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TRANSFORMATION OF THE STEEL INDUSTRY: STRATEGIES FOR CLIMATE-NEUTRAL PRODUCTION

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Abstract

Primary steel production is currently the dominant process in global steel production, but is characterized by high energy consumption and significant CO_2 emissions. In Germany, around 70% of crude steel was produced using primary steel production in 2015, while 30% came from secondary steel production. The traditional blast furnace route, which is based on the reduction of iron ore using coal, is responsible for around 28% of total industrial emissions in Germany. Given the need for a sustainable transformation of the steel industry, alternative processes are being researched to drastically reduce CO_2 emissions.

One promising approach is hydrogen-based direct reduction, in which iron ore is reduced using green hydrogen instead of coal. This enables almost CO_2-free steel production, but requires sufficient availability of renewable energy and an extensive hydrogen infrastructure. Other alternatives include increasing the recycling of steel scrap in electric arc furnaces and innovative production processes such as the electrolytic reduction of iron ore. Secondary steel production already represents a lower-CO_2 alternative, as electric arc furnaces are increasingly being operated with electricity from renewable energy sources.

The transformation of the steel industry requires technological innovation, extensive investment and regulatory and economic support. The combination of hydrogen-based direct reduction, increased steel scrap recycling and the development of new emission-free processes represents a promising strategy for achieving climate neutrality. In the long term, political measures, research funding and infrastructure investments are essential to ensure the competitiveness and sustainability of steel production.

Keywords

Green steel, decarbonization, steel production, climate-neutral production, transformation

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Problem

The transformation of the steel industry towards climate-neutral production by 2045 poses a considerable challenge due to CO_2 emissions and the high process temperatures required. Traditional processes such as the blast furnace process are highly carbon-intensive and cause significant CO_2 emissions. Innovative approaches such as direct reduction with hydrogen offer potential for reducing emissions, but require considerable investment and the development of a corresponding hydrogen infrastructure. In addition, large amounts of renewable electricity are required for the largely greenhouse gas-free production of hydrogen (Prognos 2023). Companies such as ThyssenKrupp have set themselves the goal of producing climate-neutral steel by 2045 at the latest. An interim goal is to produce three million tons of CO_2-neutral steel per year by 2030. This transformation is to be achieved by means of direct reduction, in which the process-related greenhouse gas emissions are largely eliminated by using hydrogen instead of coal. This technology incurs considerable additional costs compared to conventional processes (ThyssenKrupp 2023).

Furthermore, a long-term political framework is necessary to give the steel industry security for the necessary investments (GermanWatch 2023). Overall, the decarbonization of the steel industry is a complex undertaking that requires close cooperation between industry, politics and science in order to achieve the climate targets that have been set. This collaboration requires innovative solutions and the development of suitable infrastructures. This article examines the particular challenges facing the steel industry in the transformation to climate-neutral production and discusses potential solutions. The aim is to contribute to the scientific and practical debate on how to shape the transformation towards a climate-neutral industry.

Relevance of the chosen topic

The transformation of the energy-intensive steel industry towards climate-neutral production is one of the key challenges to achieving the climate targets. The steel industry was responsible for 23% of greenhouse gas emissions in 2023 (Wirtschaftsvereinigung Stahl 2024). This figure underlines the importance of the steel industry in reducing industrial emissions. The need for innovative technologies and political framework conditions for climate-neutral production is therefore essential. The steel industry plays a key role in the decarbonization of industrial production (Umweltbundesamt 2023).

Analysis of recent research and publications

Primary steel production is particularly energy-intensive and dominates steel production. According to the Federal Ministry for Economic Affairs and Climate Action, around 70% of the crude steel produced in Germany alone was produced via primary steel production in 2015, while 30% was obtained from steel scrap via secondary steel production. This distribution underlines the importance of primary steel production for the German steel industry and the associated challenges in reducing CO_2 emissions (Bundesministerium 2023). Steel is mainly produced using two processes (Energiebilanzen 2023):

- **Primary steel production (blast furnace process**): In this traditional process, iron ore is fed into the blast furnace together with coke and aggregates. The coke serves as a reducing agent to remove the oxygen from the iron ore, resulting in liquid pig iron. This pig iron is then processed into steel in the converter, where unwanted by-elements are removed and the desired alloying elements are added.
- **Secondary steel production (electric arc furnace):** This process is based on the processing of steel scrap. The scrap is melted down in an electric arc furnace and processed into new steel. This process is less energy-intensive and therefore produces lower CO_2 emissions than the blast furnace process. Current developments are aimed at reducing CO_2 emissions in steel production.

One innovative approach is the direct reduction of iron ore using hydrogen instead of coke. This produces water instead of CO_2 as a by-product. However, this process is still under development and requires considerable investment in the infrastructure for green hydrogen.

Primary steel production is currently the leading process in steel production. Iron ore is processed into pig iron using coal as a reducing agent and energy source. This process is associated with considerable CO_2 emissions. According to the Competence Centre for Climate Protection in Energy-Intensive Industries, steel production generates over 50 million tons of CO_2 every year, which corresponds to around 28% of total industrial emissions. A large proportion of these emissions are process-related and result from the combustion of coal (Klimaschutzindustrie 2025). In view of the high CO_2 emissions from the blast furnace route, alternative methods for reducing emissions are being researched. CO_2 emissions can be significantly reduced by using green hydrogen. However, this process is still under development and requires considerable investment in infrastructure and technology (Fraunhofer IKTS 2025). The transformation of the steel industry towards climate-neutral production processes is technically possible, but is subject to various conditions, including the availability of green hydrogen, economic framework conditions and political support.

In contrast, in secondary steel production, crude steel is produced in an electric arc furnace by casting iron scrap. As around 50% of the electricity for the electric arc furnace in the electricity mix in 2023 was already generated from renewable energies (Energiebilanzen 2023) and must be climate-neutral by 2045 at the latest, the secondary steel route is easy to decarbonize. CO_2 emissions can already be significantly reduced through the use of electric steel furnaces. A study by the Federal Environment Agency emphasizes that increasing the use of scrap and decarbonizing electric steel production are key measures on the way to a climate-neutral steel industry (Umweltbundesamt 2024).

Hydrogen-based direct reduction of iron ore to sponge iron in a shaft furnace is currently emerging as the most promising alternative route to primary steel production. In this process, iron ore pellets are directly reduced to meltable sponge iron. (Wirtschaftsvereinigung Stahl 2025). This process enables almost CO_2-free steel production, provided that the hydrogen used is produced in a climate-neutral way. Hydrogen-based direct reduction is therefore a key building block in the transformation of the steel industry towards climate-neutral production processes.

Hydrogen is used as a reducing agent instead of coal, which can be produced in an almost climate-neutral way. The sponge iron produced is then refined into crude steel using a classic converter with the help of green electricity. This reduces the carbon footprint by around 97% from 1.7 tons of CO2 to around 0.05 tons of CO2 per ton of crude steel compared to the blast furnace route. Reducing the carbon footprint in steel production through the use of green hydrogen in direct reduction is a key topic of current research. A 2021 study by the Fraunhofer Institute for Ceramic Technologies and Systems analyses the potential of hydrogen-based direct reduction and highlights its importance for the decarbonization of the steel industry. This study provides a comprehensive overview of the technological approaches and the associated CO_2 savings potential in steel production (Fraunhofer IKTS 2021).

Other alternatives to primary steel production include the electricity-based electrolysis of iron ore dissolved in caustic soda with subsequent further processing into crude steel. Although this process is theoretically more energy efficient than direct reduction, it is still under development and it is unclear when the first commercial plants can be built. Another innovative alternative to the blast furnace route is the electricity-based electrolysis of iron ore dissolved in caustic soda. This process has the potential to extract iron directly from oxidic compounds while avoiding CO_2 emissions. Although it theoretically has a higher energy efficiency than direct reduction, it is currently still in the development phase. It is unclear when the first commercial plants can be built (Neues Deutschland 2024). These developments demonstrate the steel industry's efforts to reduce CO_2 emissions and establish more sustainable production methods.

CO_2 utilization and storage are considered potential methods for decarbonizing the steel industry. However, these processes are considered outdated technologies and are inferior to the direct reduction process in terms of energy efficiency and on sight. The production process in combination with green hydrogen enables a direct reduction of the iron ore and avoids the generation of CO_2 emissions during the production process. It is considered a more efficient and environmentally friendly alternative (Holtz et al. 2023). The energy required for this could be partially covered by natural gas before switching to 100% climate-neutral energy sources such as electricity, hydrogen and biomass from 2040 onwards (Deutscher Wasserstoffverbund 2025).

Purpose of the article

The aim of the study is to identify the most important aspects and characteristics of the transformation to climate-neutral steel production. In order to achieve the formulated goal, the following tasks need to be solved:

- Examination of the nature of steel production and its underlying methods, namely primary and secondary steel production;
- Consideration of the basic principles of the concepts mentioned;
- Analysis of the advantages and disadvantages of the methodologies;
- Discussion and development of strategies for implementation in the companies.

Presentation of the main research material and results

In view of the high CO_2 emissions associated with the traditional blast furnace route, alternative production processes must be developed and implemented. The following three strategies represent key approaches to the sustainable transformation of the steel industry:

Strategy I: Hydrogen-based direct reduction as a key technology The decarbonization of the steel industry requires innovative production processes. One of the most promising alternatives to conventional primary steel production is the direct reduction of iron ore using green hydrogen. This process replaces coal as a reducing agent with hydrogen, producing only water vapor as a by-product instead of CO_2. Studies show that hydrogen-based direct reduction can reduce emissions in primary steel production by up to 97%. The prerequisite is that the hydrogen used comes from renewable energy sources. The widespread implementation of this technology requires the development of a broad hydrogen infrastructure such as pipelines and suitable storage systems. In addition, economic competitiveness must be ensured. This requires targeted funding programs and appropriate CO_2 pricing to make green steel production financially attractive.

Strategy II: Promoting recycling and strengthening secondary steel production: Another key approach to CO_2 reduction in the steel industry is the increased use of recycled steel scrap. Electric arc furnace technology enables a significant reduction in CO_2 emissions as it is based on recycled steel scrap as a raw material. This process requires less energy than primary steel production and can be operated with almost zero emissions thanks to the use of renewable electricity. In order to increase the share of the secondary steel route, targeted recycling and circular economy strategies should be promoted. This includes the expansion of renewable energy to power electric arc furnaces and the development of efficient sorting and processing methods to provide high-quality steel scrap.

Strategy III: Development of innovative CO_2-free production processes: In addition to hydrogen direct reduction and scrap enhancement, other pioneering CO_2-free production processes are being researched. One promising alternative is the electricity-based electrolysis of iron ore in alkaline solutions. This process is theoretically more energy-efficient than conventional processes and could enable emission-free steel production in the long term. In addition, there are approaches for CO_2 capture and use as well as CO_2 storage in order to minimize unavoidable emissions. Scaling up these technologies requires extensive research and development work as well as long-term investment in electrolysis-based processes.

The transformation of the steel industry towards climate-neutral production requires a combination of technological innovations and political measures. Hydrogen-based direct reduction, the strengthening of the circular economy and the development of new emission-free processes are key building blocks for decarbonization. The successful implementation of these technologies depends largely on the availability of renewable energy, infrastructure development and political support through funding programs and regulatory frameworks. Only by consistently implementing these strategies can the steel industry make its contribution to achieving the climate targets.

The decarbonization of the steel industry is of central importance for achieving the climate targets that have been set. While primary steel production is still the dominant process for steel production, alternative technologies such as direct reduction with hydrogen or secondary steel production using electric arc furnaces are the focus of current research and development. Despite the great potential of climate-neutral production processes, there are numerous challenges, particularly with regard to economic viability, infrastructural requirements and political framework conditions. The conversion of steel production to climate-neutral processes requires considerable investment. Companies such as ThyssenKrupp are already planning concrete measures to reduce emissions, but the introduction of new technologies causes significant additional costs compared to conventional blast furnace processes. The insufficient availability of green hydrogen in large quantities is particularly problematic, as the necessary capacities for its production do not yet exist. In addition, unclear political framework conditions and uncertainties regarding the promotion of climate-neutral technologies are a deterrent for many companies.

The production costs of green hydrogen are still high, which limits the economic competitiveness of this technology compared to conventional steel production. Long-term political measures are essential to give the industry planning security. Subsidies, tax breaks or CO_2 pricing systems could accelerate the introduction of climate-friendly production processes. The EU Green Deal and national support programs have already taken initial measures, but there is still a great need for action, especially with regard to reducing the production costs for green hydrogen and expanding renewable energy.

While direct reduction with hydrogen is currently the favoured alternative, there are other approaches to decarbonizing the steel industry. These include CO_2 storage and CO_2 utilization. However, these technologies are controversial from an environmental and economic perspective, as they incur high energy costs and do not contribute directly to avoiding emissions. Another innovative approach is the electrolytic reduction of iron oxide, which theoretically offers greater energy efficiency but is still at an experimental stage. The transformation of the steel industry towards climate-neutral production processes is a complex task that involves technological as well as economic and political challenges. While direct reduction with hydrogen offers enormous potential for reducing emissions, its widespread introduction requires considerable investment and infrastructural adjustments. Political support in the form of subsidies, clear regulations and support measures is essential to accelerate the transformation of the steel industry. In the long term, the success of climate-neutral steel production will depend on the development of cost-efficient technologies, the availability of renewable energy and the creation of suitable market conditions.

The use of hydrogen instead of coal is a key measure for reducing CO_2 emissions in the steel industry. This transformation not only offers considerable ecological benefits, but also opens up economic potential. The implementation of sustainable technologies makes a significant contribution to environmental protection, as the elimination of fossil fuels leads to a significant reduction in air pollution. In addition, advanced recycling methods and optimized production processes enable a more efficient use of resources, which helps to reduce manufacturing costs in the long term. Furthermore, adapting to future environmental regulations and CO_2 pricing is crucial to ensuring the competitiveness of the steel industry. Government subsidies offer companies financial support and encourage investment in innovative processes. These developments open up new market opportunities, particularly in sustainability-oriented sectors such as the automotive and construction industries, which are increasingly aligned with international climate targets. The continuous development and implementation of new technologies also strengthens the industry's innovative power and reduces dependence on fossil fuels in the long term. The transformation of the steel industry is therefore not only a necessary step towards decarbonization, but also a strategic measure to secure the future of the industry (Welt 2024).

The switch to climate-neutral steel production not only brings ecological benefits but also significant technical, economic and regulatory challenges. The implementation of hydrogen-based processes not only requires fundamental technological adjustments, but is also associated with considerable investment costs. The modernization of existing plants and the further development of the necessary technologies require billions in capital expenditure. The production of green hydrogen in particular poses a central challenge, as it requires large amounts of renewable energy, which is currently not available in sufficient quantities in many regions. In addition, the long-term storage and efficient transportation of hydrogen are not yet fully developed, which makes the economic scalability of this technology even more difficult. Another problem area concerns competitiveness on the global market. Countries with less stringent environmental regulations can continue to produce steel more cost-effectively using conventional, CO_2-intensive processes. This could lead to a shift in emissions to countries with lower environmental standards, which would jeopardize global climate targets. In addition, without harmonized carbon pricing, climate-neutral steel remains more expensive than conventional steel, which poses a challenge for export-oriented manufacturers in particular. The successful transformation of the steel industry is also heavily dependent on political framework conditions. Government support programmes, incentives for decarbonization and uniform CO_2 pricing play a decisive role in the economic profitability of climate-friendly production processes. A lack of or inadequate regulatory measures could slow down the conversion process or have a lasting negative impact on the competitiveness of the industry. A viable long-term strategy for climate-neutral steel production therefore requires not only technological innovations, but also stable economic and political framework conditions that actively support the transformation (Financial Times 2025).

Conclusions

The transformation of the steel industry towards climate-neutral production is technically feasible, but is subject to various key prerequisites (Klimaschutzindustrie 2023). The rapid expansion of renewable energies plays a central role here in order to be able to provide sufficient green energy sources such as hydrogen or green electricity in the future. In addition, the construction of the necessary infrastructure, including the adaptation of existing grids and supply routes, is essential. There is also a need for economically viable framework conditions that enable companies to shape the transformation process sustainably while remaining competitive. Added to this is the importance of social acceptance. The construction of the necessary facilities and infrastructure requires the early involvement and participation of all relevant stakeholders in order to ensure acceptance and support among the population.

In addition to these prerequisites, the realization of a climate-neutral steel industry within the next 20 to 25 years will become much more likely and sustainable if resource conservation measures are integrated. These include an increase in recycling rates, an increase in material efficiency and the promotion of sufficient lifestyles. These approaches could reduce the consumption of primary raw materials and thus additionally support the switch to climate-friendly production processes . An important factor in this context is the role of secondary steel production, which proves to be comparatively easy to decarbonize. With consistent expansion and optimized use, the steel industry can make a significant contribution to achieving climate neutrality by 2045 (Technische Universität Graz 2024). The findings show that a successful transformation of the steel industry requires not only technological, but also systemic and social changes in order to achieve sustainable results in the long term.

The decarbonization of the steel industry is an essential but highly complex transformation process that encompasses technological as well as economic and political dimensions. While the long-term ecological and economic benefits predominate, there are considerable short-term challenges to overcome. In particular, the high investment costs for the implementation of climate-neutral technologies, existing technical uncertainties and the dependence on regulatory framework conditions and state funding mechanisms represent key hurdles. The success of this transformation is largely dependent on continuous technological innovation, clear and stable long-term political control and an adequate supply of renewable energy. Effective cooperation between industry, politics and science is crucial to ensure sustainable and economically viable steel production. Only by integrating technological advances, adequate support measures and a reliable infrastructure for green energy can the transformation of the steel industry be successfully shaped in the long term.

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