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ENVIRONMENTAL AND ECONOMIC DIMENSIONS OF THE TRANSITION TO GREEN STEEL IN SPAIN: THE CASE OF THE HYDNUM STEEL PROJECT IN PUERTOLLANO

Abstract

The paper is devoted to the analysis of the environmental and economic dimensions of the transition to green steel in Spain, with a focus on the case of Hydnum Steel in Puertollano. The study examines technological approaches to the decarbonization of the steel industry and analyzes their environmental potential, which lies in a significant reduction of CO_2 emissions and a decrease in dependence on fossil fuels. Particular attention is paid to the economic aspects of the transformation, including capital expenditures, dependence on energy prices, and the need for infrastructure development. It is determined that the transition to green steel creates new opportunities, such as the formation of a low-carbon products market, increased investment attractiveness, and the strengthening of Spain's and its regions' competitive positions. Based on the analysis of scientific and applied sources, it is established that Spain has significant potential for the development of green metallurgy due to its high share of renewable energy and an active hydrogen strategy. It is demonstrated that the project in Puertollano serves as a pilot model of industrial transformation, combining environmental goals, economic feasibility, and regional development. It is concluded that the successful implementation of the transition to green steel requires a comprehensive approach, including technological innovation, government support, and consideration of social aspects.

Keywords: green steel; decarbonization; steel industry; renewable energy; Spain; economic effects; environmental effects; Hydnum Steel; Puertollano.

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ЕКОЛОГІЧНІ ТА ЕКОНОМІЧНІ ВИМІРИ ПЕРЕХОДУ ДО ЗЕЛЕНОЇ СТАЛІ В ІСПАНІЇ: КЕЙС ПРОЄКТУ HYDNUM STEEL У ПУЕРТОЛЬЯНО

Анотація
Стаття присвячена аналізу екологічних та економічних вимірів переходу до зеленої сталі в Іспанії з акцентом на кейс Hydnum Steel у Пуертольяно. У роботі досліджено технологічні підходи до декарбонізації сталеливарної промисловості, та проаналізовано екологічний потенціал цих рішень, який полягає у значному скороченні викидів CO_2 та зменшенні залежності від викопного палива. Особливу увагу приділено економічним аспектам трансформації, включаючи капітальні витрати, залежність від вартості енергії та необхідність розвитку інфраструктури. Визначено, що перехід до зеленої сталі створює нові можливості, зокрема формування ринку низьковуглецевої продукції, підвищення інвестиційної привабливості та зміцнення конкурентних позицій Іспанії та її регіону. На основі аналізу наукових і прикладних джерел встановлено, що Іспанія має значний потенціал для розвитку зеленої металургії завдяки високій частці відновлюваної енергетики та активній водневій стратегії. Доведено, що проєкт у Пуертольяно виступає пілотною моделлю індустріальної трансформації, яка поєднує екологічні цілі, економічну доцільність та регіональний розвиток. Зроблено висновок, що успішна реалізація переходу до зеленої сталі потребує комплексного підходу, що включає технологічні інновації, державну підтримку та врахування соціальних аспектів.

Ключові слова: зелена сталь; декарбонізація; сталеливарна промисловість; відновлювана енергетика; Іспанія; економічні ефекти; екологічні ефекти; Hydnum Steel; Пуертольяно.

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Introduction
The transition to green steel production is a promising pathway for the decarbonization of the European Union's industry. The steel sector plays a system-forming role in the economy, providing essential materials for construction, the automotive industry, and machinery manufacturing, while remaining one of the largest sources of industrial greenhouse gas emissions. In this context, Spain's experience is particularly illustrative, as the country has structural preconditions for a faster transition to low-carbon steel production.

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According to EUROFER, total steel production in the European Union prior to the energy crisis amounted to approximately 140 million tonnes per year, with a mixed production structure: about 60% of steel is produced using the blast furnace–basic oxygen furnace (BF-BOF) route, while around 40% is produced via electric arc furnaces (EAF) (EUROFER, 2023). Spain occupies a distinctive position, as the share of steel production through electric arc furnaces in the country is about 70–75%, one of the highest levels in the EU. This structure is of fundamental importance for decarbonization, since EAF technology, particularly when powered by renewable electricity, is associated with significantly lower CO_2 emissions compared to traditional blast furnace processes.

Steel demand in the EU is primarily driven by sectors such as construction (approximately 35%), the automotive industry (~20%), and machinery manufacturing (~15%) (EUROFER, 2023). This indicates a strong dependence of the sector on macroeconomic conditions, which in turn affects the investment capacity of companies in decarbonization efforts.

According to estimates by the International Energy Agency, global CO_2 emissions reached approximately 37 billion tonnes in 2023, with the steel industry accounting for about 7–9% of these emissions. The high carbon intensity is primarily explained by the use of coke as a reducing agent in blast furnace production, as well as the energy-intensive nature of steelmaking processes. On average, the production of one tonne of steel using conventional technology results in emissions of around 1.8–2.2 tonnes of CO_2 (International Energy Agency, 2023). In this context, the decarbonization of the steel industry is a critical condition for achieving the EU's climate targets.

The main pathways for reducing emissions in the steel sector include expanding the use of electric arc furnaces (EAF) based on secondary raw materials (scrap), implementing direct reduced iron (DRI) technologies using hydrogen, and applying carbon capture and storage (CCUS) technologies. Spain has significant potential for accelerated decarbonization of the sector. This is обусловлено a high share of electric arc furnace production in the steel industry structure, the active development of renewable energy—particularly solar and wind—and the implementation of strategic initiatives in the field of green hydrogen. Moreover, Spain is considered a promising hub for green hydrogen production, which is a key element in the decarbonization of the steel industry (ABC, 2023). Therefore, the ecological transformation of the steel sector in Spain may proceed at a faster pace compared to countries where blast furnace production, characterized by higher carbon intensity, predominates.

Alongside clear environmental benefits, the transition to green steel is accompanied by significant economic challenges. According to industry estimates, the modernization of the EU steel sector by 2050 will require investments amounting to tens of billions of euros (EUROFER, 2023). The main cost drivers include the need to upgrade production facilities, which requires substantial investments in new technologies and equipment. Another key factor is the development of infrastructure for hydrogen production, storage, and transportation, as hydrogen is considered a core energy carrier in decarbonized processes. Additional pressure on production costs arises from the high price of renewable electricity during certain periods, driven by its variability and market fluctuations. Altogether, this leads to increased capital expenditures (CAPEX), representing one of the main economic barriers to the sector's transformation. In the short term, this results in higher production costs: according to various estimates, green steel may be 20–50% more expensive than conventional steel. This creates risks of reduced competitiveness on the global market, especially in the context of imports of cheaper steel from countries with less stringent climate regulations.

At the same time, the transition to green steel also opens up significant economic opportunities. In particular, the introduction of the Carbon Border Adjustment Mechanism (CBAM) helps protect European producers from competition with countries that have less stringent environmental standards. Access to financial resources under the European Green Deal also acts as an important driver, supporting investments in industrial decarbonization. In addition, new markets for low-carbon products are emerging, creating opportunities for exports and innovation. Taken together, these factors contribute to increased

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investment attractiveness of the steel sector and strengthen its long-term competitiveness. For Spain, an additional advantage lies in the relatively low cost of renewable energy, which may reduce production costs of green steel in the long run.

The European Union's plan for the development of renewable (green) hydrogen (European Commission, 2020) has been generally positively received by Spanish businesses, which view it both as an important step toward decarbonization and as an opportunity for industrial development. In this context, Spain is positioned as a potential leader in green hydrogen production due to its strong solar and wind energy potential, favorable climatic conditions, and export opportunities. Green hydrogen contributes to reducing dependence on fossil fuels and enables significant emission reductions. Its implementation is also important for the chemical and energy sectors, reinforcing the systemic effect of decarbonization across the economy. Overall, the EU's hydrogen strategy is seen as a strategic opportunity to strengthen Spain's position in industrial decarbonization and to support the development of new markets (eldiario.es, 2020).

Literature review

The issue of transitioning to green steel is активно studied in contemporary scientific literature from multiple perspectives, including technological, economic, environmental, and social dimensions. A synthesis of existing publications provides a comprehensive understanding of the opportunities and constraints associated with the decarbonization of the steel industry.

Most studies focus on the technological foundations of green steel production. The main approaches include hydrogen-based direct reduced iron (H_2-DRI) and the use of electric arc furnaces (EAF). Research shows that these technologies can significantly reduce CO_2 emissions compared to the traditional blast furnace–basic oxygen furnace route. In particular, Teixeira (2025) notes that emission reductions can reach up to 90% when renewable energy is used. Similar conclusions are presented by Trinca et al. (2023), who emphasize that hydrogen is the most environmentally effective reducing agent among available alternatives. Rosner et al. (2023) also highlight the high potential of hydrogen-based technologies, while noting their high energy intensity and dependence on the development of renewable energy. Thus, the technological feasibility of green steel production is generally confirmed, although its effectiveness is closely linked to the decarbonization of the energy sector.

A significant body of research also emphasizes the economic aspects of this transition. Bhaskar et al. (2022) demonstrate that hydrogen-based steelmaking is technically feasible but involves substantially higher costs compared to conventional production. Similar findings are reported by Rosner et al. (2023), who associate increased production costs with the high price of hydrogen and electricity. Teixeira (2025) highlights that the economic viability of green steel largely depends on policy support, including carbon pricing mechanisms and financial incentives. At the same time, Leuratti et al. (2025) add that the use of green hydrogen can enhance the resilience of the industry to energy price volatility by reducing dependence on imported fossil fuels. This suggests that green steel can be viewed not only as an environmental solution but also as a strategically beneficial option in the long term.

Market dynamics and demand for green steel are also widely discussed in the literature. Watari and McLellan (2024), using a scenario-based approach, show that demand for low-carbon steel may grow significantly, although its scale depends on climate policy and the development of the hydrogen economy. Lundmark et al. (2024) argue that the adoption of new technologies reshapes market competition. Countries with access to low-cost renewable energy or alternative resources gain competitive advantages, while others may face the risk of losing market positions due to rising costs. This indicates the uneven nature of the global transition to green steel.

At the same time, most studies identify significant barriers to scaling up green technologies. The main challenges include the high cost of hydrogen, the need for infrastructure development, and limited availability of renewable energy (Teixeira, 2024). Trinca et al. (2023) note that transitional solutions, such as gas mixtures, may be used in the short term to reduce emissions at lower cost. Furthermore, the lack of

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timely investment in energy diversification increases the vulnerability of the industry to energy crises, highlighting the need for a systemic approach to transformation (Leuratti et al., 2024).
An important dimension of the transition to green steel concerns social aspects. Unlike techno-economic studies, Baasch et al. (2024) analyze the process through the lens of the "just transition" concept. They show that decarbonization has uneven impacts on different social groups: while it creates innovation and opportunities for businesses, it may pose risks for workers, including job losses and the need for reskilling. This demonstrates that green transformation is not only a technological process but also a socio-political one. Additionally, the literature highlights the systemic impact of climate change on the economy and industry. In particular, Nagaichuk et al. (2020) show that the climate crisis leads to an increase in the frequency of natural disasters, economic losses, and business risks, necessitating adaptation through new approaches to risk management.
It should also be noted that much of the academic literature is based on examples from Northern European countries (such as Sweden, Norway, and Germany), where pilot projects in green metallurgy have already been implemented. In this context, there is a relative lack of academic research focused on Spain, which can be explained by the early stage of such projects in the country. Instead, the Spanish context is currently more widely represented in analytical and journalistic sources reflecting practical developments in the sector. In particular, publications by ABC emphasize Spain's competitive advantages in green steel development due to its strong renewable energy potential and capacity for green hydrogen production. Reports by eldiario.es highlight the positive perception of the EU hydrogen strategy among businesses and the country's potential to become a leader in this field. Regional sources, such as La Comarca de Puertollano, provide insights into specific projects, including the construction of the Hydnum Steel plant in Puertollano, offering valuable empirical evidence of industrial transformation. Therefore, Spanish journalistic and analytical sources complement academic literature by providing practical insights into the current development of green metallurgy, indicating that Spain is in an active phase of building this industry and highlighting the need for further academic research in this area.

Aims and Objectives

The aim of the article is to provide a comprehensive analysis of the environmental and economic dimensions of the transition to green steel in Spain, as well as to assess the potential and challenges of this process using the case of the Hydnum Steel project in the city of Puertollano.
To achieve this aim, the following objectives are defined: to analyze modern technological approaches to the decarbonization of the steel industry; to examine the economic and environmental aspects of the transition to green steel; to identify the factors influencing the competitiveness of the industry under decarbonization conditions; to consider a practical case of green metallurgy implementation in Spain; and to assess the socio-economic impacts of the transition on regional development.
The implementation of these objectives makes it possible to form a comprehensive understanding of the prospects for the development of green steel in Spain and its significance in the context of the European industrial decarbonization.

Methods

This study employs a comprehensive approach that combines general scientific and specialized analytical methods to examine the environmental and economic aspects of the transition to green steel in Spain. The theoretical foundation of the research is based on the analysis of academic publications related to the decarbonization of the steel industry, the development of hydrogen energy, and the formation of low-carbon product markets. For this purpose, methods of systematization and synthesis of literature sources were applied, enabling the identification of key approaches to green steel production, as well as the main trends and constraints in the sector's development.

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To analyze industry-specific features, structural analysis was used to determine the characteristics of the Spanish steel industry and its position within the European context. The empirical component of the study was carried out using the case study method, which involves a detailed examination of the Hydnum Steel project in Puertollano as an example of green metallurgy implementation. This made it possible to assess the real conditions, opportunities, and challenges of industrial transformation at the regional level. In addition, a descriptive method was applied to interpret statistical data and to formulate conclusions regarding the environmental and economic effects of the transition to green steel.

The use of these methods ensured the comprehensiveness of the research and allowed for well-grounded conclusions on the prospects for the development of green metallurgy in Spain.

Results

Within the broader European transition to a low-carbon economy, regional industrial initiatives that combine innovative technologies, energy transformation, and government support are gaining particular importance. Spain, which already has structural advantages in the development of renewable energy and electric arc steel production, is gradually forming new industrial hubs focused on green steel production. One of the most illustrative examples of this transformation is the construction project of a metallurgical complex in the city of Puertollano, which is considered a strategic center for the development of the hydrogen economy and decarbonized industry.

The city of Puertollano, located in the autonomous community of Castile-La Mancha, has historically been an important energy and industrial center in Spain, particularly due to the development of coal and oil refining industries. In the context of the energy transition and the strengthening of the European Union's climate policy, the city is gradually transforming into a hub of the new "green" industry. Currently, Puertollano is positioned as one of the key sites for the development of renewable energy and hydrogen technologies. The region has significant potential for green electricity generation due to high solar radiation levels and the development of wind energy, creating favorable conditions for establishing a full industrial value chain for green hydrogen production and its subsequent use in metallurgy (eldiario.es, 2020).

An important element of this transformation is the development of a so-called "hydrogen hub" or hydrogen valley, which integrates hydrogen production, storage, and utilization across various sectors of the economy. According to expert assessments and regional initiatives, Puertollano has all the prerequisites to become one of such centers in Europe, as evidenced by the active involvement of local authorities and industrial companies in the development of the relevant infrastructure (eldiario.es, 2020). A significant factor reinforcing the city's role in the context of green steel is the implementation of large-scale investment projects in the steel industry. In particular, the construction of a new metallurgical facility based on hydrogen use is considered an important step toward establishing a full-fledged green steel production ecosystem in Spain.

The formation of a new industrial profile of Puertollano begins with the implementation of a large-scale metallurgical project by Hydnum Steel, which represents one of the first major examples of green steel production in Spain. The project involves the construction of a modern steelmaking complex focused on low-carbon technologies and integrated into the country's emerging hydrogen infrastructure. According to available estimates, the total investment amounts to approximately €1 billion, making it one of the largest industrial investments in the region in recent decades (Ayuntamiento de Puertollano, 2024). Importantly, the project has been granted the status of a strategic or "project of special interest," highlighting its significance not only for the local economy but also for national industrial policy (eldiario.es, 2024).

Particular attention is paid to the project's infrastructure component. To meet the energy demands of the future plant, the development of electrical capacity is planned, including the use of the Brazatortas node, where significant generation capacity is expected to be connected. This illustrates the close interconnection between metallurgical development and energy infrastructure, which is a defining feature of green steel projects. Moreover, the implementation of Hydnum Steel is already contributing to the formation of a

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broader innovation ecosystem in the region. The emergence of new companies and technological centers, particularly in the fields of digital solutions and artificial intelligence, demonstrates the project's multiplier effect on the local economy (eldiario.es, 2024).

A key element in the operation of the future Hydnum Steel plant in Puertollano is ensuring stable access to green hydrogen and renewable electricity. These resources form the basis of a new energy model for the steel industry aimed at minimizing CO_2 emissions. In this context, hydrogen serves as the primary reducing agent in the direct reduced iron (DRI) process, replacing traditional fossil-based inputs such as coke. This enables a near-elimination of direct carbon emissions at one of the most carbon-intensive stages of steel production. The effectiveness of this technology depends directly on whether the hydrogen is "green," meaning it is produced using renewable energy sources. In this regard, Spain – and particularly the Castile-La Mancha region – has significant competitive advantages. Due to the advanced development of solar and wind energy, the country is capable of providing relatively low-cost electricity for hydrogen production through electrolysis, thereby enabling the creation of a full value chain (eldiario.es, 2020).

The development of hydrogen infrastructure in the region is taking place within the broader concept of a "hydrogen valley," which involves the integration of hydrogen production, transportation, and consumption within a single region. This approach enhances resource efficiency and stimulates the development of related industries. Puertollano is considered one of the potential centers of such a model in Europe.

The implementation of the Hydnum Steel project follows a phased approach: the preparatory phase began in 2023–2024, while the active stage of construction and infrastructure development is expected to take place in 2025–2026. The commissioning of the plant is anticipated by the end of the decade, approximately in 2027–2028.

The project has significant economic potential at both regional and national levels, primarily due to large-scale investments, making it one of the largest industrial investments in the region's recent history (Ayuntamiento de Puertollano, 2024). These investments contribute not only to the modernization of the industrial base but also to the creation of new economic dynamics in the region. One of the key effects is job creation. The construction and subsequent operation of the facility are expected to involve a substantial workforce, both directly within the plant and indirectly in related sectors such as logistics, energy, and infrastructure services. This is particularly important for regions with a traditional industrial specialization that have undergone transformation due to the decline of carbon-intensive industries.

In addition to direct economic benefits, the project has a pronounced multiplier effect. Already at the implementation stage, there is evidence of the attraction of new companies, particularly in the fields of digital technologies and artificial intelligence. For example, the establishment of new innovation units cooperating with the metallurgical sector contributes to the digitalization of production processes (eldiario.es, 2024). This indicates the formation of a broader innovation ecosystem around the steel complex. The presence of a large industrial project aligned with modern environmental standards sends a positive signal to other investors and stimulates the development of related sectors. In the long term, increased investment attractiveness may lead to the formation of a new industrial cluster focused on green steel production and hydrogen technologies.

At the same time, economic challenges must also be considered. The high capital intensity of the project, dependence on energy costs, and the need for infrastructure development may affect its profitability in the short term. However, with effective implementation and support from the government and the European Union, these factors may be offset by long-term benefits, including the strengthening of Spain's competitive position in the low-carbon products market.

The implementation of the Hydnum Steel project in Puertollano has not only industrial and economic significance but also a substantial impact on the local community. This impact is комплексний and includes both positive effects and potential risks for the city's residents (Table 1).

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Table 1 – Socio-economic impact of the green steel project in Puertollano

Area of impact	Indicator (KPI)	Positive effect	Negative effect / risk	Time horizon of effect	Level of impact
Employment	Number of jobs	Creation of new jobs	Dependence on a single employer	Short- and medium-term	Local
Urban economy	Investment volume (€)	Increase in investment (~€1 billion)	Inflation, rising cost of living	Short- and long-term	Regional
Innovation	Number of R&D projects	Development of technologies, AI, digitalization	Unequal access to new technologies	Medium-term	Regional
Environment	Emission levels (CO_2, NOx)	Reduction of pollution	Local industrial impacts	Long-term	Local + global
Energy	Share of renewables (%)	Development of hydrogen economy	Dependence on energy prices	Medium- and long-term	National
Social sphere	Quality of life index	Improvement of living conditions	Social imbalances	Long-term	Local
Infrastructure	Volume of infrastructure investments	Urban modernization	Pressure on resources	Short- and medium-term	Local
Long-term development	Regional competitiveness index	Formation of an industrial/hydrogen hub	Dependence on policy	Long-term	Regional + EU

Source: compiled by the author

One of the significant advantages presented in Table 1 is the creation of more than 400 new jobs at the plant itself (Ayuntamiento de Puertollano, 2024). In addition, the construction and operation of the steel complex are expected to stimulate employment in related sectors such as transport, energy, infrastructure services, and the service industry. This is particularly important for Puertollano, which has previously undergone structural industrial changes and requires new sources of economic development. Another positive effect is the economic revitalization of the city. Large-scale investments contribute to the development of local infrastructure, the growth of small and medium-sized enterprises, and increased tax revenues for the local budget. The formation of a new industrial cluster may ensure long-term economic stability in the region.

An additional benefit lies in technological modernization and innovation development. The emergence of high-tech production stimulates the attraction of new companies, including those operating in digital technologies and artificial intelligence, thereby enhancing workforce skills and contributing to human capital development (eldiario.es, 2024). Moreover, the environmental effect of the project has a direct impact on the quality of life of the population. The transition to cleaner technologies reduces air pollution levels, which is particularly relevant for industrial regions, thereby improving public health and overall environmental conditions.

However, the implementation of the project is also associated with certain challenges for the local community. One of these is the potential dependence of the city on a single large industrial project. In the event of economic difficulties or delays in implementation, this may negatively affect employment and

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household incomes. Another factor is the possibility of socio-economic imbalances. For example, increased investment activity may lead to a higher cost of living, including rising housing and service prices, which could place additional pressure on local residents. Despite the environmental advantages, any large-scale industrial production is associated with certain environmental risks, such as noise, water resource use, and landscape changes, which may raise public concerns. Equally important is the issue of workforce adaptation. The transition to high-tech production requires new skills and qualifications, which may create difficulties for workers employed in traditional industries and necessitates additional investment in education and vocational training.

The implementation of the Hydnum Steel project in Puertollano is largely driven by active political and institutional support at multiple levels of governance: local, regional, national, and European. Such support is critically important given the high capital intensity, technological complexity, and strategic nature of green metallurgy projects. At the national level, the Spanish government considers the development of green steel production as part of a broader strategy for industrial decarbonization and energy independence. One practical manifestation of this support is the allocation of significant energy capacity for the future plant, particularly through the Brazatortas node, which ensures grid connection and creates conditions for stable energy supply (La Comarca de Puertollano, 2024). At the regional level, the government of Castile-La Mancha actively supports the project, viewing it as a driver of economic development and industrial modernization. The designation of the project as one of "special interest" highlights its priority status and facilitates administrative procedures related to construction and operation (eldiario.es, 2024). At the local level, the authorities of Puertollano also play an active role in promoting the project, emphasizing its importance for long-term urban development and job creation. Municipal support is reflected both in facilitating investments and in communication with the public, which is essential for ensuring the project's social legitimacy (Ayuntamiento de Puertollano, 2024).

Furthermore, the Hydnum Steel project is embedded within the broader framework of European Union policies, particularly the European Green Deal and the hydrogen strategy. Access to EU financial instruments and support programs creates additional opportunities for its implementation and reduces investment risks.

The project also has significant potential in terms of reducing the environmental impact of the steel industry. This is primarily связано with the implementation of technologies that allow for a substantial reduction in greenhouse gas emissions during steel production. The project contributes to the achievement of national and European climate goals, including emission reduction targets and the development of a low-carbon economy. In this regard, Puertollano serves as a practical example of the implementation of sustainable development principles in the industrial sector. At the same time, the environmental impact largely depends on the energy sources used for hydrogen production and for powering electric arc furnaces. Only the use of renewable energy ensures the maximum reduction of emissions and the truly "green" nature of production.

A summary of the economic and environmental effects of the project is presented in Table 2.

Table 2 – Economic and environmental effects of the green steel project in Puertollano

Assessment area	Indicator (KPI)	Economic effects	Environmental effects
Investments	Capital investment volume (€ million)	~€1 billion invested in the project	Investments in clean technologies reduce environmental costs in the future
Production cost	Steel production cost (€/t)	20–50% higher compared to conventional steel	Includes an "environmental premium" for low emissions
CO_2 emissions	t CO_2 / t steel	Indirect impact through decarbonization costs	Reduction from ~1.8–2.2 to <0.5 t CO_2/t steel

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Energy intensity	MWh / t steel	High dependence on electricity prices	Reduction through efficient technologies and renewables
Employment	Number of jobs	Growth in employment (direct and indirect)	Improvement of socio-environmental living conditions
Innovation activity	Number of new technologies / R&D projects	Development of DRI, hydrogen, and digital solutions	Implementation of environmentally friendly technologies
Energy structure	Share of renewables (%)	Reduced dependence on energy imports	Increase in the share of renewable energy sources
Market position	Share of "green steel" (%)	Formation of a new market segment	Compliance with EU standards (ESG, CBAM)
Environmental impact	Pollution index (NO_x, SO_2, PM)	Indirect impact through modernization	Reduction of local pollution
Long-term efficiency	ROI / payback period	Long-term return under stable policy conditions	Sustainable reduction of emissions and environmental impact

Source: compiled by the author

Despite its significant potential and strategic importance, the implementation of the Hydnum Steel project in Puertollano is accompanied by a number of challenges and risks typical of the transformation of carbon-intensive industries (see Table 2). These factors may affect both the pace of project implementation and its long-term economic efficiency. One of the key challenges is the high cost of green hydrogen, which forms the basis of the new technological model of steel production. At present, its production remains significantly more expensive than traditional energy carriers, increasing overall production costs. Although prices are expected to gradually decline with technological development and scaling, in the short term this creates substantial economic constraints.

Another critical issue is infrastructure development. The effective operation of hydrogen-based production requires well-developed systems for hydrogen generation, storage, and transportation, as well as reliable electricity grids to ensure stable energy supply. While progress is being made in the region (particularly through the development of energy nodes and the connection of new capacities) full infrastructure readiness will require considerable time and investment (La Comarca de Puertollano, 2024).

An additional challenge is technological uncertainty. As many green metallurgy solutions are still in the scaling phase, there are risks related to their efficiency, reliability, and commercial viability. This is especially relevant for the large-scale use of hydrogen in industrial processes. Another important factor is dependence on political and regulatory support. The implementation of such projects largely relies on government incentives, subsidies, and a favorable regulatory framework. Changes in policy or reductions in funding may negatively affect the pace of development and the financial stability of the project.

Furthermore, global competition must be taken into account. Steel producers in other regions with less stringent environmental regulations may offer lower-cost products, posing risks to the competitiveness of European companies. Mechanisms such as the Carbon Border Adjustment Mechanism (CBAM) are intended to address this issue; however, their effectiveness remains to be assessed in the long term.

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Discussion

The obtained results indicate that the transition to green steel in Spain should be considered a complex and multidimensional process that combines technological innovations, economic transformations, and institutional changes. The analysis shows that Spain's existing structural advantages – particularly the high share of electric arc furnace production and the significant potential of renewable energy – create favorable conditions for accelerating the decarbonization of the steel industry. In this context, the case of Hydnum Steel in Puertollano confirms that the practical implementation of a green metallurgy model is feasible, provided there is a combination of access to renewable resources, investment support, and effective policy.

The findings are consistent with the scientific literature regarding the high cost and complexity of implementing hydrogen-based technologies. Previous studies show that the economic efficiency of green steel production largely depends on the cost of hydrogen and electricity, as well as on the availability of infrastructure. In the case of Spain, these factors are partially offset by favorable natural conditions and the development of renewable energy; however, they remain significant constraints in the short term. This confirms the need for government support and coordination at the European Union level.

Particular attention should be paid to the regional dimension of the transformation. The study shows that the project in Puertollano has a significant multiplier effect, contributing to the formation of an innovation ecosystem, the development of related industries, and job creation. In this sense, green metallurgy serves not only as a tool for decarbonization but also as a driver of regional development. At the same time, there are risks associated with the region's economic dependence on a single large industrial project, as well as potential socio-economic imbalances, which require consideration of the principles of a just transition.

The results also highlight the importance of integrating green steel projects into the broader hydrogen economy. The development of so-called "hydrogen valleys" creates conditions for efficient resource use and enhanced competitiveness. In this context, Puertollano can be considered a pilot example of such integration.

The study identifies several limitations. In particular, most assessments are based on projected data, as the project is still under development. Moreover, the limited number of academic studies focusing specifically on the Spanish context complicates comparative analysis. This defines directions for future research, which should focus on evaluating the actual effectiveness of green steel projects after their implementation, as well as analyzing long-term socio-economic impacts.

Thus, the results confirm that the transition to green steel is not only an environmental necessity but also a complex economic and social process, the success of which depends on the coherence of technological, energy, and policy decisions.

Conclusions

The conducted analysis shows that the transition to green steel in Spain has a complex and multidimensional nature. On the one hand, it is an objective environmental necessity driven by the high level of emissions in the steel industry and the country's climate commitments within the framework of European Union policy. On the other hand, this process is associated with significant economic costs, technological uncertainty, and the need for large-scale investments. At the same time, the structural characteristics of the Spanish steel industry create the conditions for the formation of long-term competitive advantages. Therefore, the transition to green steel can be viewed not only as a response to environmental challenges but also as a strategic opportunity to strengthen Spain's position in European and global markets.

The case of Hydnum Steel in Puertollano demonstrates the practical implementation of this transformation, combining technological innovation, the development of hydrogen energy, and regional economic growth. The project represents a comprehensive industrial initiative that contributes to the formation of a new industrial profile for the region and creates the conditions for the development of a hydrogen hub. Puertollano is gradually transforming into a center of green metallurgy, where favorable natural conditions,

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investment activity, and government support converge, allowing it to be considered a pilot platform for scaling innovative solutions across Europe. The integration of the project into the broader concept of the hydrogen economy further enhances its significance, as it contributes not only to the reduction of CO_2 emissions but also to the development of new energy markets and the strengthening of energy security.
At the same time, the implementation of such projects is accompanied by a number of challenges, including high capital costs, dependence on infrastructure development, the cost of green hydrogen, and the need for stable national and European support. It is also important to consider the social aspects of the transformation, particularly its impact on employment and the need for workforce reskilling. Thus, the transition to green steel in Spain is both a complex and promising process, the success of which depends on the ability to combine technological innovation, economic feasibility, and social balance, ultimately determining the country's role in shaping a new model of decarbonized industry.

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ADDITIONAL INFORMATION

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