria to select the most effective supplier among a set of alternative suppliers. This study contributes to finding the main factors of green supplier selection for KSC. Analysis of key factors of KSC's supplier selection indicates that green innovation criteria should receive more attention from KSC in green supplier selection. The result of this survey is useful for ranking suppliers accordingly based on their green innovation skills. Organizations can replicate the proposed vendor selection framework for other vendors, such as spare parts, consumables, and technical, design, and development service providers. A sensitivity analysis is also performed to verify the robustness of the structure and eliminate the effect of bias. Study limitations, along with future research directions, are also presented [21].

Hallin *et al*. (2022) focused their study on how ideas of "digitization" are discursively constructed in the Swedish steel industry. Using a discursive psychology approach, we identified seven interpretive repertoires in the discursive practice of digitization: all others; speed; competition; job loss; control; security; and equality. Examining its functions and effects, we show that not only is digital transformation built as more productive, efficient, competitive, technologically advanced, safe, and equitable, but it also involves a shift so that the manual worker is more vulnerable, a construct where she is capable but lonely, physically fragile, dull and unreliable, and a victim of development beyond her control, forcing her to acquire new skills. Shifting the burden of the challenges of digital transformation onto workers reproduces unbalanced power relations between employees and employers. The development of the union of many contexts, bodies, and hierarchical levels by these local discourses has the potential to ameliorate this imbalance while also linking future steelworkers through digital technology [22].

Three methodologies, including the growth model (GM), the intensity of use hypothesis (IUH), and the fixed stock paradigm, are used to calculate the projected steel demand for Iran (FCP). Based on the expected growth factor, GM displays a wide range of apparent steel demand. According to the IUH method, the maximum amount of steel that will be consumed per person annually when the gross domestic product (GDP) per capita hits 13,000 USD (2010 USD constant) is estimated to be between 2040 and 2060. This depends on the economic growth assumptions used. As fluctuations in developing countries minimally affect the FCP, steel demand based on this model is used to study the potential to meet the demand for steel in the transport sector from scrap generated in the same sector. Iran faces a deficit of almost 8 million tons of steel scrap annually until 2025. Thus, the current analyzes the potential of supplying the necessary steel demand of the transport sector in two economic scenarios, including "regional rivalry" with development-constrained economic development and "fossil fuel-powered development," which focuses on further economic development using the temporal distribution matrix (TDM) method. Both scenarios demonstrate that peak steel consumption occurs from 2030 to 2040. Maximum demand for steel in the transportation sector is 25% lower in the regional rivalry scenario than in fossil fuel-powered development. Furthermore, although this scenario provides a steady trend of steel production and consumption until 2050, scrap from the transportation sector can meet the demand for steel in this sector; by comparison, this trend occurs 20 years behind in the fossil fuel-powered development scenario [23].

Giri *et al*. (2022) state that the measurement of efficiency has been an important indicator of a company's performance. In the study, the efficiency level of steel companies operating in India was verified through the adoption of an input-oriented data envelopment analysis (DEA). Twenty steel-producing companies for the period 2018–19 were considered for the study. The study was carried out using input variables such as raw material cost, energy, and fuel cost, gross fixed assets, current assets, and the output variable considered to measure efficiency as billing. The result of the study indicates efficient and less efficient companies with their respective technical efficiency scores. It also indicates benchmarking companies. Eleven of the twenty companies were on the efficient frontier, and the remaining nine were below the frontier. The slack and target values were calculated for the relatively less efficient company, and more in-depth analysis was done to indicate the improvement in the inputs, which will improve the companies' efficiency [29].

Sun *et al*. (2020) show that the integrated analysis and optimization of material and energy flows in the iron and steel industry have attracted considerable interest from steel mills, energy engineers, policymakers, financial companies, and academic researchers. Numerous publications in this area have identified its great potential to bring significant benefits and innovation. While much technical work has been done to analyze and optimize material and energy flows, the steel industry lacks an overview. This work first provides an overview of the different steel production routes to fill this gap. Next, the modeling, programming, and interrelation of material and energy flow in the steel industry are presented, thoroughly reviewing the existing literature. This study selects eighty publications on material and energy flows in steel mills, from which a map of the potential for integrating material and energy flows for steel mills is constructed. The article discusses the challenges to be overcome and the future directions of material and energy flow research in the iron and steel industry, including the fundamental understanding of flow mechanisms, the programming, and optimization of the dynamic flow of material and energy, the synergy between material and energy flows; flexible production processes and flexible energy systems; smart steel fabrication and smart energy systems; and revolutionary steelmaking routes and technologies [31].

Guo & Tang (2019) point out that order management is a critical and complicated issue in the steelmaking production process, as orders are the bridge between customers and semi-finished or finished products in different units. Typically, order scheduling is organized by skillful planners. However, initial programming can be unfeasible during the production process due to the dynamic and frequent variation of the production environment. This article investigates the practical problem of rescheduling orders to accommodate various changes that affect normal production. The problem is formulated as a mathematical model of mixed integer programming considering the original objective, the deviation from the initial schedule, and the balance of production capacity. A discrete differential evolution algorithm with new mutation and crossover operators is proposed to find almost optimal solutions to this problem. Computational experiments are presented in randomly generated and practical production instances. The experimental results illustrate that the proposed algorithm can obtain better solutions compared to four standard differential evolution algorithms and the manual method.

In addition, a practical decision support system based on production data that incorporates the model and the algorithm is developed to monitor the production process, diagnose if there are high-impact changes in orders and units, and make rescheduling decisions if necessary [37].

According to Beham *et al*. (2020), in the steel industry, logistics is often part of the value chain since the storage processes and, therefore, the cooling processes contribute to the product quality to a certain extent. As a result, steel logistics is concerned with storage and movement in our casework in the process (WIP). Thousands of tons of steel are transported with cranes and heavy vehicles and stored in piles in large yards daily. The entire sector is under pressure to reduce costs, which strongly influences logistics operations. The efficiency of transport and storage processes is a crucial success factor and is challenged by highly dynamic processes and environments [39].

3.4. Industry 4.0 and artificial intelligence.

According to John *et al*. (2022), enabling technologies such as Artificial Intelligence (AI) add technological value to all areas of the steel industry, such as the prediction of process parameters; optimizing operations, programming, and electrical energy; and forecasting product demand, quality, and site emissions. The steel industry's trajectory dependencies may be reinforced by AI, as AI tools are more focused on incrementally improving existing technologies rather than new, low-carbon technologies. However, AI also offers capabilities to reduce barriers to innovation in sustainability, such as systems integration challenges, flexibility challenges, demand-side barriers, and risk-related barriers [12].

Pourmehdi *et al*. (2022) show that Industry 4.0 (I4.0) is a relatively new phenomenon. Developing countries are more likely to face challenges in adapting it to improve supply chain processes and advance toward sustainability. The steel industry is the core of industrial growth and is indispensable in developing countries. Steel is a highly recyclable product, which means it can be reused infinitely, increasing the importance of its reverse logistics. Although many studies have been carried out in the area of I4.0 and supply chain management, less attention has been devoted to finding and analyzing potential challenges of integrating I4.0 technologies into steel reverse logistics activities. The study investigated the obstacles to the efficient integration of I4.0 and a sustainable steel reverse logistics system. The interrelationships of the challenges are specified by Interpretive Structural Modeling, and the final classification of the challenges was determined through the Fuzzy Analytical Network Process [16].

In this same context, Nkonyana *et al*. (2019) state that Industry 4.0 has evolved and created a great interest in automation and data analysis in manufacturing technologies. The Internet of Things (IoT) and Cyber-Physical Systems (CPS) are some of the recent topics of interest in the manufacturing sector. The steel manufacturing process relies on monitoring strategies, such as fault detection, to reduce the number of errors that can lead to large losses. Proper fault diagnosis can help in making accurate decisions. In this work, predictive analytics was employed to address the intricate problems posed by industrial data. We train and test our industrial data using Support Vector Machines, Random Forest, and Artificial Neural Networks. We assess how ensemble methods stack up against conventional machine-learning techniques. Finally, they evaluate the performance and significance of the models. Random Forest outperformed the other machine learning methods in the analysis [28].

Ianinno *et al*. (2022) state that the new generation of steel mills shaped by Industry 4.0 is digitized, networked, flexible, and adaptable. Production processes use distributed information and communication structures that are more autonomous and capable of reacting to dynamic environmental changes. Cyber-physical systems are a fundamental component of Industry 4.0 and enable a new generation of intelligent processes. This article presents a modular architecture approach to the design of cyber-physical steel production processes. The approach is tested within a production facility for long products, such as rails or tubes, taking into account the main peculiarities of the sector. The use of an industrial agent-based solution to enable intelligent features and interactions between cyber-physical modules is being investigated and adopted. The experimental results highlight the industrial applicability of the implementation scheme adopted by combining agent-based technology with the proper connection between models, communication, and optimization methods [30].

Han *et al*. (2022) state that the Integrated Energy System (IES) in the steel industry, typically involving gas, heat, and electricity, has a distributed nature and complex coupling relationships that demand effective programming optimization to use multiple energy sources cooperatively. Therefore, a Granular-Evolutionary Hybrid Computing (GEHC) framework is proposed in this study to solve the IES scheduling as a Restrictive Multiobjective Problem (CMOP). More specifically, a Collaborative Fuzzy C-Means (CFCM) clustering model is first established, where horizontal and vertical structures are well constructed to obtain granules of information about the cooperative relationship between units in different energy subsystems. Then, a Probability-Based Granular Computing (PGrC) approach is proposed to optimize the IES scheduling, which is guided by specialized knowledge packed into the information granules. To determine the collaborative parameters in CFCM that essentially control the cooperation between the multiple energy media and satisfy the complex practical constraints, a method based on Multiobjective Differential Evolution (MODE) is proposed for scheduling optimization. To evaluate the performance in terms of cooperativity, convergence, and diversity, the proposed GEHC and the compared methods that have partial collaborations or use other optimization frameworks are applied to a real-world optimization problem. The experimental results demonstrate that the proposed GEHC performs better than the other methods considering both objective functions and performance indicators, which can be potentially useful to achieve well-executed unmanned IES programming in the steel industry [38].

4. Conclusions

This systematic review presents concepts regarding technological updating toward environmental sustainability for the iron and steel industry. The literature review was performed using the ScienceDirect scientific basis by searching for articles published between 2019 and 2022. The results indicate that most of the current research points to actions in Artificial Intelligence and Industry 4.0, Energy, Decarbonization, and Supply Chain and Strategic Planning by indicating trends, opportunities, and challenges for the sector.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Taran, M.; Safaei, M.; Karimi, N.; Almasi, A. Benefits and Application of Nanotechnology in Environmental Science: an Overview. *Biointerface Research in Applied Chemistry* **2021**, *11*, 7860-7870, https://doi.org/10.33263/BRIAC111.78607870.
2. World Steel Association (Statistics). Available online: https://worldsteel.org/steel-topics/statistics/.
3. Nidheesh, P.V.; Kumar, M.S. An overview of environmental sustainability in cement and steel production. *Journal of Cleaner Production* **2019**, *231*, 856-871, https://doi.org/10.1016/j.jclepro.2019.05.251.
4. Mustafa, H.M.; Hayder, G.; Jagaba, A.H. Microalgae: A Renewable Source for Wastewater Treatment and Feedstock Supply for Biofuel Generation. *Biointerface Research in Applied Chemistry*, **2021**, *11*, 7431–7444, https://doi.org/10.33263/BRIAC111.74317444 .
5. Shefali, Kumar, R.; Sankhla, M.S.; Kimar, R.; Sonone, S.S. Impact of Pesticide Toxicity in Aquatic Environment. *Biointerface Research in Applied Chemistry*, **2021**, *11*, 10131-10140, https://doi.org/10.33263/BRIAC113.1013110140.
6. Kasipandian, K.; Saigeetha, S.; Samrot, A.V.; Abirami, S.; Renitta, R.E.; Dhiva, S. Bioelectricity Production Using Microbial Fuel Cell–a Review. *Biointerface Research in Applied Chemistry* **2021**, *11*, 9420-9431, https://doi.org/10.33263/BRIAC112.94209431.
7. Naderi, M.; Khamehchi, E.; Karimi, B. Production Optimization Based on Integrated Modeling and Gradient Methods. *Biointerface Research in Applied Chemistry* **2021**, *11*, 7665-7676, https://doi.org/10.33263/BRIAC111.76657676.
8. Gorshenina, E.; Baitelova, A.; Rakhimova, N.; Bykova, L.; Savchenkova, E. Monitoring of the Migratory Ability of Heavy Metals in the Soil-Plant System. *Biointerface Research in Applied Chemistry* **2021**, *11*, 10351 – 10357, https://doi.org/10.33263/BRIAC113.1035110357.
9. Shatokha, V. Environmental Sustainability of the Iron and Steel Industry: Towards Reaching the Climate Goals. European *Journal of Sustainable Development* **2016**, *5*, 289-300, http://doi.org/10.14207/ejsd.2016.v5n4p289.
10. Pagani, R.N.; Kovaleski, J.L.; Rezende, L.M. Methodi Ordinatio: a proposed methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication. *Scientometrics* **2015**, *105*, 2109–2135, https://doi.org/10.1007/s11192-015-1744-x.
11. Linde, K.; & Willich, S.N. How objective are systematic reviews? Differences between reviews on complementary medicine. *Journal of the Royal Society of Medicine*, **2003**, *96*, 17-22, https://doi.org/10.1177/014107680309600010.
12. John, N.; Wesseling, J.H.; Worrel, E.; Hekkert, M. How key-enabling technologies' regimes influence sociotechnical transitions: The impact of artificial intelligence on decarbonization in the steel industry. *Journal of Cleaner Production*, **2022**, *370*, 133624, https://doi.org/10.1016/j.jclepro.2022.133624.
13. Wang, X.; Yu, B.; An, R.; Sun, F.; Xu, S. An integrated analysis of China's iron and steel industry towards carbon neutrality. Applied Energy, **2022**, *322*:119453, https://doi.org/10.1016/j.apenergy.2022.119453.
14. Swennenhuis, F.; Gooyert, V.; Coninck, H. Towards a CO_2-neutral steel industry: Justice aspects of CO_2 capture and storage, biomass- and green hydrogen-based emission reductions. *Energy Research & Social Science*, **2022**, *88*, 102598, https://doi.org/10.1016/j.erss.2022.102598.
15. Mohammadi, M.A.; Sayadi, A.R.; Khoshfarman, M.; Kashan, A.H. A systems dynamics simulation model of a steel supply chain-case study. *Resources Policy* **2022,** *77*, 102690, https://doi.org/10.1016/j.resourpol.2022.102690.
16. Pourmehdi, M.; Paydar, M.M.; Ghadimi, P.; Azadnia, A.H. Analysis and evaluation of challenges in the integration of Industry 4.0 and sustainable steel reverse logistics network. *Computers & Industrial Engineering*, **2022,** *163*, 107808, https://doi.org/10.1016/j.cie.2021.107808.
17. Mehmanpazir, F.; Khalili-Damghani, K.; Hafezalkotob, A. Dynamic strategic planning: A hybrid approach based on logarithmic regression, system dynamics, Game Theory and Fuzzy Inference System (Case study Steel Industry). *Resources Policy*, **2022**, *77*, 102769, https://doi.org/10.1016/j.resourpol.2022.102769.

18. Conejo, A.N.; Birat, J-P.; Dutta, A. A review of the current environmental challenges of the steel industry and its value chain. *Journal of Environmental Management*, **2020,** *259*, 109782, https://doi.org/10.1016/j.jenvman.2019.109782.
19. Skoczkowski, T.; Verdolini, E.; Bielecki, S.; *et al*. Technology innovation system analysis of decarbonisation options in the EU steel industry. *Energy*, **2020,** *212*, 118688, https://doi.org/10.1016/j.energy.2020.118688.
20. Zhu, L.; & He, F. A Multi-stage Malmquist-Luenberger Index to Measure Environmental Productivity in China's Iron and Steel Industry. *Applied Mathematical Modelling*, **2022,** *103*, 162-175, https://doi.org/10.1016/j.apm.2021.10.034.
21. Javad, M.O.M.; Darvishi, M.; Oroojeni, A.; Javad, M. Green supplier selection for the steel industry using BWM and fuzzy TOPSIS: A case study of Khouzestan steel company. *Sustainable Futures*, **2020,** *2*, 100012, https://doi.org/10.1016/j.sftr.2020.100012.
22. Hallin, A.; Lindell, E.; Jonsson, B.; Uhlin, A. Digital transformation and power relations. Interpretative repertoires of digitalization in the Swedish steel industry. *Scandinavian Journal of Management*, **2022,** *38*, 101183, https://doi.org/10.1016/j.scaman.2021.101183.
23. Kolagar, M.; Saboohi, Y.; Fathi, A. Evaluation of long-term steel demand in developing countries- Case study: Iran. *Resources Policy* **2022**, *77*, 102675, https://doi.org/10.1016/j.resourpol.2022.102675.
24. Na, H.; Sun, J.; Qiu, Z. *et al*. A novel evaluation method for energy efficiency of process industry — A case study of typical iron and steel manufacturing process. *Energy*, **2021**, *233*, 121081, https://doi.org/10.1016/j.energy.2021.121081.
25. Kim, J.; Sovacool, B.K.; Bazilian, M. *et al*. Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Research & Social Science*, **2022,** *89*, 102565, https://doi.org/10.1016/j.energy.2021.121081.
26. Xue, R.; Wang, S.; Gao, G.; Liu, D.; Long, W.; Zhang, R. Evaluation of symbiotic technology-based energy conservation and emission reduction benefits in iron and steel industry: Case study of Henan, China. *Journal of Cleaner Production* **2022**, *338*, 130616, https://doi.org/10.1016/j.jclepro.2022.130616.
27. Huang, J-B.; Zou, H.; Song, Y. Biased technical change and its influencing factors of iron and steel industry: Evidence from provincial panel data in China. *Journal of Cleaner Production*, **2021,** *283*, 124558, https://doi.org/10.1016/j.jclepro.2020.124558.
28. Nkonyana, T.; Sun, Y.; Twala, B.; Dogo, E. Performance Evaluation of Data Mining Techniques in Steel Manufacturing Industry. *Procedia Manufacturing*, **2019,** *35*, 623-628, https://doi.org/10.1016/j.promfg.2019.06.004.
29. Giri, S.; Paul, P.; Mitra, P. Understanding the performance measurement of Indian steel Industry: A DEA approach. *Materials Today Proceedings*, **2022,** *48*, 1517-1522. https://doi.org/10.1016/j.matpr.2021.09.424.
30. Ianinno, V.; Denker, J.; Colla, V. An Application-Oriented Cyber-Physical Production Optimisation System Architecture for the Steel Industry. *IFAC-PapersOnLine*, **2022,** *55*, 60-65, https://doi.org/10.1016/j.ifacol.2022.04.170.
31. Sun, W.; Wang, Q.; Zhou, Y.; Wu, J. Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives. *Applied Energy* **2020,** *268*, 114946, https://doi.org/10.1016/j.apenergy.2020.114946.
32. Depczyński, R. MCDA based approach to supplier evaluation – steel industry enterprise case study. *Procedia Computer Science*, **2021,** *192*, 5081-5092, https://doi.org/10.1016/j.procs.2021.09.286.
33. Liu, W.; Zuo, H.; Wang, J.; Xue, Q.; Ren, B.; Yang, F. The production and application of hydrogen in steel industry. *International Journal of Hydrogen Energy*, **2021,** *46*, 10548-10569, https://doi.org/10.1016/j.ijhydene.2020.12.123.
34. Zhang, H.; Sun, W.; Li, W.; Ma, G. A carbon flow tracing and carbon accounting method for exploring CO2 emissions of the iron and steel industry: An integrated material–energy–carbon hub. *Applied Energy* **2022,** *309*, 18485, https://doi.org/10.1016/j.apenergy.2021.118485.
35. Nwachukwu, C.M.; Wang, C.; Wetterlund, E. Exploring the role of forest biomass in abating fossil CO2 emissions in the iron and steel industry – The case of Sweden. *Applied Energy* **2021,** *288*, 116558, https://doi.org/10.1016/j.apenergy.2021.116558.
36. De Souza, J.F.T.; & Pacca, S.A. Carbon reduction potential and costs through circular bioeconomy in the Brazilian steel industry. *Resources, Conservation and Recycling*, **2021,** *169*, 105517,https://doi.org/10.1016/j.resconrec.2021.105517.

37. Guo, Q.; & Tang, L. Modelling and discrete differential evolution algorithm for order rescheduling problem in steel industry. *Computers & Industrial Engineering*, **2019,** *130*, 586-596, https://doi.org/10.1016/j.cie.2019.03.011.
38. Han, Z.; Zhang, X.; Zhang, H.; Zhao, J.; Wang, W. A hybrid granular-evolutionary computing method for cooperative scheduling optimization on integrated energy system in steel industry. *Swarm and Evolutionary Computation*, **2022,** *73*, 101123, https://doi.org/10.1016/j.swevo.2022.101123.
39. Beham, A.; Raggl,S.; Hauder, V.A.; Karder, J.; Wagner, S.; Affenzeller, M. Performance, Quality, and Control in Steel Logistics 4.0. *Procedia Manufacturing* **2020,** *42*, 429-433, https://doi.org/10.1016/j.promfg.2020.02.053.
40. Goshin, T.; Vogel, M.; Flassig, R. Energy Technologies For Decarbonizing The Steel Processing Industry – A Numerical Study. *IFAC-PapersOnLine* **2022,** *55*, 1-5, https://doi.org/10.1016/j.ifacol.2022.07.001.