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An Overview of the Arguments in Literature, for and against the Use of Green Hydrogen for the Production of Direct Reduced Iron

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Abstract: The global steel industry is a major contributor to greenhouse gas emissions, and the adoption of green hydrogen in Direct Reduced Iron (DRI) production has the potential to significantly reduce CO2 emissions and support climate targets. This review explores the environmental, economic, technological, and social implications of using green hydrogen in DRI processes. The findings suggest that green hydrogen can reduce emissions by up to 90% compared to traditional methods, enhance energy security, and stimulate local economic development. However, high initial costs, energy efficiency concerns, and social acceptance issues remain significant barriers. The review also highlights the importance of integrating carbon capture and storage technologies, addressing logistical challenges, and considering the geopolitical implications of a shift towards green hydrogen. Green hydrogen presents a promising solution for decarbonising the steel industry but continued research, investment in infrastructure, and strategic planning are essential to overcome the challenges and drive widespread adoption.

Keywords: green hydrogen; direct reduced iron (DRI); decarbonisation; steel industry; carbon capture and storage (CCS); renewable energy; electrolysis; energy efficiency; geopolitical implications; social acceptance

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1. Introduction

The global steel industry is a significant contributor to greenhouse gas emissions, accounting for approximately 7% of global CO2 emissions [1]. As the world strives to mitigate climate change and achieve net-zero emissions, decarbonising the steel industry has become a critical priority. In this context, the adoption of green hydrogen in Direct Reduced Iron (DRI) production has emerged as a promising solution to reduce the industry's carbon footprint [2].

Green hydrogen, produced using renewable energy sources such as solar, wind, or hydroelectric power, offers a clean and sustainable alternative to traditional methods that rely on natural gas or coal [3]. By replacing fossil fuels with green hydrogen in DRI processes, the steel industry can significantly reduce its CO2 emissions and contribute to global efforts to combat climate change [4].

The potential of green hydrogen in DRI production has garnered increasing attention from researchers, policymakers, and industry stakeholders. Studies have shown that the use of green hydrogen in DRI processes can reduce emissions by up to 90% compared to traditional methods [**1**]. Moreover, green hydrogen can enhance energy security by reducing dependence on imported fossil fuels and using local renewable energy resources [**5**].

However, the widespread adoption of green hydrogen in the steel industry faces several challenges. The high initial costs of green hydrogen infrastructure, including electrolysers and renewable energy sources, pose a significant barrier [**6**]. Additionally, concerns regarding energy

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efficiency, logistical issues, and social acceptance must be addressed to ensure the successful implementation of green hydrogen in DRI production [7].

This review aims to provide a comprehensive overview of the current state of research on the use of green hydrogen in DRI production. By examining the environmental, economic, technological, and social implications of green hydrogen adoption, this review seeks to identify the key opportunities and challenges associated with this innovative approach to steelmaking. The findings of this review will contribute to the ongoing discourse on sustainable steelmaking and provide valuable insights for stakeholders involved in the transition towards a low-carbon steel industry.

2. Arguments for Green Hydrogen in DRI Production

2.1. Environmental Benefits

The use of green hydrogen as a clean energy source has the potential to significantly reduce carbon dioxide (CO2) emissions in various industries, including steel production through the Direct Reduced Iron (DRI) process. Green hydrogen is produced using renewable energy sources, such as solar, wind, or hydroelectric power, to electrolyse water, resulting in hydrogen gas and oxygen [8]. Compared to traditional methods that rely on natural gas or coal, green hydrogen offers a more sustainable and environmentally friendly alternative for energy production [9].

One of the key advantages of green hydrogen is its ability to cut emissions by up to 90% when used in DRI production processes, as highlighted by the International Energy Agency (IEA) in 2020 [1]. This reduction in emissions aligns with global climate targets and contributes to efforts to mitigate the impacts of climate change [4]. As the pressure to reduce greenhouse gas emissions intensifies, the adoption of green hydrogen in industries such as steel production becomes crucial for achieving net-zero emissions [10].

Research conducted by [11] emphasizes the role of green hydrogen in facilitating the steel industry's transition to net-zero emissions [11]. The use of green hydrogen in steel production processes not only helps reduce CO2 emissions but also supports the industry's efforts to become more sustainable and environmentally friendly [12].

Another significant benefit of green hydrogen is its minimal environmental impact, as it only produces water as a by-product when used for energy generation. [2] emphasize this point, highlighting the environmentally clean nature of green hydrogen as compared to conventional energy sources that result in harmful emissions and pollutants [2].

2.2. Benefit to Energy Security

The concept of green hydrogen produced from local renewable energy sources is gaining traction as a promising solution to reduce dependence on imported fossil fuels and enhance energy security. This is particularly relevant for countries or regions with limited fossil fuel resources, as it presents an opportunity to diversify their energy mix and reduce vulnerability to global energy market fluctuations [5].

One of the key advantages of green hydrogen is its potential to be produced locally from renewable energy sources such as wind, solar, and hydroelectric power. This means that countries or regions with abundant renewable energy resources can harness these sources to produce green hydrogen domestically, reducing the need for costly imports of fossil fuels. By doing so, they can bolster their energy security and reduce exposure to geopolitical risks associated with fossil fuel dependence [13].

Furthermore, the use of green hydrogen can contribute to the decarbonisation of the energy sector, as it produces no greenhouse gas emissions when used as a fuel or energy carrier. This aligns with global efforts to reduce carbon emissions, making green hydrogen an attractive option for countries seeking to meet their environmental goals while also enhancing energy security [14].

In addition to reducing dependence on imported fossil fuels, the pro6uction and use of green hydrogen can also stimulate local economic development. The establishment of green hydrogen production facilities and associated infrastructure can create new jobs and spur investment in the renewable energy sector, contributing to economic growth and resilience [**15**].

2.3. Economic Viability and Long-Term Cost Reduction

The initial investment in green hydrogen infrastructure refers to the significant capital expenditure required to set up the infrastructure necessary for the production, storage, and distribution of green hydrogen. This infrastructure includes electrolysers for water electrolysis, storage tanks for hydrogen, and a network of pipelines or transportation systems for distribution. LKAB has historically enjoyed state support in relation to other industries, making it assume that the state would not abandon its current industrial investment plans [16]. This blending of the roles of the state and the company allows avoiding accountability [16]. While the upfront costs are indeed high, it is widely recognised that these costs are expected to decrease significantly over time as technology continues to advance and mature [17]. The historically close ties between the Swedish state and LKAB, with the state often prioritising LKAB's interests, may partly explain why LKAB's highly ambitious and risky hydrogen plans have not been more critically scrutinised [16].

One of the key factors driving the anticipated cost reductions in green hydrogen production is economies of scale. As the demand for green hydrogen increases and production volumes rise, the unit cost of production is expected to decrease. This is due to the spreading of fixed costs over a larger output, which leads to cost efficiencies. Moreover, advancements in technology and the development of larger, more efficient electrolysers are also expected to contribute to cost reductions [18].

In their study, [6] discuss how these anticipated cost reductions could lead to green hydrogen becoming competitive with fossil fuels by 2030 [6]. This is a significant projection, as it suggests that green hydrogen could become a financially viable and attractive option for a range of industries and applications. If green hydrogen costs can indeed achieve parity with or even undercut fossil fuel prices, it has the potential to revolutionise the energy landscape and drive widespread adoption of sustainable energy solutions [19].

This cost competitiveness is particularly relevant for sustainable Direct Reduced Iron (DRI) production. Currently, traditional DRI production processes rely heavily on fossil fuels, contributing to carbon emissions and environmental degradation. However, the use of green hydrogen as a clean and sustainable alternative could transform the DRI production landscape. If green hydrogen costs can reach a level where they are competitive with fossil fuels, it would incentivise DRI producers to transition towards greener production methods, thereby reducing their carbon footprint and contributing to global efforts to combat climate change [20].

2.4. Potential for Carbon Capture and Storage (CCS)

DRI production is a carbon-intensive process due to the use of carbon-based reducing agents such as coal or natural gas. As the world moves towards decarbonisation, integrating green hydrogen with CCS technologies can significantly reduce the carbon emissions associated with DRI production.

Green hydrogen, produced through electrolysis using renewable energy sources, has gained prominence as a clean and sustainable alternative to traditional hydrogen production methods that rely on fossil fuels. By leveraging green hydrogen as a reducing agent in the direct reduction of iron ore, DRI producers can substantially lower their carbon footprint. This is particularly significant as DRI production is a key step in the steelmaking process, and the steel industry is one of the largest industrial emitters of carbon dioxide [2]. However, it is important to note that hydrogen is not an energy source but an energy carrier. Producing hydrogen requires more energy than the hydrogen itself generates when used [21].

Integrating CCS with green hydrogen-based DRI production can substantially amplify carbon emission reductions. CCS involves capturing CO2 from industrial sources, transporting it to suitable storage sites, and securely storing it underground to prevent its release into the atmosphere. When combined with CCS, the potential for emission reduction is further enhanced. According to [22], CCS can capture up to 90% of the CO2 emissions from industrial sources, including those from DRI processes [22].

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For instance, a study by [1] suggests that combining CCS with hydrogen-based DRI could reduce carbon emissions by an additional 30% compared to using green hydrogen alone [1]. This synergy creates a closed-loop system where CO2 emissions are minimised at both the production and post-production stages.

By integrating CCS with green hydrogen-based DRI, the industry can drastically lower its carbon footprint. As noted by [23], the combination of CCS with low-carbon hydrogen pathways is essential for the deep decarbonisation of industrial sectors [23].

CCS provides a way to handle residual emissions that are challenging to eliminate through green hydrogen alone, including emissions from auxiliary processes and fossil fuel use in other parts of the steel production chain. The ability to capture and store these emissions makes it feasible to achieve net-zero emissions, as highlighted by [5].

The integration of CCS with green hydrogen-based DRI also offers economic and technological synergies. Shared infrastructure for CO2 transport and storage can reduce overall costs. Additionally, advancements in CCS technology, such as improved capture efficiency and reduced costs, complement the ongoing improvements in electrolyser technologies [24].

CCS can also provide a buffer during the transition period to a fully hydrogen-based economy. As hydrogen production scales up and becomes more cost-competitive, CCS can mitigate emissions from interim fossil-based processes, ensuring a continuous path towards decarbonisation [1].

2.5. Technological Advancements

The use of green hydrogen in Direct Reduction Iron (DRI) processes has become increasingly feasible due to technological improvements in hydrogen production and storage. [24] emphasize the significance of innovations in electrolyser technologies, which are expected to enhance efficiency and reduce costs [24,25].

In addition to improvements in hydrogen production, advancements in hydrogen storage and transportation are also crucial in mitigating logistical challenges associated with the use of hydrogen in industrial processes. [26] highlight the importance of innovations in hydrogen storage and transportation technologies in making green hydrogen more accessible and practical for industrial applications [26]. Efficient and cost-effective storage and transportation solutions are essential for ensuring a reliable and sustainable supply of green hydrogen for DRI processes [27].

Furthermore, the use of hydrogen-based DRI technology offers additional advantages such as operating at lower temperatures, which reduces energy requirements and enhances process flexibility. [10] point out that the lower operating temperatures of hydrogen-based DRI processes not only contribute to energy efficiency but also open up opportunities for more flexible and sustainable iron production [28]. This is significant in the context of transitioning towards more sustainable and environmentally friendly industrial processes, where minimising energy consumption and resource use is a key priority [29].

Overall, the research literature emphasizes the importance of technological advancements in hydrogen production, storage, and transportation for making green hydrogen a viable and attractive option for DRI processes. These advancements not only contribute to the economic feasibility of using green hydrogen but also offer additional benefits such as energy efficiency and process flexibility. However, there is a risk that H2GS will not be able to secure sufficient high-quality iron ore since supply is limited and demand is expected to increase globally [30]. As the demand for sustainable industrial processes continues to grow, continued research and development in the field of hydrogen production and use are essential for driving the widespread adoption of green hydrogen in DRI processes and beyond [31].

3. Arguments Against Green Hydrogen in DRI Production

3.1. Technological Readiness

The technological readiness level (TRL) of green hydrogen-based DRI production is currently between 6 and 8, indicating that the technology is in the demonstration phase, with several pilot projects and early commercial applications already in operation [32]. For instance, the HYBRIT project in Sweden has successfully demonstrated the use of hydrogen in DRI production at a pilot scale, and plans are underway to scale up to commercial production [33]. The Hybrit project's plans were based on insufficient evidence, energy consumption was ignored, and the incentives for politicians to act responsibly were weak, similar to the Stålverk 80 project in the 1970s [21]. Similarly, other projects in China and Europe are exploring and implementing hydrogen-based DRI technologies [34]. However, the technologies LKAB, SSAB and H2GS are basing their projects on are not commercially proven at scale. There are risks that other emerging technologies could prove more viable and outcompete hydrogen-based steel production [30].

Pilot and Demonstration Projects:

- HYBRIT Project: This project has demonstrated the feasibility of using hydrogen for DRI production and is moving towards larger-scale operations [33].
- HBZX High Tech: In China, this project has implemented ENERGIRON® ZR technology, using over 60% hydrogen in the gas mix for DRI production, achieving significant reductions in CO2 emissions [34].

The technology is well-established in terms of its basic principles and has been proven to work at smaller scales. However, scaling up to full commercial operations presents several challenges, particularly in maintaining the metallisation degree in the shaft furnace and managing the different melting characteristics of carbon-lean DRI in Electric Arc Furnaces [35]. Further research is required to optimise the DRI process when using hydrogen, particularly in terms of heat distribution and the endothermic nature of hydrogen reduction. Additionally, balancing the carbon content in the final steel product and removing gangue materials from the iron ore are ongoing challenges [35]. In addition, as the availability of high-quality iron ore is critical for the DRI process. As global iron ore quality degrades, new methods for processing lower-grade ores need to be developed [36].

3.2. High Initial Costs and Economic Barriers

The transition to green hydrogen presents significant financial challenges due to the substantial capital expenditures required for various infrastructure components. One of the major expenses is electrolysers, which are essential for the production of green hydrogen. Electrolysers are devices that use electricity to split water into hydrogen and oxygen [37]. Renewable power plants require more non-renewable materials for construction compared to fuel-based alternatives [38]. Additionally, significant investment is needed for renewable energy infrastructure to provide the electricity required for electrolysis. This includes solar and wind farms, as well as grid infrastructure for the transmission of renewable power to electrolysis facilities [39]. Furthermore, the development of hydrogen storage facilities is a crucial investment for ensuring the availability of green hydrogen for industrial and transportation use [40]. If LKAB's and H2GS's plans are realised without a corresponding increase in electricity production, electricity prices in the Nordics could rise sharply, undermining the profitability of the projects themselves [41]. The cost of wind power plus battery storage can be up to 30 times higher than the cost of nuclear power, especially when wind power accounts for a large share of electricity production [42]. The cost of making Sweden's electricity production 100% renewable could exceed 1,600 billion SEK according to a study by Sweco [43]. Phasing out Swedish nuclear power and replacing it with wind power and natural gas for balancing could increase electricity costs by a factor of 2-10 [44].

In regions with existing fossil fuel-based steel production infrastructure, the high initial costs of transitioning to green hydrogen can particularly deter investment. This is because these regions may have well-established and efficient processes for obtaining and using fossil fuels, making it difficult for stakeholders to justify the initial costs of transitioning to green hydrogen production. Furthermore, these regions may have invested heavily in infrastructure that supports fossil fuel-based production, making the transition even more challenging [45].

The economic feasibility of green hydrogen production is also hindered by the current high cost of green hydrogen compared to natural gas. This cost disparity makes it less financially attractive for industries and other consumers to switch to green hydrogen, as natural gas remains a cheaper option.

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Countries with a high share of solar and wind power, such as Denmark and Germany, have significantly higher electricity prices than countries with traditional electricity systems, while also having high carbon emissions [42]. The high cost of green hydrogen is mainly attributed to the significant investment required for renewable energy infrastructure, as well as the electrolysers and storage facilities. As an example, Swedish grid subscribers must bear significant costs for transporting electricity to wind power companies' foreign customers while getting no access to this wind power themselves [42]. Additionally, the economies of scale for green hydrogen production have not yet been fully realised, further contributing to its high cost [46]. It is much more expensive to produce iron sponge with hydrogen compared to using natural gas, even when accounting for carbon emission costs. LKAB's fossil-free sponge iron is estimated to become the most expensive on the market [47].

To overcome these financial challenges and promote the transition to green hy-drogen, it is crucial for governments, industry stakeholders, and financial institutions to work together to develop financial incentives and mechanisms that can lower the initial investment costs. This can include policies such as investment tax credits, grants, and subsidies for green hydrogen infrastructure development. Additionally, innovative financing models, such as public-private partnerships and green bonds, can be used to attract private in-vestment and lower the financial barriers to green hydrogen adoption [48].

3.3. Energy Intensity and Efficiency Concerns

Producing green hydrogen, which is hydrogen produced from renewable sources such as wind or solar power, is seen as a key component in transitioning to a more sustainable energy future. However, as highlighted by [5], the production of green hydrogen is currently energy-intensive due to the large amounts of renewable electricity required for the electrolysis process [5]. As the share of wind power increases, so does the number of serious incidents related to grid stability and power margin [42]. Wind power has a much lower Energy Return on Investment (EROI) than nuclear power, especially when accounting for the need for energy storage, meaning it delivers significantly less net energy [50,51]. Building wind power in remote areas is not a sustainable solution as it requires massive expansion of transmission grids without addressing power shortages [42] and in addition there is significant costs for new transmission capacity and substantial grid losses of, in the case of Sweden, around 10% from north to south and 20% for exports [42]. It would be more cost-efficient and environmentally beneficial to produce electricity locally [42].

Electrolysis, the process of splitting water into hydrogen and oxygen using an electric current, is the most common method for producing green hydrogen. However, this process is not without its challenges. One of the major concerns is the overall energy efficiency of the process. Significant energy losses occur during electrolysis and subsequent hydrogen use, which raises questions about the sustainability and effectiveness of green hydrogen production [5]. Furthermore, as highlighted by [51], this inefficiency not only impacts the cost-effectiveness of green hydrogen but also raises concerns about the optimal use of renewable energy resources [52].

In light of these concerns, it becomes crucial to explore ways to improve the energy efficiency of green hydrogen production. Research and development efforts are focused on finding innovative electrolysis technologies, such as proton exchange membrane electrolysis and solid oxide electrolysis, that can improve the overall efficiency of the process [53]. Additionally, integrating energy storage solutions, such as batteries or hydrogen storage, can help mitigate the energy losses associated with fluctuating renewable electricity generation [54]. Moreover, advancements in hydrogen using technologies, such as fuel cells for power generation and hydrogen blending in natural gas pipelines, can contribute to maximising the use of green hydrogen and minimising energy waste [55].

Furthermore, it is essential to consider the broader implications of green hydrogen production on the renewable energy sector. As the demand for renewable electricity to power electrolysis processes increases, there is a need to ensure the sustainable and optimal use of renewable energy resources. This requires a comprehensive understanding of the interplay between green hydrogen

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production and renewable energy generation, as well as the development of policies and frameworks that support the integration of green hydrogen into the existing energy infrastructure [56].

From the above can be seen that production of green hydrogen holds great potential for decarbonising various sectors, but its energy-intensive nature and associated efficiency concerns necessitate ongoing research and innovation. By addressing the energy efficiency challenges and optimising the use of renewable energy resources, green hydrogen can play an important role in the transition towards a sustainable and low-carbon energy future.

3.4. Infrastructure and Logistical Challenges

The existing infrastructure for hydrogen production, storage, and distribution is indeed a critical aspect that needs further development to support the widespread adoption of green hydrogen in industrial applications. As highlighted by the International Renewable Energy Agency (IRENA), the lack of a robust hydrogen infrastructure poses significant challenges [57].

Hydrogen has the potential to play an important role in decarbonising various industries, such as steelmaking. However, logistical issues such as hydrogen leakage and the need for specialised storage solutions add complexity and cost to the implementation of hydrogen infrastructure [58].

Hydrogen leakage is a major concern as it can lead to safety hazards and potential environmental impacts. Addressing this issue requires the development of advanced leak detection and prevention technologies, as well as the implementation of stringent safety regulations and guidelines for handling and transporting hydrogen [59].

Moreover, the need for specialised storage solutions further complicates the infrastructure development. Traditional storage methods may not be suitable for hydrogen due to its unique chemical properties, such as low density and high reactivity. Therefore, research and development efforts are necessary to design and implement safe and efficient hydrogen storage systems that can meet the specific requirements of industrial applications [60].

Transitioning to hydrogen-based steelmaking, as noted by [12], also presents significant challenges in terms of infrastructure and technology. Steelmaking processes rely heavily on the availability of high-temperature heat, which is typically generated by burning fossil fuels. Integrating hydrogen into steelmaking processes requires substantial investments in modifying existing infrastructure and developing new technologies to harness the potential of hydrogen as a replacement for fossil fuels [61].

In this context, the development of a comprehensive hydrogen infrastructure for industrial applications demands collaborative efforts from governments, industry stakeholders, and research institutions. Policy support, financial incentives, and collaborative research and development initiatives are essential to overcome the technological and economic barriers associated with the establishment of a robust hydrogen infrastructure [59].

Furthermore, the integration of hydrogen into existing industrial processes requires a holistic approach that addresses not only the technological aspects but also the regulatory, safety, and economic considerations. To achieve this, interdisciplinary research and innovation are vital to develop tailored solutions for different industrial sectors, taking into account the specific requirements and challenges of each application [62].

From the above follows that the potential of green hydrogen in industrial applica-tions is substantial, but the underdeveloped infrastructure for hydrogen production, storage, and distribution presents significant hurdles that need to be addressed. Tackling logistical issues, developing specialised storage solutions, and overcoming technological challenges are critical steps in laying the foundation for the widespread adoption of green hydrogen in industrial processes. Collaboration and concerted efforts across various stakeholders are essential to drive the development of a robust hydrogen infrastructure that can support the transition to a more sustainable and low-carbon industrial future.

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3.5. Competition with Other Sectors

Green hydrogen is expected to play a crucial role in the decarbonisation of various sectors, including steel production, transportation, and chemical manufacturing. As the demand for green hydrogen increases across these sectors, competition for limited hydrogen resources is inevitable. This competition has the potential to impact the availability and cost of green hydrogen for Direct Reduced Iron (DRI) production, which relies heavily on hydrogen as a reducing agent [63].

The transportation sector is one of the major sectors that may compete with the steel industry for green hydrogen resources. With the increasing focus on decarbonisation, many transportation companies are exploring hydrogen fuel cell technology as an al-ternative to traditional fossil fuels. This surge in demand from the transportation sector could potentially strain the available green hydrogen resources, leading to competition with the steel industry for access to these resources [64].

The chemical production sector is also expected to be a key competitor for green hydrogen resources. As the chemical industry transitions towards greener and more sustainable production methods, the demand for green hydrogen is anticipated to increase. This growing demand from the chemical sector can further exacerbate the competition for green hydrogen, impacting its availability and driving up costs for steelmakers relying on green hydrogen for DRI production [65].

The potential competition for green hydrogen resources could have significant implications for the steel industry, particularly for DRI production. DRI production is heavily dependent on green hydrogen as a clean and efficient reducing agent for iron ore. Any constraints on the availability of green hydrogen or an increase in its cost could directly impact the cost and feasibility of DRI production. This, in turn, could affect the overall competitiveness of steelmakers using DRI as a feedstock for steel production [66].

To mitigate the potential impact of competition for green hydrogen resources, stakeholders in the steel industry must proactively engage with other sectors and policymakers to ensure a secure and affordable supply of green hydrogen. Collaboration between the steel industry, transportation sector, and chemical producers can help in developing coordinated strategies for the sustainable production and distribution of green hydrogen. Additionally, policymakers play a crucial role in creating a conducive regulatory framework and incentivising investments in green hydrogen production infrastructure to meet the growing demand across various sectors [67].

From the above follows that as the demand for green hydrogen increases across multiple sectors, competition for limited hydrogen resources is likely to intensify. The steel industry, particularly in DRI production, may face challenges in accessing affordable green hydrogen due to potential competition from the transportation and chemical production sectors. Proactive collaboration and strategic planning will be essential for ensuring a sustainable and secure supply of green hydrogen for the steel industry while accommodating the needs of other sectors in the transition towards decarbonisation.

3.6. Geopolitical Implications

The shift towards green hydrogen-based direct reduced iron (DRI) production has the potential to reshape the geopolitical landscape, especially for countries or regions that heavily rely on fossil fuel exports. This shift is driven by the global effort to reduce carbon emissions and combat climate change, leading to the increasing adoption of green hydrogen as a clean and sustainable energy source for industrial processes such as DRI production. The ongoing energy transition shifts dependence from one resource-critical system (fossil fuels) to another (strategic metals), as renewable power requires ten times more strategic metals than fuel-based alternatives [42]. As a result, countries that are major exporters of fossil fuels, such as oil and natural gas, may face significant economic and political consequences [68].

One of the primary geopolitical implications of the shift towards green hydro-gen-based DRI production is the potential loss of market share and revenue for fossil fuel-exporting countries. As the global demand for green hydrogen increases, there is a risk that the demand for traditional fossil fuels will decline, leading to reduced export revenues for countries that rely heavily on these commodities [69]. This can have sig-nificant economic repercussions for these countries, as their national budgets and eco-nomic stability are often highly dependent on revenues from fossil fuel exports [70].

Furthermore, the geopolitical power dynamics among countries and regions that are major exporters of fossil fuels may undergo significant shifts. Traditional fossil fuel-exporting countries have historically held significant geopolitical influence due to their role as major energy suppliers. However, the rise of green hydrogen as a viable alternative and the increasing focus on sustainable energy sources could lead to a redistribution of geopolitical power [71]. Countries that are able to emerge as leaders in green hydrogen production and export may gain greater geopolitical influence, while traditional fossil fuel exporters may see a decline in their geopolitical standing [72].

The shift towards green hydrogen-based DRI production can also have political consequences for fossil fuel-exporting countries. A decline in export revenues and economic in-stability due to the shift towards green hydrogen could lead to internal political chal-lenges, social unrest, and potential shifts in government policies and priorities [73].

Moreover, the international relationships and alliances among countries may also be affected by the shift towards green hydrogen-based DRI production. Traditional fossil fuel-importing countries that have been reliant on fuel imports may seek to strengthen ties with green hydrogen-producing nations to secure a stable and sustainable energy supply [70]. This could lead to the formation of new partnerships and alliances, while also potentially straining existing relationships with traditional fossil fuel-exporting countries [73].

From the above can be concluded that the shift towards green hydrogen-based DRI production has the potential to have geopolitical implications, particularly for countries or regions that heavily rely on fossil fuel exports. The economic and political consequences of this shift may lead to shifts in global power dynamics, international relationships, and domestic stability within fossil fuel-exporting countries. As the world continues to transition towards sustainable energy sources, it is essential for policymakers and stakeholders to carefully consider and address the geopolitical implications of this shift.

3.7. Social Acceptance

The large-scale deployment of renewable energy infrastructure necessary for green hydrogen production faces several social acceptance issues. These issues can significantly impact the feasibility and success of such projects. The large land areas required by industrial forestry for biofuels and by wind power are particularly problematic for biodiversity [42]. Green hydrogen production requires large amounts of electricity. In terms of land use, wind power requires 10-1000 times more area than nuclear power when considering the full industrial area, roads, power lines, and balancing power [42]. Replacing all of Sweden's nuclear power with wind power plus battery storage could cost up to 8,000 billion SEK [42]. Industrial wind power can cause disturbances and chronic health conditions for people living in the surrounding areas due to its impact on the sound and light environment [42]. The production of hydrogen through electrolysis is a major contributor to increased electricity demand in future scenarios [74]. LKAB's plans to expand downstream and produce iron sponge using hydrogen would alone require half of Sweden's planned doubling of electricity consumption until 2050 [49]. This poses major challenges for Sweden's electricity system and prices [41]. Wind power projects in Sweden are largely financed and owned by foreign companies, and a significant portion of the electricity produced is exported, correlating with high levels of wind power production [42]. This exported wind power takes up important capacity in the grid, causing bottlenecks that affect Swedish grid customers [42] The very large wind power expansion required to produce the electricity for green hydrogen poses challenges. It would have major land use requirements compared to nuclear power [75,76]. It could also have negative impacts on some primary industries [77] and potentially cause health issues for humans and animals nearby [78].

While there is broad public support for renewable energy at a national level due to its environmental benefits and role in mitigating climate change, this does not always translate to local acceptance [7,79]. Local communities often oppose renewable energy projects due to concerns about

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their immediate impact. This phenomenon, known as NIMBYism (Not In My Back Yard), can lead to significant delays and even cancellations of projects [80,81].

Trust in government, industry, and other stakeholders is crucial for the acceptance of renewable energy projects. Studies have shown that a lack of trust can lead to resistance, as communities may doubt the intentions and benefits promised by project developers [82,83]. Fair and transparent decision-making processes are essential. Communities need to feel that their concerns are heard and addressed through inclusive and meaningful public participation in the planning and implementation stages of projects [7].

Ensuring that the benefits of renewable energy projects are fairly distributed is critical. Communities are more likely to support projects if they see tangible benefits, such as job creation, local investments, and improved infrastructure [79]. Models that involve community ownership and control of renewable energy projects can enhance acceptance, ensuring that economic benefits flow directly to local communities [50].

Concerns about the local environmental impact of renewable energy projects, such as noise, visual intrusion, and effects on wildlife, can lead to opposition [84]. For example, wind farms and solar parks can alter landscapes and ecosystems, which may be unac-ceptable to local residents. Perceived health risks associated with renewable energy in-frastructure can also be a source of resistance [80].

Public awareness and understanding of green hydrogen and its benefits are still limited. Effective communication strategies that provide clear, accurate, and accessible information are necessary to build support [83]. Misinformation and misconceptions about renewable energy technologies can fuel opposition. Addressing these through education and transparent communication is essential [7].

Acceptance can vary based on socio-demographic factors such as age, income, education, and gender. Higher-income and more educated individuals tend to be more supportive of new energy technologies [80]. Cultural attitudes and regional contexts also play a significant role in shaping perceptions and acceptance. Tailoring engagement strategies to specific cultural and regional contexts can help mitigate resistance [50].

4. Findings and Discussion

This review explores the potential of green hydrogen for Direct Reduced Iron (DRI) production, emphasizing its environmental, economic, and technological impacts, as well as social acceptance issues and geopolitical implications.

Green hydrogen, produced using renewable energy sources, can reduce CO2 emissions by up to 90% compared to traditional methods relying on natural gas or coal [1]. It produces only water as a by-product, making it a sustainable alternative that aligns with global climate targets [11].

Green hydrogen offers countries with limited fossil fuel resources a way to enhance energy security by reducing dependence on imported fuels and using local renewable energy resources [5].

The high initial costs of green hydrogen infrastructure, including electrolysers and renewable energy sources, are a significant barrier. However, anticipated cost reductions through economies of scale and technological advancements could make green hydrogen competitive with fossil fuels by 2030 [6]. Concerns about potential increases in electricity prices and the overall economic impact on regions with existing fossil fuel-based infrastructure remain [45].

Integrating green hydrogen with CCS technologies can further reduce carbon emissions, capturing up to 90% of CO2 emissions from industrial sources [22]. This synergy is essential for achieving net-zero emissions in the steel industry [23].

Technological improvements in hydrogen production, storage, and transportation are critical for making green hydrogen a viable option for DRI processes. Innovations in electrolyser technologies and hydrogen storage solutions are expected to enhance efficiency and reduce costs [24].

The deployment of renewable energy infrastructure for green hydrogen production faces significant social acceptance issues. Effective communication, fair decision-making processes, and com-munity involvement are essential to mitigate these issues.

The shift towards green hydrogen could alter geopolitical dynamics, particularly for fossil fuel-exporting countries. These countries may face economic and political challenges as demand for fossil fuels declines, potentially leading to reduced export revenues and shifts in global power dynamics [69].

5. Future Research Directions

Future research should focus on addressing the challenges and knowledge gaps identified in this review. Some key areas for further investigation include:

- Techno-economic analyses of green hydrogen-based DRI production at a commercial scale, considering various technological configurations and regional contexts [85].
- Optimisation of hydrogen storage and transportation infrastructure to ensure a reliable and cost-effective supply of green hydrogen for industrial applications [27].
- Development of advanced electrolyser technologies and renewable energy integration strategies to improve the energy efficiency and economic viability of green hydrogen production [31].
- Exploration of innovative financing mechanisms and policy frameworks to incentivise investments in green hydrogen infrastructure and promote its adoption in the steel industry [48].
- Investigating the potential synergies between green hydrogen and other emerging low-carbon technologies, such as biomass-based reducing agents and carbon capture and utilisation (CCU) [4].
- Assessing the social acceptance and environmental impact of large-scale renewable energy infrastructure for green hydrogen production [*84*]
- Examining the geopolitical implications of a global shift towards green hydrogen, including the potential redistribution of power dynamics and the formation of new international partnerships and alliances [73].

By addressing these research gaps, future studies can contribute to the development of sustainable and economically viable green hydrogen-based DRI production, supporting the steel industry's transition towards a low-carbon future.

6. Conclusions

Green hydrogen presents a promising solution for decarbonising the steel industry through its application in Direct Reduced Iron (DRI) production. It offers significant environmental benefits, enhancing energy security, and potential economic advantages. However, substantial challenges remain, including high initial costs, energy efficiency concerns, and social acceptance issues. Technological advancements and supportive policies are crucial for overcoming these barriers and realising the full potential of green hydrogen.

Integrating Carbon Capture and Storage (CCS) with green hydrogen-based DRI production can further amplify emission reductions, making it feasible to achieve net-zero emissions. The combination of these technologies provides a robust pathway for the steel industry's transition towards sustainability.

Addressing social acceptance issues through transparent communication, equitable benefit distribution, and community involvement is essential for the successful deployment of renewable energy infrastructure. Additionally, the geopolitical implications of the shift towards green hydrogen must be carefully managed to ensure stable international relationships and domestic stability for fossil fuel-exporting countries.

Green hydrogen has the potential to change the steel industry and contribute significantly to global climate targets. Continued research, investment in infrastructure, and strategic planning are essential to overcome the challenges and drive the widespread adoption of green hydrogen in DRI production and beyond.

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