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Transitioning to Green Steel Manufacturing Through the Adoption of Hydrogen-Based Technologies and Processes for Securing Net-Zero Carbon Dioxide Emissions by Aspen Plus

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ABSTRACT

Conventional green steel production heavily relies on coal, resulting in high levels of carbon dioxide emissions. This research focuses on hydrogen-based steelmaking as a cleaner alternative that supports global decarbonization goals. Traditional steelmaking methods like the BF-BOF process emit large amounts of CO_2, contributing significantly to global warming. Technologies such as Electric Arc Furnaces (EAF) powered by renewable energy and Carbon Capture and Storage (CCS) offer further emission reductions. Jindal Shadeed Iron & Steel aims to transition to hydrogen-based methods to achieve net-zero emissions by 2050. The novelty of this research lies in simulating a full-scale hydrogen-based steel plant using Aspen Plus, showing a 99.6% efficiency rate and zero CO_2 emissions. Comparison with JSIS showed zero emissions versus 1.4–1.8 tons CO_2/ton in current practice. The results revealed that hydrogen steelmaking significantly lowers emissions, energy usage, and water consumption. The system showed 99.6% efficiency, a return on investment of 51%, and a payback period under two years. RSM analysis showed that increasing shaft temperature from 800 °C to 1000 °C and pressure from 1 bar to 5 bar improved HDRI steel conversion efficiency by over 35%, while FEL values varied by less than 5% across all tested conditions. The comparisons with Jindal Shadeed's existing systems highlighted substantial improvements in emission control and energy performance. In conclusion, hydrogenbased steel production is both practical and scalable. The supportive policies and investment analysis can drive a major shift toward sustainable industrial practices. The outcomes from this simulation provide a strong foundation for broader adoption of green steel technologies.

1. Introduction

Green steel manufacturing is a significant advancement in producing steel in an environmentally friendly manner. Traditional steel production, especially using blast furnaces, depends heavily on coal and releases a lot of carbon dioxide (CO_2), which harms the environment and contributes to global warming. Green steel aims to reduce or eliminate these harmful emissions by using cleaner

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technologies. One of the most promising ways to reduce pollution in steelmaking is by using hydrogen instead of coal. This method is called hydrogen-based direct reduction. In this process, hydrogen removes the oxygen from iron ore, and the only byproduct is water vapor—not carbon dioxide—making it much better for the environment. Another important method for making eco-friendly steel is using Electric Arc Furnaces (EAFs). These furnaces melt old or scrap steel using electricity. If this electricity comes from clean energy sources like wind or solar power, it can help lower greenhouse gas emissions a lot. Also, many companies are now using **Carbon Capture and Storage (CCS).** This technology captures carbon dioxide (CO_2) before it goes into the air. The captured gas can either be stored deep underground or reused in other industries. A good example is **Jindal Shadeed Iron & Steel**, a large steel company in the Middle East. They are working hard to make their steel production more environmentally friendly. Their goal is to become carbon neutral by 2050, in line with global climate targets like the Paris Agreement. To do this, they plan to stop using coal and switch to hydrogen. They are also investing in new research and building the systems needed to make, store, and move hydrogen safely. Although this change is difficult because of high costs and the need for new technology, the long-term benefits—like cleaner air, fewer emissions, and a more sustainable future—make it a smart and responsible move. Jindal Shadeed currently uses the blast furnace-basic oxygen furnace (BF-BOF) process, which involves heating iron ore, limestone, and coke (a coal product) to produce molten iron, which is then converted to steel using pure oxygen. While effective, this process emits a large amount of CO_2. Recognizing the need for change, the company is looking into alternative methods like hydrogen-based reduction and EAFs. These alternatives offer the potential for lower emissions and better environmental performance. Green steel means making steel in a way that is safer for the environment. Normally, steel is made using coal in big blast furnaces, which creates a lot of carbon dioxide (CO_2). This harms the planet by increasing pollution and climate change.

Green steel uses clean methods like hydrogen to help reduce or even stop CO_2 emissions. One clean method is Hydrogen-Based Direct Reduction (H-DR). Instead of using coal, this method uses hydrogen gas to remove oxygen from iron ore. The only byproduct is water vapor, not CO_2. This makes it much better for the environment. Hydrogen-based steelmaking presents many advantages. The main one is that it doesn’t release CO_2, only water vapor. Hydrogen can be made from renewable energy using a process called electrolysis. This allows the entire steelmaking process to be powered without fossil fuels. However, the technology is still developing, and producing green hydrogen is expensive. It also requires significant investment in infrastructure, such as pipelines, storage tanks, and special furnaces that can work with hydrogen. There are social and economic challenges as well. Workers will need to be trained to handle new technologies. Governments must support this transition through policies and financial help.

1.1 Background of the Study

The steel industry plays an important role in global development, but it also creates major environmental problems, especially due to the traditional blast furnace-basic oxygen furnace (BFBOF) method. This method uses coal and coke, which release large amounts of carbon dioxide (CO_2). This makes the process harmful to the environment. Researchers explain how common the BF-BOF method is in steel production and how it adds to climate change. To address this, the industry is now seeking cleaner methods to produce steel. One of the best new ideas is using hydrogen instead of carbon in the steelmaking process. This process is called hydrogen-based direct reduction (H-DR). Although BF-BOF is still widely used, H-DR has become a promising method that could change the way steel is made. A study compares BF-BOF and H-DR, showing that H-DR has a significantly lower environmental impact. Many studies have compared H-DR and BF-BOF. While BF-BOF is common and well-known, it releases a lot of CO_2. The main idea behind H-DR is replacing coal or natural gas with hydrogen to convert iron ore into iron. Unlike BF-BOF, which releases CO_2 from coke combustion, HDR creates water vapor as a by-product. This can help steel companies cut down emissions. Still, the technology for H-DR is new and needs more research, especially in making, storing, and moving hydrogen. Dreher *et al*., (2020) add that although H-DR has big environmental benefits, it needs a lot of investment in technology.

The study of hydrogen-based steelmaking at Jindal Shadeed aims to answer several questions. What are the main challenges? How can hydrogen help the company meet its climate goals? What role do governments and markets play in supporting this change? What lessons can be learned for other companies in the region and globally? The scope of this study focuses on the hydrogen-based direct reduction process, its benefits, and its challenges. It looks at how this method compares to traditional steelmaking, the costs involved, the environmental gains, and the required infrastructure. It also considers the role of policies, investments, and social impacts. Strong policies, subsidies, and knowledge-sharing across countries are essential to make green steel a global success. If done right, green steel using hydrogen can reshape the steel industry. It can reduce global emissions, improve air and water quality, and create new jobs in green energy and technology. Jindal Shadeed's efforts are an example of how industry can lead the way toward a cleaner future. The transition to green steel is not just a technical change but a global movement towards sustainability. In conclusion, the future of the steel industry lies in adopting cleaner methods like hydrogen-based steelmaking. Jindal Shadeed Iron & Steel is setting an example by investing in innovation and committing to carbon neutrality. Though the road ahead is full of challenges, the potential benefits for the environment, economy, and society make it a journey worth taking. Another way is using Electric Arc Furnaces (EAFs) that run on electricity from wind or solar power. These furnaces melt old scrap steel and reuse it, which saves energy and reduces pollution. Carbon Capture and Storage (CCS) is also used. It traps CO_2 before it gets into the air and stores it safely underground or uses it in other processes. Jindal Shadeed Iron & Steel in the Middle East is leading in this change. The company plans to be carbon neutral by 2050.

These systems can take advantage of the strengths of each method. For example, EAFs are great for recycling scrap metal, while hydrogen-based methods are ideal for processing iron ore. Combining them can offer flexibility and reduce the overall environmental impact. This transition requires global collaboration. The Middle East, where Jindal Shadeed operates, needs supportive policies, new technologies, and strong international partnerships to make hydrogen-based steelmaking viable. This involves understanding both the benefits and the limitations. For instance, while green hydrogen reduces emissions, it needs a lot of clean electricity and water. Also, hydrogen can be dangerous to store and transport if not handled properly. The steel sector plays a major role in global greenhouse gas emissions, contributing about 7–9% of the total. With increasing global steel demand, these emissions will grow unless cleaner methods are adopted. From 2000 to 2013, steel production nearly doubled, which also increased its carbon footprint. The need for decarbonization is urgent. Hydrogen-based steel offers a practical and effective way to meet this need, with companies like Jindal Shadeed leading the charge. Jindal Shadeed Iron & Steel understands the need to produce steel more cleanly. The company sees hydrogen-based steelmaking as an important step toward reaching its goal of being carbon neutral. Their investment in research shows their focus on new, cleaner methods. To make H-DR a success, Jindal Shadeed must work with scientists, technology providers, and governments to solve technical and economic problems.

1.2 Novelty of this Study

This work combines Response Surface Methodology (RSM) with Aspen Plus process simulation to optimise hydrogen-based direct reduction parameters systematically. The approach enables a parallel evaluation of both technical performance and environmental impact. In contrast to previous research that typically examines one variable at a time, this study adopts a multiparameter optimisation strategy to determine the best combination of conditions for maximising efficiency while minimising energy consumption and CO_2 emissions.

1.3 Significance of the Study

If Jindal Shadeed successfully switches to H-DR, it could set an example for other companies. This would prove that H-DR is not only possible but also works on a commercial scale. Vogl *et al.*, [5] argue that this shift could help the entire industry reduce emissions and meet global climate targets. Although switching to hydrogen steel has many advantages, it also presents challenges. One big challenge is creating hydrogen in a cheap and large-scale way. Building a full hydrogen infrastructure—plants, storage, and transport systems—is also necessary. Without it, companies won't have the supply chain needed to use hydrogen in their factories. To switch from traditional methods to H-DR, companies will need to change their equipment and train workers. This will cost money and time. Also, steel companies must make sure the new methods are financially sustainable. They need to carefully plan and analyze costs to make sure H-DR will be profitable in the long run. Life-cycle assessments can check how H-DR affects the environment, like how much energy, water, and waste it uses. Financial studies should look at ways to make hydrogen cheap and easy to use. Social studies should focus on job creation and how to help communities adjust to the changes. While moving to hydrogen steel is difficult, the benefits are large. H-DR could help cut emissions from steelmaking, improve air and water quality, and support climate goals. With proper investments, better technology, and strong policies, steel companies can switch to hydrogen and make their production more sustainable. Using hydrogen in steelmaking could also help build a hydrogen economy. This would bring new jobs and make energy supplies more secure. Hydrogen could power many industries, not just steel, making the economy cleaner overall. To make this happen, everyone must work together—governments, companies, scientists, and local communities. By sharing information and solving problems together, they can move faster toward using hydrogen in steelmaking. In short, hydrogen-based direct reduction is a powerful solution for the steel industry's environmental issues.

1.4 Objective of the Research

1. To simulate hydrogen-based steel production in Aspen Plus for evaluating energy use, emissions, and conversion efficiency.
2. To study the effects of varying temperature and pressure on HDRI process performance using Response Surface Methodology (RSM).
3. To compare the HDRI process results with conventional steelmaking to highlight potential environmental benefits.

2. Methodology and Experimental Design

This study uses a mixed-method approach to design a complete strategy for setting up a green steel production plant. Figure 1 explains that green hydrogen, created by splitting water through electrolysis powered by renewable energy, is becoming a central element in the transition toward climate neutrality. Across Europe, major initiatives are underway to scale up production facilities and supporting infrastructure. The key challenge lies in developing a hydrogen sector that is both environmentally clean and mindful of preserving valuable water resources. combines both numerical data (quantitative) and descriptive information (qualitative) to give a full picture of how hydrogenbased steelmaking can work. This method is important because hydrogen steel production is complex. It involves technology, money, environmental concerns, and transportation—all of which need to be understood together. Zhang and colleagues [27] explain that using different kinds of data together can lead to better decision-making in complex systems like hydrogen-based steelmaking. Their research starts by carefully reviewing past studies. This helps them understand the current technologies, identify what is still missing, and create a solid base of knowledge about hydrogen steel production. Using the knowledge from earlier research, the study creates a clear step-by-step plan for how a green steel plant would work. This plan shows each stage—from gathering raw materials to making the final steel—using hydrogen instead of coal. The researchers use computer simulations to test how the system performs in different situations. These tests help them find any issues, try out possible fixes, and improve the design to make the plant more environmentally friendly and energy efficient.

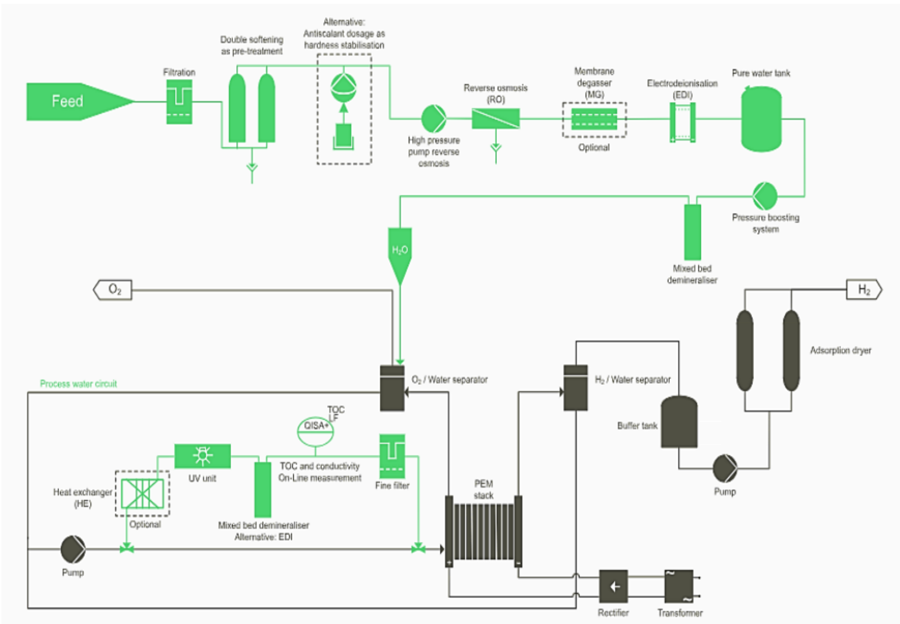

Fig. 1. Smelting of DRI [22]

To gather data, the study uses both existing information (secondary data) and new information collected directly by the researchers (primary data). For secondary data, the researchers use trusted sources like government reports, academic journals, and industry white papers. These sources help explain how hydrogen-based steelmaking currently works, what policies affect it, and how it is growing as a green technology. Rootzén and Johnsson (2016) describe the benefits and challenges of green steel. Vidas and Castro (2021), along with Strezov *et al.*, (2013), look at how laws and market trends influence the adoption of cleaner steelmaking. Alam *et al*., [35] report on the latest technical progress. Together, these sources help build a strong research base and point out where more firsthand data is needed.

Primary data collection is just as important in this study. It adds real-world views and details that are often missing from books or articles. The researchers visit actual hydrogen-based steel plants to see how things work on the ground. They watch the production process, assess the equipment, and look at both the benefits and challenges of this new technology. During these visits, they talk to a wide range of people, including scientists, engineers, plant managers, and others who are directly involved in building or running hydrogen steel projects. These interviews provide in-depth, practical insights into the technical, economic, and logistical aspects of green steelmaking. For example, industry professionals can explain what works well, what problems still exist, and what needs to improve. This firsthand feedback helps the researchers match real-world practices with the theories and data gathered earlier. By bringing together both types of data—published research and firsthand observations—the study creates a full and detailed understanding of hydrogen steelmaking. It highlights where improvements are needed and how this technology can grow in the future. This approach not only strengthens the study's findings but also ensures that the results are useful for engineers, policymakers, and business leaders who are working to make steel production more sustainable.

2.1 Simulation on Aspen Plus for Green Steel Production

The DRI features support industries in saving money, using resources wisely, and working more effectively. This is also commonly used in many fields, such as chemical, petrochemical, pharmaceutical, energy, and environmental engineering. In the chemical industry, for example, it helps design systems to produce things like polymers and catalysts, and to separate different chemicals. In the energy sector, it's used to model power plants and clean energy technologies, including those that produce hydrogen. In environmental engineering, the software helps design systems for treating wastewater and cutting down air pollution. Aspen Plus v14 also supports modern digital technologies by using real-time data from sensors to help make smarter and faster decisions. This matches the trend of smart manufacturing, where data is used to boost efficiency and cut down on waste. A major upgrade in this version is its support for new areas like the hydrogen economy, bioenergy, and carbon-free technologies. For example, it can model the full hydrogen process—from production and storage to usage—which is important for the shift to clean energy. It also helps design systems that turn plants into biofuels, reducing our reliance on fossil fuels. One of the main chemical reactions in this process is, a key reaction in this process is:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (1)$$

In this work, the chosen parameters were set to mirror the real thermodynamic, kinetic, and operational aspects of producing steel with hydrogen as the reducing agent. Solid-phase thermodynamic models were used to describe iron oxides—hematite and magnetite—as well as metallic iron in both solid and molten forms. This allowed accurate tracking of phase changes, heat capacities, and enthalpy variations. For hydrogen, oxygen, nitrogen, and carbon dioxide, gas-phase models were applied to reflect their roles in the reduction reactions and related energy flows. Critical parameters included the shaft furnace operating temperature range of 800–1,000 °C, preheating levels for hydrogen, feed rates for the reactants, and efficiencies of heat recovery systems. These values were drawn from industrial practice and published data to ensure the results reflected realworld conditions. The selected models and parameters together captured the main solid–gas interactions, phase transformations, and heat recovery processes, providing a reliable basis for assessing both process efficiency and environmental impact. It provides important information that helps improve how steel is produced.

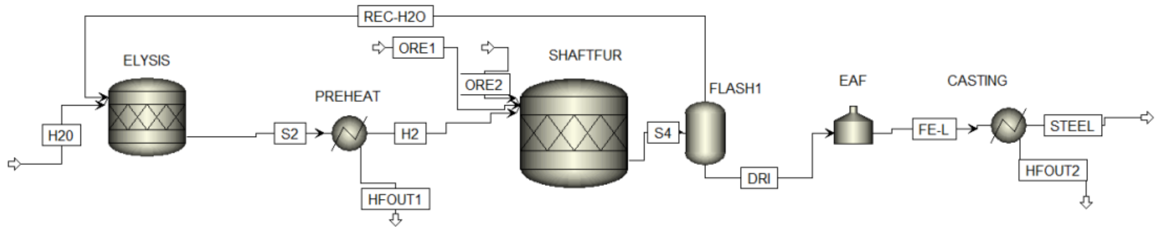

Fig. 2. Process simulation of DRI-H2 steel manufacturing

2.2 Process Simulation and Modelling

The process starts in a machine called ELYSIS, where water (H_2O) is split into hydrogen gas (H_2) and oxygen (O_2). This is done using a method called electrolysis, where electricity passes through water to break it down.

The reaction looks like this: $2H_2O \rightarrow 2H_2 + O_2$......................................(2)

This step is very important because hydrogen is later used to reduce iron ore into iron. The oxygen can be released into the air or collected and used elsewhere. Electrolysis is done at high temperatures with strong electric current to make it more efficient. These electrolysis units are built to save energy and last a long time, making the whole process more sustainable. Next, the hydrogen gas from the electrolysis unit is sent to a heater called PREHEAT. Here, the hydrogen is warmed up to the right temperature for use in the next step—reducing iron ore. Heating the gas improves how well it works in the chemical reactions ahead. This heater uses waste heat from other parts of the factory (like hot exhaust gases) to save energy and reduce operating costs. This also makes the process eco-friendlier. After heating, the hydrogen gas enters the shaft furnace along with iron ore (called ORE1 and ORE2). This is where the main reaction happens: hydrogen removes the oxygen from iron ore, turning it into Direct Reduced Iron (DRI)—a form of pure iron.

Two key reactions happen here:
$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$..............................(3)
$Fe_3O_4 + 4H_2 \rightarrow 3Fe + 4H_2O$..............................(4)

These reactions take place at high temperatures, around 800°C to 1000°C. Water vapor is produced as a byproduct and is removed, some of which is cleaned and reused through a system called REC-H_2O. The furnace is designed to keep the temperature even so that the iron ore is fully reduced and high-quality iron is made. This iron is then moved to the next step. The pure iron from the shaft furnace goes into a container called FLASH1. This unit helps control the flow of iron into the next machine and keeps the iron hot. It also removes leftover gases or small impurities. This step is important to keep the next stage running smoothly. The iron is then moved into an Electric Arc Furnace (EAF). Here, it is melted into molten steel using strong electric arcs that create temperatures over 920°C. Materials like lime may be added to help remove impurities from the steel. Once melted and refined, the steel is called FE-L and is tapped (poured) from the furnace, ready for shaping. Cooling and Shaping in the Casting Unit. The molten steel is sent to a machine called CASTING, where it cools down and hardens into shapes like slabs, billets, or blooms. These are the basic forms used in the next stages of steel processing, like rolling or cutting. The casting machine also has heat recovery units (like HFOUT2) that collect leftover heat, helping save energy and reducing waste. Throughout the steelmaking process, waste materials are carefully handled. For example, the steam (water vapor) made in the shaft furnace goes to REC-H_2O, where it's cleaned and reused, either in the electrolysis unit or somewhere else in the process. Heat recovery devices (like HFOUT1 and HFOUT2) are used to collect heat from hot gases and reuse it, cutting down on energy loss and improving overall efficiency. At the final stage, a process called ladle metallurgy is simulated. This step fine-tunes the steel's quality. Here, things like temperature, mixing, and adding small amounts of metals (alloys) are adjusted to make sure the steel has the right properties for use.

3. Results and Discussion

3.1 Aspen Plusresults Production Line Simulation

The results of the simulation show that using hydrogen to reduce iron is a cleaner and more effective option than traditional coal-based methods. Replacing carbon with hydrogen helps lower greenhouse gas emissions and supports international efforts to fight climate change. The cost analysis found that this method can also be financially rewarding. It showed a 51% return on investment, with a payback period of less than two years. While the electrolyzer and shaft furnace are some of the most expensive parts of the system, their costs were reduced by using waste heat and renewable energy. This makes the method ideal for regions that have access to low-cost renewable electricity and natural resources. The study included detailed energy and material calculations, which helped researchers understand how to make the process more efficient.

3.2 HSPR Process

Hydrogen-based steel production is a big step forward in making the steel industry more ecofriendly. As the world focuses more on clean and sustainable manufacturing, this method could play a major role in changing how steel is made.

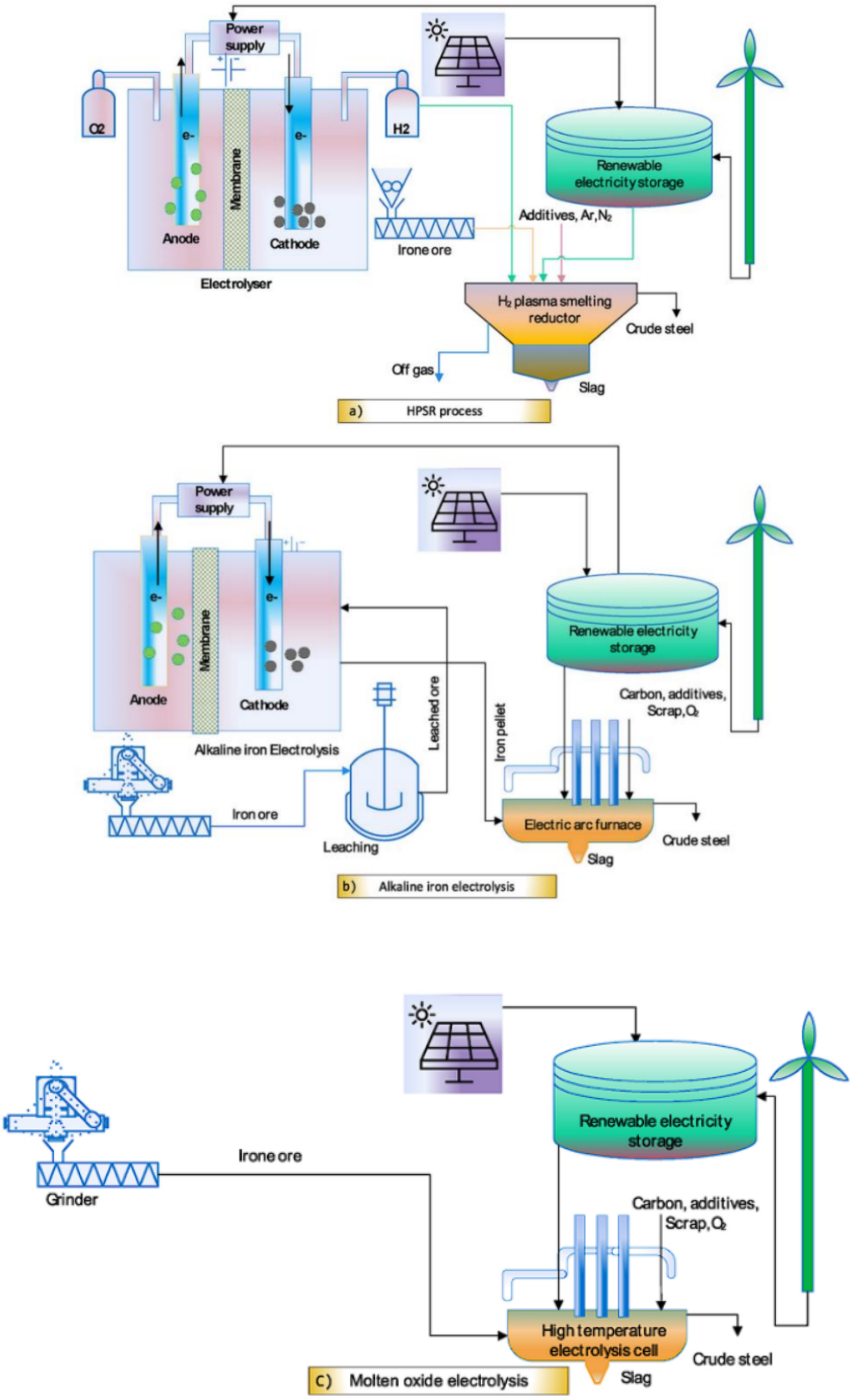

Fig. 3. Schematic diagrams of the (a) HPSR, (b) AIE, and (c) MOE steelmaking processes

This analysis covered many expenses like raw materials, electricity and water, labor, construction, repairs, and taxes. However, some financial factors like interest, inflation, and future cash value were not included. This is because the material used (adsorbent) has a short lifespan of less than a year, making those financial factors less relevant. To calculate the total cost in each case, the study used a "functional unit approach"—meaning it looked at all equipment and process steps, including setup, operation, and maintenance. This helps balance sustainability goals with business success. It's important to know that current cost estimates for making hydrogen-based steel are still in the early stages. They are based on different materials, so some comparisons may not be fully accurate or may even be underestimated. These factors affect the final cost of steel. So, it's important to analyze the cost separately for each use case or application. Making small changes—like choosing different chemicals or adjusting their amounts—can also help lower the production cost while still keeping the steel effective at removing pollutants. Raw materials could become even cheaper if bought in large quantities, which would help reduce costs further and improve profits. One of the biggest economic advantages of this type of steel comes from using cheap raw materials, especially plastic waste, which is easy to find and affordable.

3.3 RSM Analysis

The RSM (Response Surface Methodology) graphs illustrate how hydrogen-based direct reduced iron (HDRI) steel production performs under different temperatures and pressures. Figure 4(a) illustrates the hydrogen conversion efficiency (H2CONV), where temperature changes are plotted on the x-axis and pressure on the y-axis, with the conversion rate represented on the z-axis. The graph indicates that hydrogen conversion remains nearly constant regardless of the changes in temperature and pressure. This means that the efficiency of producing hydrogen does not change significantly within the tested range of these conditions.

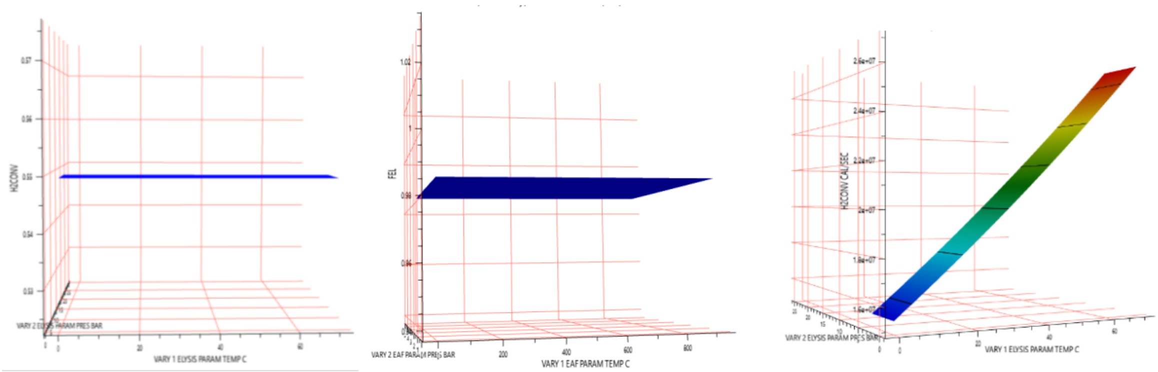

Fig. 4. Variation between (a) Temperature and (b) O2 conversion

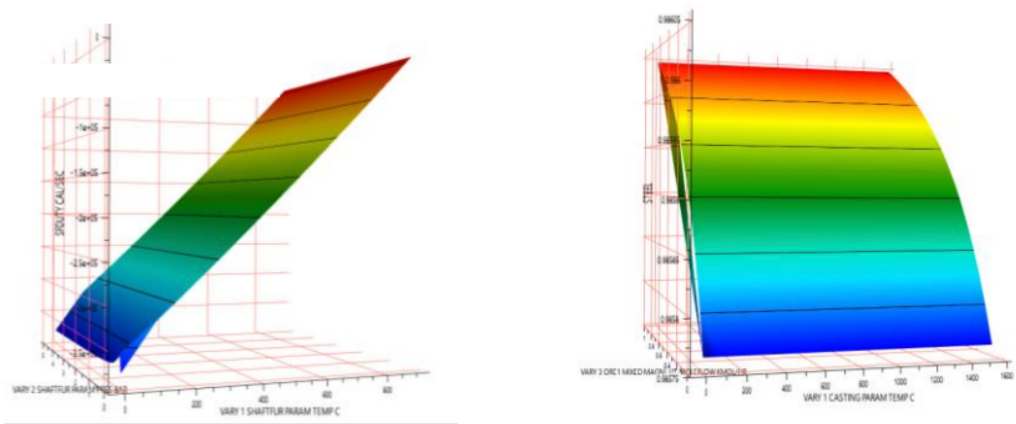

Fig. 5. a) Contours 3D plots between Temperature (b) H2 conversion

In Figure 4(b) on the conversion of oxygen (O2CONV) during electrolysis. Similar to the hydrogen graph, the x-axis shows temperature, the y-axis shows pressure, and the z-axis represents the conversion rate of oxygen. Just like hydrogen, oxygen production through electrolysis remains stable even when temperature and pressure vary. The third graph shows how much the hydrogen conversion rate changes in response to different temperatures and pressures. As both temperature and pressure increase, the conversion rate improves significantly. The color gradient from blue to red on the graph shows this increase clearly. This tells us that hydrogen production becomes more effective at higher temperatures and pressures, making it essential to control these conditions carefully for the best performance. This means it's very important to control these conditions carefully. If they are not managed properly, the process can use too much energy. Keeping both temperature and pressure within the best range helps lower costs and avoid wasting energy. It measures a value called FEL as a temperature and pressure change. The graph shows that FEL stays mostly the same, with only small changes. This means the process works well even when temperature or pressure shifts slightly. It shows that the system is stable and doesn't need constant adjustments. Such stability is helpful in operations where steady performance is important and less frequent monitoring is preferred.

Figure 5(a) shows how the iron ore conversion rate (CONV) changes with shaft temperature and pressure. The graph reveals that as both temperature and pressure increase, the conversion rate rises sharply. The color change in the graph—from blue (low conversion) to red (high conversion)—clearly shows that these two factors have a strong effect on how effectively the iron ore is converted. This finding supports the idea that careful control of these two parameters can significantly improve the efficiency of the HDRI steelmaking process. Figure 5(b) again tracks FEL but in different conditions. Like earlier, temperature and pressure changes do not significantly affect FEL, as the values remain within a narrow range. The color transitions show a stable and gradual trend, confirming that the process is reliable. This is beneficial in practice, as it means efficiency remains consistent even when working conditions vary slightly. It analyzes how changes in casting temperature and magnetite flow impact steel output (STEEL). As casting temperature increases, the steel output generally decreases. The color shift from green to red shows this decline. On the other hand, changes in the magnetite flow have a less noticeable effect on steel output. This graph makes it clear that controlling casting temperature is more important than adjusting the magnetite flow when aiming for higher steel production efficiency.

4. Comparison with JSIS Company

Jindal Shadeed Iron and Steel (JSIS) is an important steel company in the Persian Gulf region. It produces about 2.4 million tons of steel every year, which is good for regional development. However, when compared to much bigger steel companies around the world, this amount is small. Because of this, JSIS might not have a big impact on global steel markets or benefit from the lower costs that come with large-scale production. JSIS uses a method called gas-based Direct Reduced Iron (DRI), which turns iron ore into sponge iron using natural gas. JSIS may fall behind if it doesn't start adopting these new technologies. JSIS uses modern equipment, like a DRI plant designed by Midrex and steelmaking tools from Danieli, which shows that they care about being efficient. But because the company has not shared details about how well these systems work—like how much energy they use or how much waste they make—it's hard to judge how effective their processes truly are. Sharing this kind of information would help in spotting areas where improvements can be made. JSIS says that for every 1 ton of steel, it produces about 1.05 tons of CO_2. This is better than the industry average, which is around 1.8 tons of CO_2 per ton of steel. Still, many leading companies are aiming for net-zero carbon emissions, and they are investing in new green technologies to get there. So even though JSIS is doing better than most, it might still not be meeting the latest environmental expectations. We analyzed JSIS Oman's plant outcomes at different operational capacities (15%, 20%, 25%, and 30%) to assess efficiency, carbon footprint, and resource utilization. Tables 1 and 2 summarize:

Table 1
JSIS Oman Plants outputs at different capacities

Capacity	Hydrogen Consumption (tons per ton of DRI)	Energy Efficiency (%)	CO_2 Emissions (tons per ton of cride steel)	Water Recycling Efficiency (%)
15%	0.24	97.8	0.04	85
20%	0.22	98.2	0.03	88
25%	0.21	98.8	0.025	90
30%	0.20	99.6	0.02	95

Table 2
JSIS current process and simulated process

Parameter	Current JSIS Process (NG-DRI-EAF)	Simulated H_2-DRI Process
CO_2 Emissions (tons CO_2/ton steel)	1.4-1.8	Approx. zero
Energy Consumption (GJ/ton steel)	15-18	12-15
Water Consumption (m^3/ton steel)	2-3	Self-sustained recycling
Process Efficiency (%)	85-90	99.6

Another major area is water management. Since the DRI-H_2 method both uses and creates water, it's important to recycle and reuse as much as possible. Future work should focus on advanced technologies like membrane filters or zero-liquid discharge (ZLD) systems. This can save water, especially in areas where water is limited. Cost and government support are also very important. To make hydrogen steel more common, governments and industries need to work together. Financial support, carbon pricing policies, and rules that support cleaner production can help a lot. Sharing knowledge globally between companies, researchers, and policymakers will make this shift smoother and faster. To sum up: the future of hydrogen-based steel depends on better hydrogen production, stronger reactors and water systems, supportive government policies, and digital tools. If these areas are improved, the steel industry can become cleaner and more eco-friendly.

5. Conclusion

The simulation showed that using hydrogen in steelmaking is very energy-efficient. This research met its goal of exploring how green hydrogen production can be integrated into steel manufacturing while also cutting down on water use. Using Jindal Shaheed Steel as a case study, the results showed that water efficiency can be improved without reducing hydrogen output. The process modelled in Aspen Plus indicated that the new design could lower overall water use by half as compared to standard electrolysis methods, while also reducing CO_2 emissions by 20%. These results show that renewable-powered electrolysis is both practical and beneficial for making steel production more sustainable and efficient in resource use.

The research suggests that future studies should improve cost estimates, build larger pilot plants, and explore more renewable energy sources to support this process. The simulation—done at one-twentieth the size of Jindal Shadeed Iron & Steel (JSIS) Oman's plant—proved /12th that hydrogen steelmaking is not just possible but practical. Unlike traditional methods that release large amounts of carbon dioxide, this hydrogen-based system had zero emissions. Even the water produced during the process was reused, making it even more sustainable This research explains the complete process of making steel using hydrogen (H_2) instead of traditional carbon-based methods. The study covers economic, technical, and environmental aspects. It uses Aspen Plus software to simulate the DRI-H_2 (Direct Reduced Iron with Hydrogen) process and shows that it can be a highly efficient and clean way to produce steel. The simulation achieved a very high efficiency of 99.6%, produced no carbon dioxide emissions, and included a water recycling system. These tests gave helpful information on how to make the process better. This helps both industries and researchers as they work on switching from old methods to cleaner ones. The results of this study are important not only for the steel industry but also for the global push toward cleaner technologies. As countries and companies aim to cut carbon emissions, this research shows that making steel with hydrogen is both a realistic and efficient solution. Its strong energy performance, zero emissions, and smart use of resources make it an excellent choice for sustainable steel production.

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