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**International Journal of Research Publication and Reviews**

Journal homepage: www.ijrpr.com ISSN 2582-7421

# A Review on Green Steel Technology Manufacturing Towards Net-Zero

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**A B S T R A C T**

Green steel manufacturing is emerging as a critical component of global efforts to achieve net-zero emissions in the industrial sector. Traditional steel production methods, primarily reliant on coal-based blast furnaces, contribute significantly to global $CO_2$ emissions. In response, innovative technologies aimed at decarbonizing the steel industry have gained momentum. This paper provides a comprehensive overview of cutting-edge green steel manufacturing technologies, including hydrogen-based direct reduction (DR), electric arc furnaces (EAF) powered by renewable energy, and the use of bio-based alternatives to coke and coal. We explore the technical challenges and economic implications of these approaches, such as the need for green hydrogen production, scalability, and the integration of renewable energy sources into steelmaking processes. Additionally, the role of carbon capture, utilization, and storage (CCUS) technologies in reducing emissions from traditional methods is discussed. The paper highlights ongoing pilot projects, policy frameworks, and market incentives that are shaping the future of green steel. Finally, it examines the broader impact of green steel on achieving global decarbonization targets, particularly within the context of the Paris Agreement, and the potential for green steel to become a cornerstone of sustainable industrial practices in the 21st century.

Keywords: Green Steel, Net-zero Emissions, Hydrogen-based direct reduction, Electric arc furnace, Carbon capture, Renewable energy, Decarbonization, Industrial Sustainability.

## INTRODUCTION

Steel production is one of the largest industrial sources of carbon emissions worldwide, mainly due to the use of coal in traditional manufacturing methods. As the world moves toward achieving net-zero emissions to combat climate change, reducing the carbon footprint of steelmaking has become a critical goal. Green steel technology refers to innovative methods for producing steel with significantly lower $CO_2$ emissions compared to conventional processes.

Several promising technologies are being developed to make steel in a more sustainable way. These include hydrogen-based direct reduction, electric arc furnaces powered by renewable energy, and the use of bio-based alternatives to coal. These technologies aim to replace the carbon-intensive practices of the past with cleaner alternatives that use renewable energy sources and reduce reliance on fossil fuels.

This shift towards green steel is essential for achieving global climate targets, such as those outlined in the Paris Agreement. However, the path to widespread adoption of green steel faces challenges, including the high costs of new technologies, the need for large-scale production of green hydrogen, and the integration of renewable energy into steelmaking processes.

This paper explores these new technologies, the challenges they present, and their potential to transform the steel industry. We also discuss the role of policy frameworks, financial incentives, and ongoing pilot projects in driving the transition to green steel. Ultimately, the goal is to understand how green steel can contribute to the global effort to achieve net-zero emissions and a more sustainable future.

## Literature Review

- Bataille, Chris, et al. (2023) reported that; This study review green steel refers to steel produced by less carbon-intensive processes. It aims to reduce greenhouse gas emissions compared to traditional steel production methods. Green steel can be used in construction, automotive, and infrastructure, focusing on areas that require a lower carbon footprint. Demand for green steel remains limited due to higher production costs, but demand is likely to increase in sectors where sustainability is prioritized. The investigation holds great importance as it focuses on CO2 emissions from steel production, which is responsible for 7-10% of global energy and industrial process CO2 emissions. Achieving net-zero emissions in this sector is critical to meeting climate goals. The objective is to develop decarbonization pathways for the steel sector in Brazil, India, and south Africa, aiming for net-zero CO2 emissions through the use of different policy and technological interference. finally concludes that decarbonizing steel production will require international cooperation, technology transfer, and strong regulatory support. It highlights the role of carbon capture and the use of electric arc furnaces as effective measures for reducing emissions.

- Wang, C., Walsh, S. D., Weng, Z., Haynes, M. W., Summerfield, D., & Feitz, A. (2023). study that; The paper addresses the challenge of decarbonizing steel manufacturing by using green hydrogen and renewable energy. It explores Australia's potential to produce green steel for export by using its abundant renewable resources and iron ore deposits. The study aims to explore the potential for green steel production and export in Australia, leveraging the country's renewable resources, existing infrastructure, and mining expertise to Majumder, A., & Phani, M. K. (2023emissions, but it requires substantial government support, technological advancements, and investment in renewable infrastructure. The study concludes that green steel production can significantly reduce emissions, but it requires substantial government support, technological advancements, and investment in renewable infrastructure. The optimized mix of renewable sources (wind and solar) is key to reducing energy storage needs and production costs, making green steel competitive in the long term.
- Muslemani , H., Liang, X., Kaesehage , K., Ascui , F., & Wilson, J. (2021) explained that; The paper investigates the challenges of decarbonizing steel production by creating markets for green steel products, concentrating on the need of a common definition for "green steel," market determination, and policy mechanisms to support green steel. The methodologies used in the research Qualitative Research Methodology. The investigation highlights the importance of reducing greenhouse gas emissions in steel production, which accounts for a significant share of global emissions. develop sustainable markets for green steel to achieve climate goals aligned with the Paris Agreement. The aim of the study is to explore the opportunities and challenges of creating a market for green steel and to provide policy recommendations that can help decarbonize the steel industry. The study concludes that establishing a market for green steel will require government intervention, clear definitions of what constitutes "green" steel, and a combination of policy mechanisms that promote demand and supply.
- Majumder, A., & Phani, M. K. (2023) study that; Green steel also known as sustainable steel production. It refers to the environmentally friendly practice in steel manufacturing's main aim of green steel is to reduce the carbon emission, reduce energy consumption for sustainable future. the transformative potential of Green Steel Technology in making the steel industry more sustainable and environmentally friendly. By integrating renewable energy sources, advanced manufacturing techniques.to investigate the potential of green steel technology (GST) as a viable approach for reducing the environmental impact of the steel industry and achieving a sustainable world. Advanced manufacturing techniques like direct reduction and electric arc furnaces are used . However, the widespread adoption of this technology faces challenges such as high initial investments, technological barriers, and the need for integration with existing processes. With collaborative efforts from steel producers, governments, and stakeholders, green steel technology can play a crucial role in achieving a sustainable future for the steel industry.
- Trinca, A., Patrizi, D., Verdone, N., Bassano, C., & Vilardi, G. (2023) investigated that; The paper examines how to decarbonize steel production by evaluating the entire cycle of steel production, especially the Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF) process. The focus is on environmental and economic aspects using various reducing gases (e.g., hydrogen, syngas from municipal solid waste). This study's significance lies in its approach to decarbonizing steelmaking, an industry that contributes significantly to global $CO_2$ emissions. By assessing alternative reducing agents like hydrogen and waste-sourced syngas, the study aligns with global sustainability goals and supports transitioning the steel industry toward greener practices. The primary aim is to model and analyze the environmental and economic impacts of various reducing gases, including methane, syngas from municipal solid waste, and green hydrogen, in direct reduced iron (DRI) processes combined with electric arc furnace (EAF) steelmaking . The study concludes that while green hydrogen offers the highest reduction in greenhouse gases, its economic feasibility depends heavily on renewable energy availability and costs. Syngas from waste is a more cost-effective alternative but with moderate emission reduction benefits. Carbon capture enhances emission reductions further, though it increases operational costs.
- Rosner, F., Papadias , D., Brooks, K., Yoro, K., Ahluwalia, R., Autrey, T., & Breunig, H. (2023) reported that; This study Analysis of hydrogen-based direct reduced iron (H2-DRI) as a low-carbon alternative for steel production. Determining CO2 emission reduction potentials. these are some methodologies are used in green steel design Process simulation using ProSim Plus software. Detailed process modelling of integrated mills with NG-DRI and H2-DRI This paper presents a comprehensive analysis of transitioning steel production to hydrogen-based processes for decarbonization. Through detailed techno-economic modelling, it establishes target costs for renewable hydrogen production and identifies optimal operating conditions. The work is particularly valuable for setting technical performance criteria for hydrogen supply and storage in the iron and steel. The analysis provides concrete numbers for decision-makers regarding required hydrogen costs and potential emission reductions, making it a useful reference for industry transformation planning . presents a comprehensive analysis of transitioning steel production to hydrogen-based processes for decarbonization. Through detailed techno-economic modeling, it establishes target costs for renewable hydrogen production and identifies optimal operating conditions. The work is particularly valuable for setting technical performance criteria for hydrogen supply and storage in the iron and steel.
- Singh, J. K., & Rout, A. K. (2018) investigated that; The study addresses the high CO2 emissions and energy inefficiencies associated with traditional steel production methods. It explores advanced green steelmaking technologies to enhance productivity, reduce carbon emissions, and improve environmental sustainability. The methodologies used are Pulverized Coal Injection (PCI),Continuous Casting Technology (CCT),Coke Dry Quenching (CDQ),Coke dry cooling plant (CDCP). There are some drawbacks in green steel manufacturing High initial investments for technology implementation (e.g., PCI, CCS).Challenges in scaling up some green technologies to industrial levels. This review serves as a comprehensive guide for stakeholders in the steel industry. It highlights the urgency of adopting green technologies and their potential to drive sustainability. For policymakers and industrial leaders, the study provides insights into feasible interventions to reduce emissions and enhance efficiency. The article underscores the necessity of transitioning to green steel technologies to mitigate the

environmental impact of the industry. Innovations like PCI, CCT, CDQ, CCS, and steel recycling offer promising pathways to achieve this. However, realizing the full potential of these technologies requires addressing economic and operational barriers.

- Griffin, P. W., & Hammond, G. P. (2021) focused that; Evaluating different options for decarbonizing and making UK steel production more environmentally friendly, particularly in regard to reducing greenhouse gas emissions. These are the technologies used like Techno-Cost Effective Road mapping, Marginal Abatement Cost Curve (MACC),Cross-Cutting Measures, Life-Cycle Assessment (LCA)This paper provides a comprehensive review of options for decarbonizing the UK steel industry, including CCS, bioenergy, hydrogen-based production, and electrification. It develops roadmaps to illustrate potential pathways to 2050, considering both technological and economic factors. The work highlights the challenges and opportunities in transitioning to 'green steel' production in the context of the UK's net-zero emissions target, while also discussing broader concepts like circular economy approaches.
- Vogl, V., Åhman, M., & Nilsson, L. J. (2021) reported that; The paper addresses systemic barriers to the commercialization of green steel in the EU. These barriers include lack of infrastructure, unclear demand, and cost competitiveness for low-emission steel production methods. Methodologies used are Demand-side market creation, Production subsidies. The study highlights the importance of decarbonizing the steel sector, which is a major emitter of CO2. Transitioning to green steel production is essential to meet the EU's climate goals, such as achieving carbon neutrality by 2050.The primary objective is to evaluate the effectiveness of different policy approaches to support the early commercialization of green steel technologies in the European Union. The study concludes that while CCFDS are the most promising policy tool for early commercialization, complementary policies such as market creation and transitional support for disadvantaged regions are essential. It calls for a fair distribution of costs and benefits to ensure that regions without access to renewable energy are not left behind in the green transition.
- Kawabata, N. (2023) study that; The paper explores the technological path that Japanese steelmakers are pursuing to produce environmentally friendly or "green steel" and the challenges they face in reducing CO2 emissions in the steel industry. International Energy Agency (IEA)The importance of this investigation is in examining how large steelmakers, particularly in Japan, are lagging behind in adopting green technologies. The study highlights the need for the steel industry to decarbonize to meet global climate targets, especially in light of Japan's carbon neutrality goals. The aim of the study is to evaluate the technological pathways Japanese steelmakers are adopting to produce green steel. It analyses why these firms have been slow in shifting away from high-emission technologies and how they are adapting to global warming pressures. The study concludes that Japanese steelmakers have been slow to adopt green technologies due to their commitment to maintaining high-grade steel production and the substantial fixed capital tied to traditional methods. However, the Paris Agreement and Japan's 2050 carbon objectivity goal are pushing them toward electric arc furnaces and hydrogen-based production. The study calls for more tough policies and reason to accelerate the adoption of low-carbon technologies.

## CONCLUSION

Green steel technologies offer a promising pathway to significantly reduce the carbon emissions from the steel industry, which is a major contributor to global $CO_2$ emissions. By adopting cleaner methods like hydrogen-based direct reduction, electric arc furnaces powered by renewable energy, and bio-based alternatives to coal, the steel sector can move towards more sustainable and environmentally friendly production. While there are still challenges to overcome, such as high costs, the need for green hydrogen production, and the integration of renewable energy, progress is being made through ongoing research, pilot projects, and supportive policies. These efforts are helping to make green steel more viable and scalable in the future. Ultimately, green steel has the potential to play a key role in achieving global climate goals, including those set under the Paris Agreement. By advancing these technologies and addressing current challenges, the steel industry can contribute to a net-zero future, making a significant impact on global sustainability efforts.

The transition towards green steel manufacturing represents a pivotal step in achieving net-zero emissions within the industrial sector. With steel production contributing approximately 7-9% of global $CO_2$ emissions, decarbonizing this industry is crucial to aligning with international climate goals. Emerging technologies, such as hydrogen-based direct reduction, electric arc furnaces powered by renewable energy, and advancements in carbon capture and storage (CCS), offer promising pathways to significantly reduce emissions. Innovations in material recycling, circular economy strategies, and the integration of smart energy systems further enhance the potential for sustainability in steel production. These approaches not only reduce environmental impact but also position the industry to meet increasing regulatory and consumer demands for greener products. However, challenges remain, including high capital costs, the availability of renewable hydrogen at scale, and the need for infrastructure upgrades. Collaborative efforts among governments, industry stakeholders, and research institutions are essential to address these barriers. Policy incentives, carbon pricing mechanisms, and investments in R&D can accelerate the adoption of green steel technologies.

In conclusion, green steel manufacturing is a cornerstone of the global effort to achieve net-zero emissions. While significant hurdles persist, the combination of technological innovation, policy support, and industry collaboration has the potential to transform steel production into a more sustainable and environmentally friendly process. The successful implementation of these solutions will not only mitigate climate change but also ensure the long-term viability and competitiveness of the steel industry in a low-carbon economy.

***Acknowledgements***

The authors wishes to acknowledge M/s GMR Institute of Technology for the moral support.

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