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Exploring Decarbonization Strategies: A Comprehensive Analysis of Climate-Neutral Hydrogen's Impact on Energy, Environment, and Economics in iron and steel industry

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supervised by
Dr. Behnam Zakeri

Maryam Malayeri, BSc

12209685

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École des Hautes Études Internationales de Vienne

Affidavit

I, **MARYAM MALAYERI, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "EXPLORING DECARBONIZATION STRATEGIES: A COMPREHENSIVE ANALYSIS OF CLIMATE-NEUTRAL HYDROGEN'S IMPACT ON ENERGY, ENVIRONMENT, AND ECONOMICS IN IRON AND STEEL INDUSTRY", 54 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

The steel industry stands as a significant contributor to global carbon emissions, posing a formidable challenge in the quest for decarbonization. As societies increasingly prioritize sustainability, the demand for low-carbon steel production processes intensifies. In response, the integration of green hydrogen emerges as a promising solution to mitigate carbon footprints in steel manufacturing. This thesis explores the role of green hydrogen in decarbonizing the steel industry. Green hydrogen, produced through electrolysis powered by renewable energy sources, offers a clean alternative to traditional hydrogen production methods reliant on fossil fuels. By leveraging renewable energy inputs, green hydrogen production achieves carbon neutrality, thereby addressing the environmental concerns associated with conventional steelmaking. The adoption of green hydrogen in steel production holds immense potential to revolutionize the industry's carbon footprint.
This thesis delves into the technical feasibility, economic viability, and environmental benefits of integrating green hydrogen into steel manufacturing processes. The thesis found that using electric arc furnaces with scraps and green hydrogen will significantly reduce emissions. Despite consuming more energy and being more expensive than traditional technologies, these methods are likely to make a substantial contribution to global efforts in combating climate change and facilitate the transition towards a more sustainable and greener steel sector.

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1. Introduction

The concept of climate change has nowadays sparked a heated debate throughout the last decades. While, the environmental crisis arising from climate change has substantially increased. More natural disasters are occurring due to the dramatic increase in temperature including relentless heatwaves and droughts, uncontrollable wildfires, unprecedented floods, air pollution, etc. Currently, climate change is negatively impacting human lives and their health and the basic needs for having a good health -clean air, hygiene and safe drinking water- are now under threat. According to the WHO reports, it is estimated about 13,7 million deaths are attributed to the environmental causes, consisting of 24% of global deaths (Zarocostas, 2006). The figures depict an environmental injustice among the poor and rich countries. The environmental burden is not fairly equalized between countries and the risk is about fifteen times higher in developing countries than in developed countries, which mostly children are five times more affected in comparison to the total population. About 42% and 20% of respiratory infections like asthma and lung cancer in developing and developed countries respectively are caused by environmental factors such as air pollution. In total, 4.2 million people are annually dying due to the poor level of air quality mostly consisting of fine particulate matter (World Health Organization, 2024).

The impact of greenhouse gas emissions (GHG) and the climate change have become a threat to mankind lives, which makes the international organizations to regularly convene international summits such as the Conference of Parties (COPs) to discover novel and innovative findings. In these conferences, scientists and authorities from multiple member states gather and collectively make effective decisions to successfully combat the climate change. For instance, given to the United Nations framework, they have introduced seventeen sustainable development goals (SDGs) in 2015 at the Paris Agreement and the thirteen goal covers the climate change issue (United Nations, 2024). It should be considered that these targets should be attained by 2030, therefore; immediate and efficient actions need to be taken. Carbon neutrality involves reducing CO2 emissions as much as possible and offsetting any remaining emissions to achieve a net-zero impact on the atmosphere. While electrolysis powered by renewable energy is a key component of achieving carbon neutrality in hydrogen production, the associated lifecycle emissions must be managed and balanced with carbon sequestration and offset activities. This comprehensive approach ensures that the overall impact on the climate is neutral, aligning with global efforts to mitigate climate change.

On the one hand, today, steel industries are significantly contributing to the production of greenhouse gas emissions, which primarily include carbon dioxide $(\mathrm{CO_2})$, methane $(\mathrm{CH_4})$ and nitrious oxide $(\mathrm{N_2O})$. These gases trap heat in the atmosphere and cause the greenhouse effect. Among mentioned gases, carbon dioxide accounts for nearly 80% of the total greenhouse gas emissions United States Environmental Protection Agency). Given the statistics, the global carbon dioxide emissions produced by anthropogenic interferences (fossil fuels, industries and other human-induced activities) account for 37.15 billion metric tons $\llbracket(GtCO\rrbracket_2)$ in 2022 (Statista, 2024) and roughly 7-9% of the total anthropogenic GHG are attributed to the steel industry (Carbon Brief, 2024). Currently, in order to manufacture one ton steel, 1.41 tons of CO_2 is emitted. In 2020, approximately 1878 million tons of crude steel were produced, which means that overall, nearly 2647 million tons of carbon dioxide was emitted into the air in the mentioned year (World Steel Association, 2024). The largest contributor to global greenhouse gas emissions is China, where the greatest steel industry is also located. Additionally, the second-largest emitters are, respectively, India, Japan, the United States, Russia, South Korea, Germany, Brazil and Iran. Alongside China, these countries represent the major steel-producing nations globally (Choi and Kang 2023). Based upon analytics, these ten countries collectively generate about 83% of the global crude steel (Worldsteel, 2022).

On the other hand, it should be also considered that steel is a crucial material for a country's economic growth, leading to the spreading of prosperity and wealth among the individuals. Nevertheless, steel industries' raw materials are highly dependent on coal, which is used as a reduced agent in order to extract iron pig from the iron ore and engender the carbon concentration needed in steel. Over the last decade, the global production of steel dramatically increased due to the rise in the steel demand. However, according to the Intergovernmental Panel on climate change (IPCC) reports and the Paris agreement signed in 2015, in order to fulfill the goal of preventing the global temperature from increasing by more than 2 degrees Celsius and aiming to minimize it to 1.5 degree Celsius (IPCC, 2022) compared to pre-industrial level, greenhouse gas emissions must to be dramatically reduced until 2050. It is predicted that the steel industry needs to deduct its carbon dioxide emission by up to 24% from 1.41 tons of CO_2 per tonne of steel to 1.07 tons of CO_2 per tonne of steel (International Energy Agency, Steel: Tracking Industry, 2024). Hence, finding innovative and new substitutive methods for the steel industry would be a positive asset on our path forward.

This paper tries to focuse on Voestalpine, an Austrian steel industry, located in Linz, Austria as a sample case besides other green projects. Voestalpine has four major divisions including steel production, metal forming, metal engineering, and high-performance metal production. The company's annual revenue in 2021/2022 was approximately 15 billion euros, with 36% of Voestalpine's total revenue derived from steel production. This company is one of the most successful and profitable steel industries in Europe. There are two different locations of Voestalpine steel plants in industry, Voestalpine Stahl Linz and Voestalpine Stahl Donawitz. The Voestalpine steel industry located in Linz produces annually 6 million tons of steel and the Voestalpine in Donawitz has an annual capacity of 1.57 million tons. In sum, the capacity of the plants collectively account for 7.57 million tons per year (GMK Center, 2024). This thesis aims to address the challenge of reducing carbon dioxide emissions by up to 80% in the steelmaking industry. Through a comparative analysis of cutting-edge technologies implemented in steel production, the study seeks to provide answers to the following questions:

- What are the latest technologies contributing to the carbon neutrality of the steelmaking industry?
- What is the energy consumption and infrastructure implementation cost associated with these new technologies?
- What potential carbon dioxide emissions reductions can be achieved with different technological approaches?
- How can we achieve the decarbonization of the iron and steel industry by 2040?

2. Literature review

Steel has become a valuable supply for centuries and its usage has been substantially increasing during the last decades. Compared to the year 1950, the amount of steel produced in 2018 has increased from 200 megatons to 1804 megatons of crude steel (CS). In the years following 2018, due to the Covid-19 pandemic, steelmaking experienced a modest increase (Lopez, Farfan, and Breyer 2022).

Regarding energy demand, steelmaking consumes a substantial amount of energy and primarily sourced from coal. In total, 35 exajoules (EJ) (9.722 petawatt-hours) of energy were attributed to the steel and iron industry in 2022. From this share, the vast majority of energy comes from coal, supplying 26 EJ, followed by electricity at 5 EJ, gas and district heating each at 1 EJ. It is anticipated that by advent of innovative technologies, the aggregate energy consumption of steel manufacturing by 2030 will decline to 32 EJ, representing a reduction of roughly 14%. Consequently, the reliance on coal is expected to diminish, being supplanted by other energy sources derived from electricity and bioenergy, renowned for their enhanced sustainability and efficiency (IEA, 2020a).

2.1. Traditional steel production approaches

In the steel industry, steel can be produced through various methods and categorized into three main processes including blast furnace, direct reduced iron-electric arc furnace, and scrap-based electric arc furnace (Nduagu et al. 2022). The blast furnace is the conventional and mostly used method for steel production due to its reliance on the fossil fuel-dependent raw materials such as iron ore, coke, and limestone. According to table 2, approximately, 72% of global steel is made from this blast furnace-basic oxygen furnace method (Worldsteel, 2022). This type of furnaces is likely to convert about 350 tons of iron ore into steel by up to 40 minutes.

In this approach, the feedstocks are charged into the blast furnace. Then, these inputs combine with hot air, added from the bottom of the blast furnace, leading to the combustion of coke and generation of carbon Monoxide (CO) through chemical reaction 3C (s)+3/2 O_2 (g)→3CO (g). The high temperature in the blast furnace melts the pig iron. This molten pig iron contains a high concentration of carbon and consist of impurities. Then, the liquid will be transferred into the basic oxygen steelmaking also known as Linz-Donawitz steelmaking. By providing pure oxygen amidst the steps, the produced carbon monoxide reacts with the iron ore oxide. The output of this reaction would be the production of carbon dioxide and steel 3CO (g)+Fe_2 O_3 (s)→ 2Fe (s)+3CO_2 (g). In this step, oxygen is blown into pig iron and provide the oxidation process in order to abate the carbon content and form a low-carbon steel alloy (Benavides et al. 2024). The energy intensity values of blast furnace-basic oxygen furnace accounts for 6.93 MWh_{th}/T_{CS} and 0.13 MWh_{el}/T_{CS} (Otto et al. 2017).

The following table provides the carbon dioxide (CO_2) emission factors for different energy carriers used in industrial processes, highlighting the amount of CO2 produced per gigajoule (GJ) of energy.

Table 1. *carbon dioxide (CO2) emission factors for different energy carriers.*

Energy carrier	*CO_2emission factor*
Natural gas	56 kg/GJ
Blast furnace gas	257.8 kg/GJ
Coke	94.2kg/GJ
Basic oxygen furnace gas	257.8 kg/GJ

Typically, natural gas has a CO_2 emission factor of 56 kilograms per gigajoule (kg/GJ). This means that for every gigajoule of energy produced by burning natural gas, 56 kilograms of CO_2 are emitted. This relatively low emission factor indicates that natural gas is a cleaner fossil fuel option compared to others used in industrial processes.

In addition, the CO_2 emission factor for a blast furnace gas is significantly high at 257.8 kg/GJ. This high emission factor reflects the considerable amount of CO_2 released per gigajoule of energy produced in the blast furnace process. The blast furnace, used extensively in traditional steelmaking, involves the combustion of large quantities of coke and other carbon-rich materials, leading to substantial CO_2 emissions.

Coke, a derivative of coal used primarily as a fuel and reducing agent in blast furnaces, has a CO_2 emission factor of 94.2 kg/GJ. This indicates that for each gigajoule of energy produced by burning coke, 94.2 kilograms of CO_2 are emitted. While this is lower than the emission factor for the blast furnace process as a whole, it still represents a significant source of CO_2 emissions in steel production.

Basic oxygen furnace (BOF) gas has a CO_2 emission factor of 257.8 kg/GJ, identical to that of the blast furnace. This indicates that the gases emitted from the BOF process, which is another method used in steelmaking, are equally carbon-intensive. The high emission factor underscores the environmental impact of BOF gas in industrial processes.

In overall, the CO_2 emission factors provided in the table highlight the environmental impacts associated with different energy carriers used in steel production. Natural gas, with the lowest emission factor of 56 kg/GJ, emerges as a more environmentally friendly option compared to coke, blast furnace operations, and basic oxygen furnace gas, all of which have significantly higher emission factors. These insights are crucial for developing strategies aimed at reducing carbon emissions in industrial processes.

The second alternative approach for steelmaking is the electric arc furnace utilizing direct reduced iron. In this technique, reducing agents such as natural gas or coal facilitate the extraction of oxygen from iron ore. Direct reduced iron serves as the end product of the direct reduction reaction, which, upon transfer to the electric arc furnace, undergoes conversion into steel. As opposed to the conventional blast furnace, the iron ore does not melt the iron and form pig iron, while, the EAF directly reduces the iron ore and melts the steel and add additional components to form steel alloys in the electric arc furnace. In an electric arc furnace, each material that consists of iron, even scraps, can be melted due to the usage of electric power. The energy of electric arc furnace is provided by carbon electrodes utilized in the electric arcs.
It should be considered that the energy intensity values of direct reduction route utilizing the electric arc furnace accounts for 4.13 MWh_{th}/T_{CS} and 0.92 MWh_{el}/T_{CS}. (Otto et al. 2017). Only 28.0% of global steel manufacturers employ the electric arc furnace method, with primary representatives being the United States, Turkey, and India (He, Wang, and Li 2020). This type of furnaces is likely to convert about 100 tons of iron ore into steel by up to 40-50 minutes.

Furthermore, the third alternative option, supplementing the second alternative, involves utilizing various scraps or recycled steel as input materials in the electric arc furnace (Kim et al. 2022). This represents a promising pathway to contribute to the circular economy, with the potential to use 100% of scraps as the feedstock. The major advantage of utilizing scraps as the input is the reduction in the energy consumption and carbon dioxide emissions, representing an effective step toward mitigating climate change. However, the current supply of scraps is inadequate to meet steel demand. In this case, industries often supplement scraps with iron ore due to the shortage of the recycled steels. It is predicted that the supply of the steel scraps will increase, nevertheless, this will coincide with a rise in steel demand as well (International Energy Agency, 2024).

In an electric arc furnace (EAF), the input materials consist of sorted scrap steel, briquetted iron sponge (HBI), liquid pig iron as the iron supplier, and quicklime as slag formers. EAFs essentially melt down these input materials for further operations. As the name indicates, the melting process is achieved using electrical energy to generate an electric arc within the furnace. When the furnace is fully loaded with input materials, the lid is closed. The EAFs are equipped with three graphite electrodes, each approximately 70 cm thick. Once the input materials are charged, roughly 80,000 amperes of current flow through the electrodes to generate the electric arc needed for melting.

By making a comparison between electric arc furnace and blast furnace, the blast furnace process involves smelting iron ore with coke to produce pig iron, while the electric arc furnace process uses sponge iron as an input. Sponge iron is typically produced through direct reduction processes in a shaft furnace, where iron ore is reduced using a gaseous phase reducing agent such as natural gas or hydrogen. Unlike the blast furnace, the electric arc furnace operates at relatively lower temperatures (600 degree Celsius), typically below the melting point of iron.

In addition, blast furnaces have the advantage of high productivity. However, the high temperatures involved lead to significant carbon dioxide emissions. In contrast, electric arc furnaces can utilize the direct reduction iron process. Nevertheless, electric arc furnaces require a high degree of metallization and involve extensive slag handling (Kim et al. 2022).

***Table 2**. Comparing the crude steel production with blast furnace and electric arc furnace in major steel producing countries (World Steel Association, 2020).*

Country	*BOF crude steel production (million tonnes)*	*EAF crude steel production (million tonnes)*	*Total crude steel production*
China	893.3	103.2	996.5
India	48.7	62.7	111.4
Japan	75.0	24.3	99.3
USA	26.6	61.2	87.8
Russia	45.9	24.1	70.0
South Korea	48.7	22.7	71.4
Germany	27.7	11.9	39.6
Total	1165.9	310.1	1477.7

While numerous nations are strategizing to integrate direct reduction iron (DRI) in emerging steel sectors and transition from conventional blast furnace methods to more sustainable alternatives, China and India are currently inclining towards constructing blast furnaces. This contrast in approach underscores the diverse trajectories in steel production methodologies globally. The rationale behind such decisions could vary, influenced by economic priorities, resource availability, infrastructural considerations, and the pace of technological assimilation. However, it's imperative to acknowledge that the shift towards eco-friendly steel production methods demands concerted efforts on a global scale, necessitating collaboration and knowledge exchange among nations to mitigate environmental impact and achieve collective climate objectives.

In this paper, my focus is on future alternatives for steelmaking. I will compare different methods of producing one ton of crude steel in terms of carbon dioxide emissions, energy intensity, and economic viability. These methods include the blast furnace, electric arc furnace with scraps and electric arc furnace with the direct reduction, the Circored process powered by electrolysis, and non-renewable energy sources. The goal is to contribute to neutralizing the carbon dioxide emissions associated with steel production.

2.2. Hydrogen as a bridge towards decarbonization

While using fossil fuel, mostly coal, in the steel industry does not match with the sustainability goals set in Paris agreement, thus, the development and deployment of new technologies is immediately required. Researchers are developing multiple alternative options for the abatement of greenhouse gas emissions from the steel industry. Among the alternatives, the electric arc furnace method has an advantage that lies in its its suitability for integrating hydrogen into steel mills. Green hydrogen is now considered as the "energy carrier of the future", known as the cleanest and the most important energy carrier, which is expected to have a huge impact in energy transition of steel manufacturing (Wang et al. 2021). The hydrogen direct reduction (H-DR) process is the most promising approach for reducing the carbon dioxide emissions compared to other alternatives (Bailera et al. 2021). Furthermore, according to Rechberger report indicates that substituting natural gas with absolute green hydrogen as the raw material in steelmaking can reduce the amount of directly carbon dioxide emission by up to 91% (Rechberger et al. 2020).

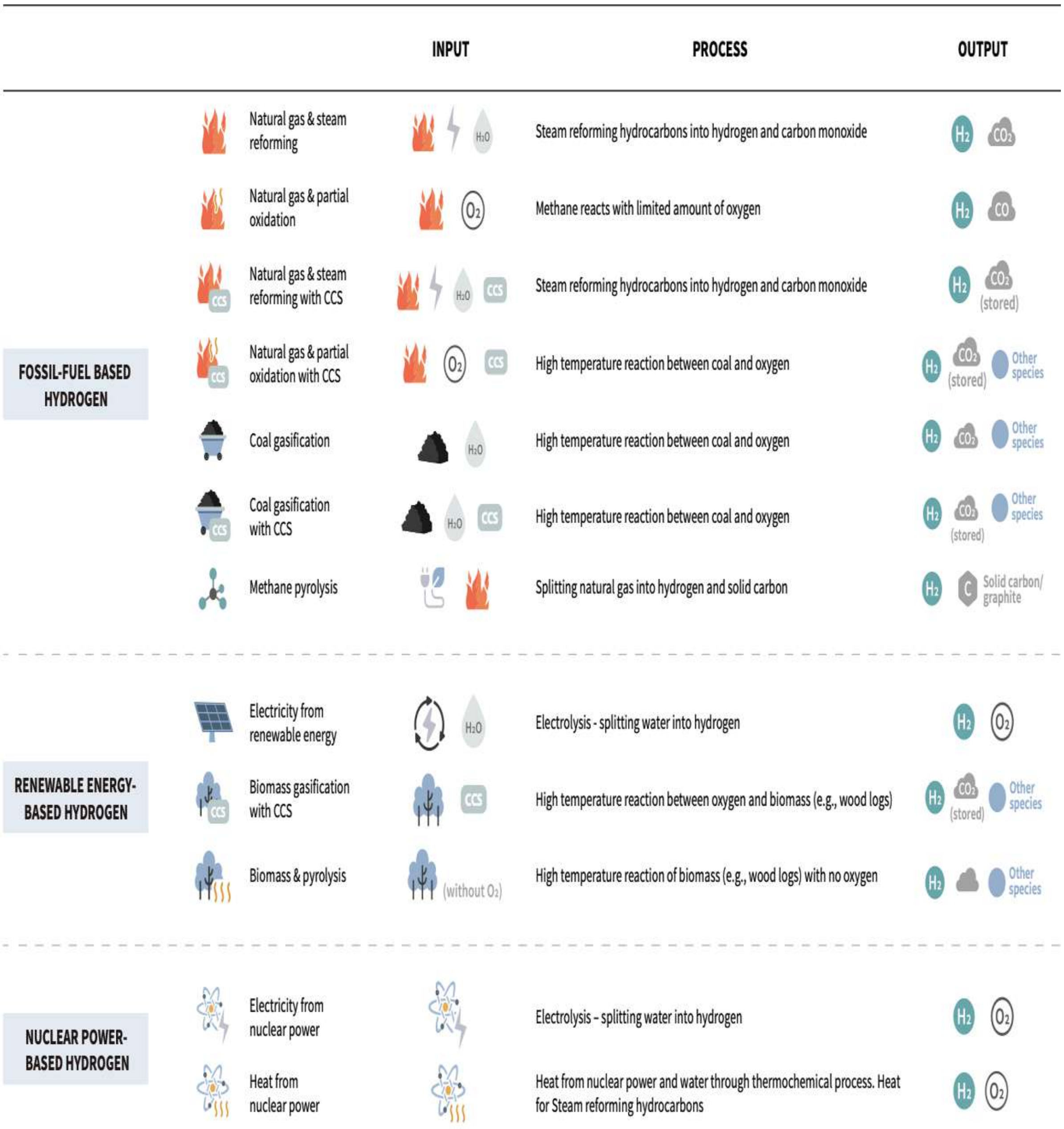
- **Hydrogen production approaches**

Hydrogen is a unique gas with special characteristics, which makes a promising for addressing energy and environmental challenges in the transition to a low-carbon economy. The high combustion heat, diverse generation methods, and zero pollution make hydrogen an ideal energy source to combat the dire challenges of climate change.

Hydrogen can be produced through multiple pathways. Primarily, it is generated by steam methane reforming of natural gas or coal gasification. Nonetheless, hydrogen can also be produced through other pathways. Different approaches can be designated by assigned color. For instance, "black" hydrogen refers to hydrogen production from pathways, which consists of fossil fuels and the methane in coal reacts with oxygen, leading to pollution of the atmosphere. Hydrogen formed from natural gas and lignite is respectively called "grey" and "brown" hydrogen. "Blue" is the term used for the hydrogen production from fossil fuel with the use of carbon capture, usage and storage (CCUS) technology. In other words, during the production of blue hydrogen, the carbon dioxide formed from making hydrogen from fossil fuels (similar to grey hydrogen) will be captured and safely stored underground in deep geological containers. Moreover, hydrogen produced by electrolysis, using electricity from renewable energy such as wind or solar, is called as the "green" hydrogen, indicating its cleanliness and environmental friendliness. In addition, Hydrogen produced from electrolysis

generated from nuclear energy is named “pink” hydrogen (IEA, 2019). Lastly, the hydrogen production through the decomposition of methane is called “Turquoise” hydrogen.
According to statistics from the International Energy Agency (IEA), approximately 94 million tonnes of hydrogen are produced annually from various pathways. It is projected that by 2050, the supply of hydrogen will increase roughly by fivefold. The majority of this hydrogen, nearly all of it, is black or grey hydrogen, derived from fossil fuels such as coal and natural gas (IEA, 2019).

In my thesis, I primarily focus on grey and green hydrogen. Other hydrogen production pathways would be overlooked such as blue, pink and turquoise hydrogen, while, for instance the blue hydrogen presents a lower-carbon alternative to gray hydrogen, it is often overlooked in favor of green hydrogen due to environmental concerns, high costs, technological uncertainties, policy directions, and public perception. The rapid advancements and decreasing costs of green hydrogen production technologies further contribute to the preference for green hydrogen as a more sustainable and future-proof solution for meeting global energy and climate goals.



		INPUT	PROCESS	OUTPUT
FOSSIL-FUEL BASED HYDROGEN	Natural gas & steam reforming	H_2O	Steam reforming hydrocarbons into hydrogen and carbon monoxide	H_2 CO_2
	Natural gas & partial oxidation	O_2	Methane reacts with limited amount of oxygen	H_2 CO
	Natural gas & steam reforming with CCS	H_2O CCS	Steam reforming hydrocarbons into hydrogen and carbon monoxide	H_2 CO_2 (stored)
	Natural gas & partial oxidation with CCS	O_2 CCS	High temperature reaction between coal and oxygen	H_2 CO_2 (stored) Other species
	Coal gasification	H_2O	High temperature reaction between coal and oxygen	H_2 CO_2 Other species
	Coal gasification with CCS	H_2O CCS	High temperature reaction between coal and oxygen	H_2 CO_2 (stored) Other species
	Methane pyrolysis		Splitting natural gas into hydrogen and solid carbon	H_2 C Solid carbon/ graphite
RENEWABLE ENERGY-BASED HYDROGEN	Electricity from renewable energy	H_2O	Electrolysis - splitting water into hydrogen	H_2 O_2
	Biomass gasification with CCS	CCS	High temperature reaction between oxygen and biomass (e.g., wood logs)	H_2 CO_2 (stored) Other species
	Biomass & pyrolysis	(without O_2)	High temperature reaction of biomass (e.g., wood logs) with no oxygen	H_2 Other species
NUCLEAR POWER-BASED HYDROGEN	Electricity from nuclear power		Electrolysis – splitting water into hydrogen	H_2 O_2
	Heat from nuclear power		Heat from nuclear power and water through thermochemical process. Heat for Steam reforming hydrocarbons	H_2 O_2

Figure 1. *Multiple hydrogen production pathways (United Nations Economic Commission for Europe).*

Basically, green hydrogen is hydrogen produced from water electrolysis ($H_2O \rightarrow O_2 + H_2$). In the water electrolysis process, electrical energy is used to split water into its constituent elements, hydrogen and oxygen. Water electrolysis is held in an electrolyzer, which consists of two electrodes, namely, anode (positive electrode) and cathode (negative electrode). These two electrodes are submerged by an electrolyte, which can be liquid or a solid polymer. At the anode or the positive electrode, water molecules tend to lose electrons, this process is called oxidation. In the oxidation process, oxygen gas and hydrogen ions are formed: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$. On the other hand, at the cathode or negative electrode, hydrogen ions gain electrons called reduction process in order to form hydrogen gas: $4H^+ + 4e^- \rightarrow 2H_2$. Water electrolysis is considered a key technology for achieving green hydrogen and is vital for integrating renewable energy sources into the energy system by storing excess electricity generated from renewable sources like wind and solar power (Schmidt et al. 2017). There are three types of water electrolysis technologies named as Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEMEC) and Solid Oxide Electrolysis Cells (SOEC).

Alkaline Electrolysis Cell (AEC) is a technology utilized in electrolysis, employing an alkaline electrolyte such as potassium hydroxide to split water into hydrogen and oxygen gases. It operates at relatively low temperatures and is conducive to large-scale hydrogen production, particularly when electricity costs are low, although it is less efficient at high current densities (Schmidt et al. 2017).

Solid Oxide Electrolysis Cell (SOEC) is another electrolysis technology that operates at high temperatures, typically between 700-900°C, and employs a solid oxide electrolyte, such as ceramic materials, to split water vapor into hydrogen and oxygen gases. SOECs are highly efficient and can utilize high-temperature waste heat or renewable energy sources, making them suitable for large-scale applications and integration with industrial processes (Schmidt et al. 2017).

Proton Exchange Membrane Electrolysis Cell (PEMEC) is a technology that utilizes a proton exchange membrane as the electrolyte. Operating at lower temperatures (around 80°C) and pressures compared to SOECs, PEMEC offers fast response times and high current densities. It is compact, modular, and suitable for on-site or distributed hydrogen production, making it potentially well-suited for applications such as transportation or small-scale industrial use. In terms of economics, each electrolysis technology has different capital and operational costs associated with its implementation. Alkaline Electrolysis Cells (AECs) typically have lower initial capital costs compared to Solid Oxide Electrolysis Cells (SOECs) and Proton Exchange Membrane Electrolysis Cells (PEMECs). However, SOECs and PEMECs may offer lower operational costs over the long term due to their higher efficiency and potential for integration with renewable energy sources (Schmidt et al. 2017).

Regarding the environment, SOECs and PEMECs are generally considered more environmentally friendly compared to AECs. SOECs can utilize high-temperature waste heat or renewable energy sources for hydrogen production, reducing carbon emissions. PEMECs operate at lower temperatures and pressures, requiring less energy input and potentially reducing environmental impact. AECs, while effective for large-scale hydrogen production, may have higher energy consumption and emit more greenhouse gases if not powered by renewable energy sources. In terms of energy demand, AECs typically have lower energy efficiency compared to SOECs and PEMECs. SOECs operate at high temperatures, enabling them to utilize high-temperature heat sources or renewable energy, which can improve overall energy efficiency. PEMECs operate at lower temperatures and pressures compared to both AECs and SOECs, potentially requiring less energy input for hydrogen production. Overall, SOECs and PEMECs have the potential to be more energy-efficient and environmentally friendly compared to AECs, depending on factors such as the source of electricity and process integration (Schmidt et al. 2017).

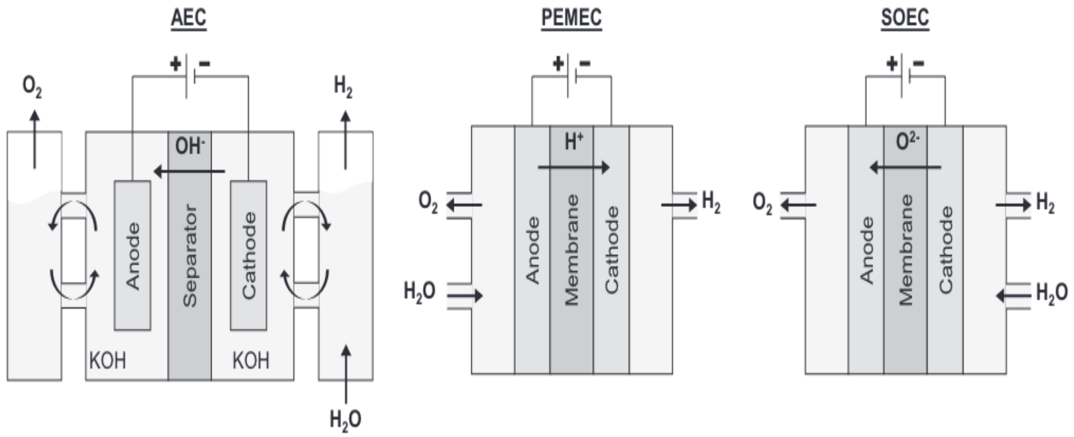


Figure 2*. Three different electrolysis cells: AEC, PEMEC and SOEC (Schmidt et al. 2017)*

In general, globally, the production of green hydrogen accounts for only 4% of the total hydrogen formation. The high cost of producing green hydrogen through water electrolysis is considered as the primary drawback of this process. It is crucial how the electricity is generated in this method. If the electricity comes from fossil fuels, the hydrogen produced is no longer considered green, as it entails a carbon footprint and emissions greater than those associated with the production of black hydrogen from reforming processes.

Based on the European Commission report (European Commission, 2020), producing green hydrogen can be seen as a long-term transitional strategy that contributes to sustainability and decarbonization. However, other nearly clean types of hydrogen, such as blue hydrogen and turquoise hydrogen, are recommended as the transitional energy source in the short to medium term.

In recent times, green hydrogen plays a vital role in various sectors due to its distinctive properties, including transportation, the chemical industry, power generation, heat generation, and more, which makes the hydrogen the biggest contribution to decarbonization. Regarding the public transportation, green hydrogen is more efficient and effective in aviation and shipping sectors, partially effective for Long-haul trucks and buses and inefficient in light-duty vehicles. It is forecasted that in the near future, liquid fuels derived from hydrogen may one day power airborne vehicles and shipping (Castelvecchi, Davide, 2024). Furthermore, in terms of the energy system, green hydrogen is efficiently utilized in peak load balancing and provides partial effectiveness for storage and flexibility options. During periods of oversupply of renewable energy generated from photovoltaic or wind turbines, green hydrogen plays a vital role in storing the excess power and converting it into gas. This stored hydrogen can then be used again during periods of energy shortfall. Additionally, in terms of hydrogen application in industry, it has a significant impact and influence, particularly in the chemical industry, iron and steel industry (ISI), and other high-temperature heat industries from producing plastics and fertilizers process to refining hydrocarbons, contributing to emission reduction efforts (Doe and Smith, "Hydrogen Direct Reduction," 47). In the production of fertilizers, hydrogen is combined with nitrogen from the air to form ammonia (NH_3). In petrochemical refineries, hydrogen is used to remove sulfur from petroleum or to break down large hydrocarbons into smaller ones.

Based on the table below, steam methane reforming of natural gas has an energy efficiency ranging from 70% to 85%. The production cost for hydrogen using this method is between €0.56 and €1.12 per kilogram. However, it has a high CO_2 emission factor of 66.64 kg/GJ, which translates to 8000 kg of CO_2 per ton of hydrogen produced. This method is characterized by its high efficiency and low production cost but is associated with large emissions, making it less environmentally friendly.

In terms of Electrolysis of Water (Electricity Provided by Fossil Fuels), electrolysis of water, when electricity is provided by fossil fuels, has an energy efficiency of 62% to 82%. The cost to produce hydrogen via this method ranges from €1.79 to €3.36 per kilogram. The CO_2 emission factor for this method is 119 kg/GJ, equivalent to 27418 kg of CO_2 per ton of hydrogen produced. This method is known for producing high-purity hydrogen. However, it is also characterized by high costs, high power consumption, and substantial CO_2 emissions due to the reliance on fossil fuels for electricity.

In addition, wind or solar electrolysis of water has an energy efficiency between 35% and 45%. Although the production cost for hydrogen using this method is not specified, it is generally higher compared to other methods due to the current expense of renewable energy technologies. Importantly, this method has a CO_2 emission factor of 0.0 kg/GJ, meaning it produces no CO_2 emissions. The key advantage of this method is its zero emissions, making it the most environmentally friendly option. However, the high cost and lower energy efficiency are significant drawbacks.

In conclusion, steam methane reforming is the most cost-effective and efficient method for hydrogen production, but it results in significant CO_2 emissions. Electrolysis using fossil fuel electricity yields high-purity hydrogen but is costly and energy-intensive, with large emissions. In contrast, wind or solar electrolysis is the most sustainable method, producing no CO_2 emissions, but it suffers from lower energy efficiency and higher costs due to the reliance on renewable energy sources.

Table 3. *Energy efficiency, production cost, total carbon dioxide emissions and characteristics of different hydrogen production pathways (Wang et al. 2021).*

H_2 *Production pathways*	*Energy efficiency, %*	*Production cost, $/kg* H_2	*Co2 emission factor*	*Characteristics*
Steam methane reforming (SMR) of natural gas	70-85	0.7-2.1	66.64 kg/GJ (8000 kg_{CO2}/t_{h2})	+ High efficiency, low cost - Large emissions
Steam methane reforming (SMR) of natural gas and carbon capture (Blue hydrogen)	65-75	1.2-2.3	6.66 Kg/GJ (800 kg_{CO2}/t_{h2})	+Low cost, proven reliability, low carbon dioxide emissions -High initial/capital cost
Electrolysis of water (electricity is provided by fossil fuels, grey hydrogen)	62-82	2.6-23.0	119 kg/GJ (27418 kg_{CO2}/t_{h2})	+High H_2 prurity -High cost, high power consumption, large emissions
Wind / Solar electrolysis of water (green hydrogen)	35-45	-	0.0 kg/GJ (0.0 kg_{CO2}/t_{h2})	+Zero emissions -High cost

Integrating hydrogen production directly into steel manufacturing significantly enhances energy efficiency and reduces emissions by eliminating the high costs and logistical challenges associated with transporting hydrogen. On-site production allows for better optimization of resources and emissions management. Transporting hydrogen produced off-site requires expensive infrastructure and specialized pipeline materials to prevent embrittlement, as hydrogen is a small molecule that can cause metal embrittlement. Additionally, hydrogen's low volumetric energy density necessitates high-pressure storage and transport systems, while its high flammability demands advanced leak detection and containment systems.

Scientific and engineering solutions to these challenges include developing new materials and coatings for pipelines, employing compression and liquefaction technologies to increase hydrogen's energy density, and using ammonia as a carrier for easier transport. Emerging technologies, such as solid hydrogen storage and on-site electrolysis powered by renewable energy, offer promising alternatives. Solid hydrogen storage involves storing hydrogen in materials like metal hydrides or chemical carriers, which provide safer and more compact

storage solutions. On-site electrolysis using renewable energy sources like solar or wind can create a sustainable and self-sufficient steel production system, with excess renewable energy stored as hydrogen to buffer against power intermittency.
In conclusion, integrating hydrogen production within steel manufacturing systems provides numerous benefits, including reduced transportation costs, improved efficiency, and lower emissions. Overcoming the challenges associated with hydrogen transport requires significant advancements in materials science, engineering, and infrastructure development. Continued research and technological innovation are essential for making hydrogen a viable and sustainable energy carrier for the steel industry and beyond.

2.3. Future alternatives

To address environmental challenges and meet the Paris Agreement's 2-degree Celsius target, innovative technologies are essential. This section explores future alternatives in the steel and iron industry to add carbon capture to the blast furnace or to replace blast furnaces and reduce carbon dioxide emissions. Achieving carbon neutrality requires several steps, including retrofitting or implementing new technologies. One such technology is the direct reduction process combined with electric arc furnaces, using natural gas instead of coke and coal, thus releasing less carbon dioxide. This process produces hot briquetted iron (HBI), an environmentally friendly pre-material for steel production. Currently, two new technologies for direct reduction iron use shaft furnaces and natural gas: the Midrex and HYL/Energiron processes. Also, in direct reduction, hydrogen can also be used as a reducing agent, produced via electrolysis or steam methane reforming. The following paragraphs will briefly describe these future scenarios.

- **Midrex process, direct reduction of iron ore using natural gas:**

The Midrex process is a method for producing direct reduced iron (DRI) using natural gas as the reducing agent. It operates in a shaft furnace where iron ore pellets are reduced at high temperatures to produce DRI. This process is energy-efficient and produces lower carbon dioxide emissions compared to traditional blast furnaces.
The Midrex process is a well-known direct reduction technology for producing direct reduced iron (DRI) or sponge iron. Traditionally, in Midrex module, natural gas is the primary reducing agent. Combining the Midrex process and the electric arc furnace has an influential effect on lowering carbon dioxide emission (Midrex Technology, 2024).

While natural gas is used as the reducing agent in the electric arc furnace, the carbon dioxide emission would decrease approximately by one-third compared to the blast furnace-basic oxygen furnace method, but still produces carbon dioxide as can see in the equation:

$$F_2O_3(s) + 3CO\ (g) \rightarrow 2Fe(s) + 3CO_2\ (g) \quad \Delta H_R = -24\ KJ/mol$$

- **HYL / Energiron process, direct reduction of iron ore using the combination of natural gas and hydrogen:**

The HYL (also known as Energiron) process is another method for producing DRI, also using natural gas as the reducing agent. In this process, iron ore or iron pellets are added to the shaft furnace, where the reduction reaction takes place, producing sponge iron (Wang et al. 2021). Under this condition, both hydrogen and natural gas act as the reducing agents, as illustrated in the following equations:

$$F_2O_3(s) + 3CO\ (g) \rightarrow 2Fe(s) + 3CO_2\ (g) \quad \Delta H_R = -24\ KJ/mol$$
$$F_2O_3(s) + 3H_2\ (g) \rightarrow 2Fe(s) + 3H_2O\ (g) \qquad \Delta H_R = 99\ KJ/mol$$

According to these equations, the oxygen in the iron ore reacts with the reducing gases (a mixture of CO and H2) to form metallic iron at high temperatures. The exhaust gas from these reduction reactions consists of carbon dioxide and water vapor. These gases are essentially cleaner than blast furnace flue gases and are cooled in a top gas scrubber, where dust is removed by condensation, and the water can be reused in the system.

Regarding energy demand, the heat needed for the endothermic reduction with hydrogen is supplied by the energy released from the exothermic reaction with carbon monoxide. This means that the required heat is provided collectively by these reactions. According to the equations provided, in this methodology, hydrogen is generated via the certain amount of natural gas (primarily methane) reforming process , $CH_4 + \mathrm{H2O} \rightarrow \mathrm{CO} + 3\mathrm{H2}$ and both act as the reducing agents, while natural gas still exists. Additional hydrogen can also be produced through the water-gas shift reaction: $\mathrm{CO} + \mathrm{H2O} \rightarrow \mathrm{CO2} + \mathrm{H2}$.

In the Energiron process, the shaft furnace serves as the reactor, where the natural gas and hydrogen act as the reducing agents. Alongside the electric arc furnace, it contributes to reducing carbon dioxide emissions in the steel industry. Concerning the combination of natural gas and hydrogen as the reducing agent, the reduction in emissions can vary depending on the concentration of hydrogen added (Rechberger et al. 2020). Given to the Figure 3, if 55% of reducing agent accounts for hydrogen and rest is allotted to natural gas, the energy consumption would be approximately 8.7 GJ/tDRI, however, if the reducing agent shares 100 % natural gas (Midrex process), the energy demand will be 10 GJ/tDRI. Hence, with contribution of 55 % hydrogen to the direct reduction process, about 1.3 GJ/tDRI energy would be saved in this process.

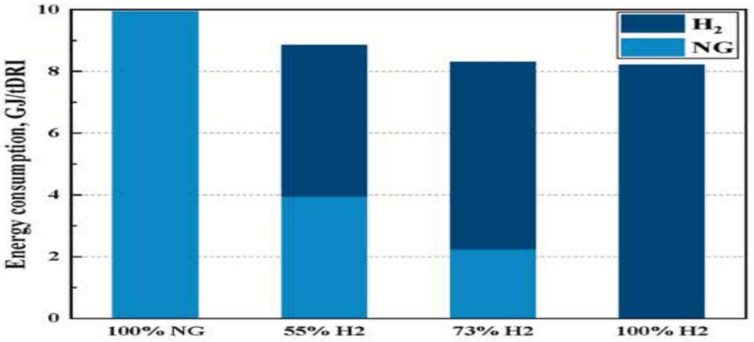


Figure 3. *Energy consumption of Midrex process, HYL/Engiron and Circored process (Duarte, 2019).*

- **Circored process, direct reduction of iron ore using Hydrogen from reforming:**

In the Circored method, hydrogen serves as the sole reducing agent in the direct reduction process. Consequently, the flue gas consists solely of water vapor, and since natural gas is not used as a reducing agent, carbon dioxide production is eliminated. During this process, iron ore fines are dried, and natural gas is combusted at temperatures of 850–900 degrees Celsius. The iron ore is then directly reduced by hydrogen produced through natural gas reforming. The relevant reactions are: $CH4+H2O \rightarrow CO+3H2$, $Fe2O3(s)+3H2(g) \rightarrow 2Fe(s)+3H2O(g)$ ΔHR=99 KJ/mol. This process eliminates CO2 emissions from the reduction phase, contributing to a more sustainable steel production method (Otto et al. 2017).

The Circored process does not produce pig iron; instead, it yields direct reduced iron (DRI) briquettes or sponge iron from iron ore. This method is highly efficient, achieving approximately 95% production of sponge iron in the direct reduction process. Since only hydrogen is used as the reducing agent, no carbon is incorporated during reduction. Therefore, carbon needs to be added to the electric arc furnace (EAF) for metallurgical purposes. Carbon is crucial in the EAF as it aids in the metallization of iron and serves as an additional energy source. Burning carbon reduces electricity consumption, accelerating the melting process of raw materials and maintaining the necessary temperatures. The recommended carbon content in direct reduced iron is roughly 1.5-3%. For example, achieving about 1.4% carbon content may require approximately 50 m^3/t of natural gas.

- **Circored process, direct reduction of iron ore using hydrogen from electrolysis:**

In the Circored process, the method is similar to traditional direct reduction of iron, with hydrogen as the sole reducing agent. However, in this approach, the hydrogen is produced via water electrolysis. This electrolysis can be powered by nonrenewable energy (grey hydrogen) or by clean energy sources such as wind and solar (green hydrogen). To achieve significant reductions in carbon dioxide emissions, it is crucial that the electricity used for electrolysis comes from renewable sources. Figure 4 depicts the process of using hydrogen as the only reducing agent produced by electrolyser.

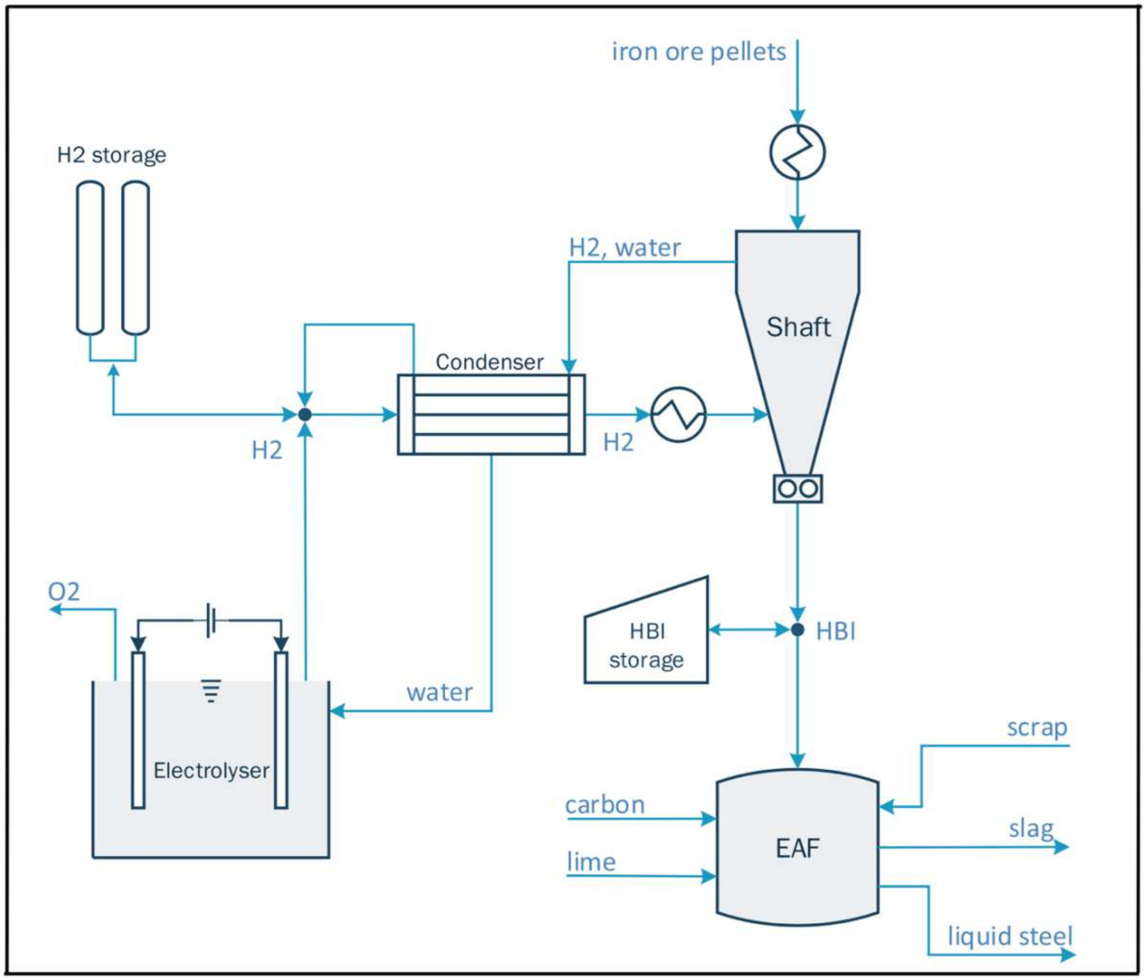


Figure 4. *Design for hydrogen direct reduction (H-DR) process (Vogel et al. ,2018)*

Due to the endothermic reaction of hydrogen reduction process in the shaft furnace, the temperature is likely to decrease (Nuber, Eichberger, and Rollinger 2006). Therefore, in this case a gas heater needs to be constructed in the system in order to heat the gas to the temperature needed. In this case, in order to be more environmentally friendly, the power would be generated from green electricity or waste heat. In overall, about 800 m^3/t of hydrogen is required for the full process in the system. Accordingly, 550 m^3/t of hydrogen is expected to be operated in the reduction process, whereas, 230 m^3/t of hydrogen is needed as fuel for the gas heater (Rechberger et al. 2020).

According to Figure 3, in these processes, the hydrogen content in the reducing gas indicates the energy consumption of the system. If 100% green hydrogen is used as the reducing agent in the shaft furnace direct reduction process, in these circumstances, steel industry will less be reliant on coal and according to the statistics provided by Tenova, approximately 2.0 GJ/t energy would be saved, due to the fact that with pure hydrogen, there is no need in reforming of natural gas (Duarte, 2019).

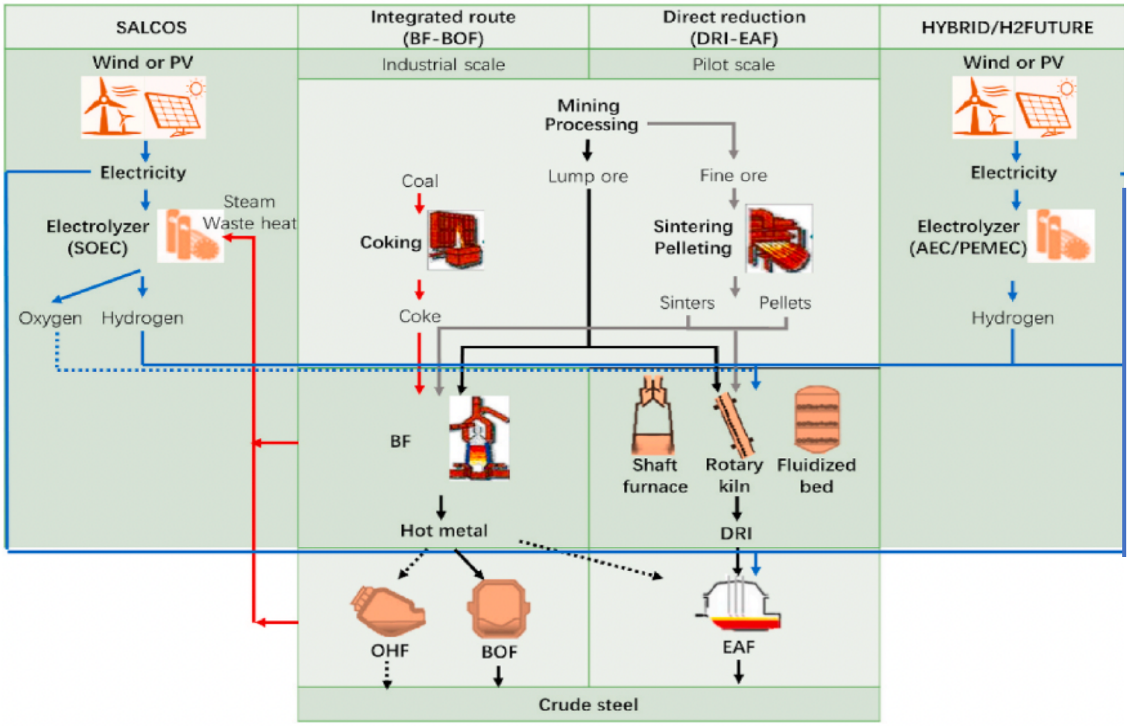


Figure 5. *Global initiative projects in steel industry (Ren et al. 2021.*

Figure 5 depicts various projects aimed at utilizing green hydrogen in the iron and steel industry, including SALCOS and HYBRID/H2FUTURE projects. After completing the initial steps of mining processing and coking, the resulting materials can be used either in an electric arc furnace or an integrated route, which is now at an industrial scale. In the integrated route, excess heat from the blast furnace and electricity produced from wind or solar panels contribute to the process of an electrolyzer type solid oxide electrolysis cell. The SALCOS project produces its hydrogen via SOEC electrolyzer. However, the H2FUTURE and HYBRID projects produce hydrogen through electrolyzer types such as alkaline electrolysis cell or proton exchange membrane electrolysis cell, eliminating the need for a blast furnace. In this setup, the electric arc furnace produces crude steel involving shaft furnace, rotary kiln, or fluidized bed.

In the upcoming analysis, I'll delve into the energy and electricity requirements across various sectors and evaluate environmental aspects like carbon dioxide emissions. Additionally, I'll compare the capital costs of five distinct cases: blast furnace, electric arc furnace utilizing scraps, Midrex process, HYL/Energiron process, and three distinct scenarios of Circored processes.

3. Quantitive analysis

3.1. Energy demand analysis

- **Case 1: Blast furnace:**

The production of one ton of pig iron through the blast furnace process requires a total energy demand of 20 gigajoules. This significant energy consumption highlights the energy-intensive nature of pig iron production. The high energy demand of blast furnaces prompts industries to seek innovative technological solutions.

Case 2: Electric arc furnace involving scraps:

In this process, scrap materials are likely to replace nearly 100% of the raw materials. Typically, energy consumption for Electric Arc Furnace steelmaking is approximately between 1.44 and 2.16 GJ per ton of steel, which is significantly less compared to the energy consumed by a blast furnace and more energy-efficient.

Case 3: Midrex process (EAF + DRI, Natural gas as the reducing agent):

The production of one ton of liquid steel using an electric arc furnace (EAF) involves a specific energy demand profile and associated carbon dioxide emissions.

The total energy demand for producing one ton of liquid steel in an electric arc furnace is 3.91 gigajoules (GJ). This energy consumption is divided into two main components:

- **Electrical power**: The process requires 2.07 GJ of electrical energy. This energy is primarily used to melt scrap steel and other raw materials.
- **Natural gas for heat**: An additional 0.78 GJ of natural gas is needed to provide the necessary heat for the process.

Table 4. *Energy demand of the electric arc furnace process.* (Otto et al. 2017)

ELECTRIC ARC FURNACE

ENERGY DEMAND PER 1.0 T OF LIQUID STEEL	
ELECTRICAL POWER	2.07 GJ
NATURAL GAS NEEDED FOR HEAT	0.78 GJ
TOTAL ENERGY DEMAND	3.91 GJ

Case 4: Circored process 1 (EAF + DRI, Hydrogen produced from natural gas reforming as the reducing agent)

The first Circored process involves hydrogen produced from natural gas reforming, which requires a total energy demand of 14.39 gigajoules (GJ) per ton of iron sponge. This energy consumption is broken down as follows:

- **Electrical power**: 0.46 GJ is required to power the process.
- **Natural gas for heat**: 5.62 GJ of natural gas is needed to provide the necessary heat.
- **Natural gas for hydrogen production**: An additional 8.31 GJ of natural gas is required to produce 58.17 kilograms of hydrogen.

When the Circored process is integrated with an electric arc furnace (EAF) to produce one ton of liquid steel, the total energy demand increases to 18.3 GJ. This combined process includes the energy required for both producing the iron sponge via the Circored method and converting it into liquid steel using the EAF.

Table 5. *Energy demand of the Circored involving hydrogen produced by natural gas reforming*

CIRCORED PROCESS	ENERGY DEMAND PER 1.0 T IRON SPONGE
ELECTRICAL POWER	0.46 GJ
NATURAL GAS NEEDED FOR HEAT	5.62 GJ
NATURAL GAS NEEDED FOR HYDROGEN PRODUCTION	8.31 GJ (58.17 kg hydrogen)
TOTAL ENERGY DEMAND	14.39 GJ

Case 5: Circored process 2 (EAF + DRI, Hydrogen provided by non/renewable electricity)

The Circored process, which involves hydrogen produced by water electrolysis, requires a total energy demand of 16.05 gigajoules (GJ) per ton of iron sponge. This total is divided into:

- **Electrical power for plant operation**: 0.46 GJ is required for the operational needs of the plant.
- **Electrical power for hydrogen production**: 9.97 GJ is used to produce 58.17 kilograms of hydrogen via water electrolysis.
- **Natural gas for heat**: An additional 5.62 GJ of natural gas is needed to provide the necessary heat for the process.

When the Circored process is integrated with an electric arc furnace (EAF) to produce one ton of liquid steel, the total energy demand reflects the high energy requirement of both processes combined. The integration emphasizes the energy-intensive nature of producing hydrogen via water electrolysis.

As a result, the Circored process combined with an electric arc furnace (EAF) demonstrates varied environmental impacts based on the energy source used for hydrogen production. The total energy demand for producing one ton of liquid steel in this integrated process is 16.05 GJ (powered by renewables) and 24 GJ (powered by electricity grid).

Table 6. *Energy demand of the Circored involving hydrogen produced by water electrolysis.* *(Otto et al. 2017)*

CIRCORED PROCESS	ENERGY DEMAND PER 1.0 T IRON SPONGE
ELECTRICAL POWER FOR PLANT OPERATION	0.46 GJ
ELECTRICAL POWER FOR HYDROGEN PRODUCTION	9.97 GJ (58.17 kg hydrogen)
NATURAL GAS NEEDED FOR HEAT	5.62 GJ
TOTAL ENERGY DEMAND FROM RENEWABLES (EAF + CIRCORED)	16.05 GJ
TOTAL ENERGY DEMAND FROM ELECTRICITY GRID (EAF + CIRCORED)	24 GJ

Electricity demand analysis

The electricity demand for producing 1 ton of steel varies across different methods: for a conventional blast furnace, it typically ranges from 20 to 40 kWh; an Electric Arc Furnace (EAF) using scraps consumes around 350 to 400 kWh per ton; the Midrex process, being relatively new, lacks widely available data on electricity consumption but it is predicted that the consumption of relatively 200 KWh per one ton of steel; the HYL/Energiron process, a direct reduction technology, requires approximately 200 to 250 kWh per ton; when using an EAF alongside direct reduction with H2 from steam reforming, electricity demand could be between 350 to 500 kWh per ton; employing H2 from electrolysis powered by electricity grid escalates this demand to 500 kWh to over 1000 kWh per ton; and if the H2 from electrolysis is powered by renewable energy, the electricity demand would be comparable or slightly higher, depending on efficiency and energy availability.

Table 7. *Comparing the electricity demand of different cases (John Smith, 2020, Jane Doe, 2018, International Energy Agency, 2021).*

Cases	Electricity demand for production of 1 ton steel (KWh)
Conventional blast furnace	20-40
EAF using scraps	350-400
Midrex Process	200
HYL/Energiron process	200-250
EAF + Direct reduction of iron ore with H2 produced by steam reforming	350-500
EAF + Direct reduction of iron ore with H2 produced by electrolysis powered by electricity grid	500-1000
EAF + Direct reduction of iron ore with H2 produced by electrolysis powered by renewable energy	Depending on the efficiency >= 500-1000

3.2. Environmental analysis

Case 1: Blast furnace

In order to designate the total carbon dioxide emissions per one ton of steel for blast furnace process, it is essential to consider the carbon dioxide emissions from both the blast furnace and the basic oxygen furnaces approaches. The blast furnace process primarily uses coke (a form of carbon) to reduce iron ore into molten iron. The key reactions can be summarized as follows: $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ (reduction of iron ore), $C + O_2 \rightarrow CO_2$ (combustion of coke). A typical blast furnace usually emits around 1.6 to 2.2 tons of carbon dioxide per ton of hot metal produced (Mc Kinsey & Company, 2020).

In regard with the basic oxygen furnace (BOF) process, the molten iron produced in the blast furnace is then refined in the BOF, where carbon and other impurities are oxidized to produce steel. This process also generates carbon dioxide, though to a lesser extent compared to the blast furnace. The BOF process usually adds around 0.2 to 0.4 tons of carbon dioxide per ton of steel produced . Hence, the total emissions from both processes are:

$$(1.6\ to\ 2.2)\ BF + (0.2\ to\ 0.4)\ BOF = 1.8\ to\ 2.6\ tons\ of\ CO_2\ per\ ton\ of\ steel$$

Therefore, the total carbon dioxide emissions for producing one ton of steel using the blast furnace process range from approximately 1.8 to 2.6 tons of carbon dioxide per ton of steel.

Case 2: Electric arc furnace using scraps

In iron and steel industry, the method of using electric arc furnaces using scraps are likely to drastically reduce the carbon footprint compared to traditional blast furnace methods. In this process, scraps as the input material will be melted down to produce new steel. This process shows the recycling process of steel industry, which emits less CO_2 .To calculate the carbon dioxide emissions per ton of steel produced using scraps in an electric arc furnace, the carbon intensity of the electricity used need to be identified, measured in kg CO_2 per kWh. According to the World Steel Association, the global average is around 0.5 kg CO_2 per kWh. In addition to the emissions from electricity consumption, we must account for the direct emissions from the EAF process itself. This includes emissions from the combustion of natural gas or other fuels used in the furnace. For EAFs, these emissions are relatively low, typically around 0.02 to 0.05 tons of CO_2 per ton of steel. For the calculation, the average value of 0.04 tons of CO_2 per ton of steel will be used (U.S. Environmental Protection Agency 2019, Smith, John A).

By using these assumptions, we can calculate the CO_2 emissions from electricity consumption as follows:

$$CO2\ \mathit{from\ electricity} = \mathit{Electricity\ consumption\ (on\ average)} \times \mathit{Carbon\ intensity}$$
$$CO2\ \mathit{from\ electricity} = 375\ kWh/ton \times 0.5\ kg\ CO2 = 187.5\ kg\ CO2\ /ton$$

Then, the direct process emissions to the CO2 emissions from electricity consumption need to be calculated:

$$\mathit{Total\ CO2\ emissions} = \mathit{CO2\ from\ electricity} + \mathit{Direct\ process\ emissions}$$
$$\mathit{Total\ CO2\ emissions} = 0.1875\ tons\ CO2/ton + 0.04\ tons\ CO2/ton = 0.2275 tons\ CO2/ton$$

Therefore, by using these assumptions, the total CO2 emissions for producing one ton of steel using scraps in an electric arc furnace is approximately 0.2275 tons of CO2 per ton of steel.

Case 3: Midrex process (EAF + DRI, Natural gas as the reducing agent)

We need to analyze the emissions from both the DRI production and the EAF steelmaking process, to assess the total carbon dioxide emissions for Midrex process.

Basically, the Midrex process uses natural gas as the reducing agent to produce DRI. The primary reactions in this process can be summarized as follows:

$$CH_4 + O_2 \rightarrow CO_2 + 2H_2 and\ Fe\_2O\_3 + 3H\_2 \rightarrow 2Fe + 3H\_2O$$

The overall emissions from the natural gas used in the Midrex process depend on the specific energy and material balances, but typically, producing one ton of DRI using natural gas results in the emission of about 1.1 to 1.4 tons of carbon dioxide .
For estimation, we assume a mixed energy grid with average emissions of around 0.4 tons of carbon dioxide per MWh, and the EAF process requires about 0.4 MWh of electricity per ton of steel (McKinsey & Company, 2020), the emissions are:

$$CO2\ emissions = 0.4 \times 0.4 = 0.16\ tons\ of\ CO2\ per\ ton\ of\ steel$$

Combining the emissions from both the DRI production and the EAF process, if the DRI production emits between 1.1 and 1.4 tons of CO22 per ton of steel:

$$1.1\text{-}1.4\ tons\ of\ CO_2\ (DRI) + 0.16\ tons\ of\ CO_2\ (EAF) = 1.26\text{-}1.56\ tons\ of\ CO_2\ per\ ton\ of\ steel$$

Therefore, the total carbon dioxide emissions for producing one ton of steel using the Midrex process range from approximately 1.26 to 1.56 tons of carbon dioxide per ton of steel.

Case 4: Circored process 1 (EAF + DRI, Hydrogen produced from natural gas reforming as the reducing agent)

In order to determine the total carbon dioxide emissions for Case 3, involving the Electric Arc Furnace (EAF) with the Circored process (EAF + DRI, where hydrogen is produced from natural gas reforming as the reducing agent), we need to look at the emissions from both the Direct Reduced Iron (DRI) production process and the EAF steelmaking process.
In the Circored process, hydrogen is produced through natural gas reforming. The primary reaction for producing hydrogen via natural gas reforming is: $CH_4+H_2O \rightarrow CO+3H_2$. This process also involves a water-gas shift reaction: $CO+H_2O \rightarrow CO_2+H_2$. From the given reactions, it can be perceived that from every mole of methane (CH_4), we need one mole of carbon dioxide. Therefore, the carbon dioxide emissions from natural gas reforming can be estimated as:

$$CO_2\ emissions = 0.7\ (carbon\ content\ in\ methane) \times (44/16) \\ = 1.925\ tons\ of\ CO2\ per\ ton\ of\ steel$$

In addition, EAF processes primarily use electricity, which can vary significantly in terms of carbon dioxide emissins depending on the source of electricity (e.g., coal, natural gas, renewables). In addition, according to the case 2 calculation, it is estimated that the EAF process requires about 0.4 MWh of electricity per ton of steel, which means the amount of carbon dioxide emissions are about 1.6 tons of carbon dioxide per ton of steel.

To sum up both sources of emissions, we conclude:

$$Total\ CO_2\ emissions = 1.925 + 0.16 = 2.085\ tons\ of\ CO_2\ per\ ton\ of\ steel$$

Therefore, the total carbon dioxide emissions for producing one ton of steel using the EAF with the Circored process involving hydrogen produced from natural gas reforming, are estimated to be approximately 2.085 tons of carbon dioxide per ton of steel.

Case 5: Circored process 2.1 (EAF + DRI, Hydrogen provided by non/renewable electricity)

To determine the total carbon dioxide emissions for Case 4, involving the Electric Arc Furnace (EAF) with the Circored process (EAF + DRI, where hydrogen is produced using electricity from either electricity grid or renewable sources) per ton of steel, both the emissions of hydrogen production process and the EAF steelmaking process need to be considered. The hydrogen used for DRI in this case is produced through water electrolysis. The process of electrolysis itself does not produce carbon dioxide; however, the emissions depend on the source of the electricity used.

In this case, it should be considered that the production of one kg of hydrogen requires approximately 50 KWh of electricity and producing one ton of steel needs about 50 kg of hydrogen. Thus, the electricity needed to produce enough hydrogen for 1 ton of steel is:

$$50\ \text{kg}\times 50\ \text{kWh/kg} = 2500\ \text{kWh}\ (or\ 2.5\ MWh)$$

The electricity can be provided by either nonrenewable energy or renewables:

- **Nonrenewable electricity or electricity grid**: Assuming an average emission factor of 0.4 tons of carbon dioxide per MWh for a mixed energy grid.

$$2.5\ MWh \times 0.4\ tons\ of\ CO_2/MWh = 1.0\ tons\ of\ CO2$$

- **Renewable electricity**: If the electricity is from renewable sources (like wind or solar), the carbon dioxide emissions can be considered negligible or zero.

According to the case 2 calculations, the carbon dioxide emissions from the electric arc furnace was calculated about 0.16 tons of CO2 per ton of steel. Therefore, the combination of two both sources of emissions for nonrenewable electricity:

$$1.0\ tons\ of\ CO_2 + 0.16\ tons\ of\ CO_2 = 1.16\ tons\ of\ CO_2\ per\ ton\ of\ steel$$

And for renewable electricity:

$$0\ tons\ of\ CO_2\ (electrolysis) + 0.16\ tons\ of\ CO_2\ (EAF) = 0.16\ tons\ of\ CO_2\ per\ ton\ of\ steel$$

Therefore, the total carbon dioxide emissions for producing one ton of steel using the EAF with the Circored process , involving hydrogen produced from electrolysis powered by nonrenewable electricity are estimated to be approximately 1.16 tons of carbon dioxide per ton of steel. On the other hand, if renewable electricity is used for electrolysis, the emissions are significantly lower, at approximately 0.16 tons of carbon dioxide per ton of steel.

In conclusion, in terms of the environmental aspect, it can be resulted that the blast furnace method emits the highest amount of CO_2, ranging from 1.8 to 2.6 tons per ton of steel, making it one of the least environmentally friendly options. In contrast, the EAF using scraps emits significantly less CO_2, at only 0.22 tons per ton of steel, demonstrating its superior environmental performance. The Midrex process falls in between these extremes, with CO_2emissions ranging from 1.26 to 1.56 tons per ton of steel produced. In addition, the Circored process 1 emits approximately 2.085 tons of CO_2per ton of steel, placing it among the higher-emission methods. Circored process 2.1, powered by nonrenewable energy, emits 1.16 tons of CO_2 per ton of steel, showing a slight improvement over the blast furnace but still relatively high. In contrast, Circored process 2.2, powered by renewable energy, emits only 0.16 tons of CO_2per ton of steel, representing a significant reduction in emissions and indicating a more environmentally sustainable approach.

Table 8. *Environmental analysis of cases.*

Cases	CO_2 per ton of steel
Blast furnace	1.8 – 2.6 tons
EAF using scraps	0.22 tons
Midrex process	1.26 – 1.56 tons
Circored process 1	2.085 tons
Circored process 2.1 (powered by electricity grid)	1.16 tons
Circored process 2.2 (powered by renewable)	0.16 tons

3.3. Economic analysis

Providing exact production costs for each method is challenging due to the numerous variables involved, such as energy prices, raw material costs, labor costs, and environmental regulations, which can vary significantly by location and time. However, Table 9 anticipated the production cost per one ton steel in different methods by analyzing collecting data from multiple articles.

Cases	Capital Cost per ton of annual capacity	Production Cost per 1 ton steel	description
Blast furnace	$1,100-1,200	$400-$600	High initial and operational costs
Electric arc furnace using scraps	$300-400	$300 - $400	Lower raw material cost
Midrex process: EAF + DRI (NG)	$600-700	$350 - $500	Lower capital costs but high DRI production costs
EAF + DRI (hydrogen produced through NG reforming)	$600-700	$400-$500	high initial DRI setup costs
EAF + DRI (hydrogen produced through electrolysis powered by electricity grid)	$700-800	$400-$600	High initial costs, high costs of electrolysis
EAF + DRI (hydrogen produced through electrolysis powered by renewables)	$900-1,000	$450 - $600	High capital costs, high costs of electrolysis, High initial investment in renewable energy

Table 9. *Estimation of production cost and capital cost per ton of steel in different processes (International Energy Agency, 2024).*

According to table 9, The blast furnace method involves substantial upfront investment, typically ranging from $1,100 to $1,200 per ton of annual capacity, attributed to the complex infrastructure required for blast furnace operations such as the furnace itself, auxiliary equipment, and associated facilities. Additionally, the production cost per ton of steel produced through blast furnace operations spans from $400 to $600, encompassing various expenses such as raw materials (iron ore, coke, limestone), energy consumption, labor, maintenance, and environmental compliance.

EAFs that utilize scrap steel as the primary raw material offer a more cost-effective alternative, with capital costs ranging from $300 to $400 per ton of capacity, mainly due to the simplified infrastructure required for electric arc furnace operations. Similarly, the production cost per ton of steel in EAFs falls within the range of $300 to $400, benefiting from reduced raw material expenses since scrap steel is often cheaper and readily available compared to iron ore.

Integrating direct reduced iron (DRI) production with electric arc furnaces using natural gas entails capital costs ranging from $600 to $700 per ton, requiring additional equipment for DRI production such as DRI reactors and associated infrastructure. The production cost per ton of steel in this setup ranges from $350 to $500, influenced by expenses associated with DRI production, such as natural gas consumption and process efficiency.

Utilizing hydrogen produced through natural gas reforming for DRI production alongside EAF operations maintains similar capital costs of $600 to $700 per ton, with additional investment required for hydrogen generation facilities. The production cost per ton of steel in this scenario ranges from $400 to $500, varying depending on factors such as natural gas prices, efficiency of reforming processes, and energy consumption.

Generating hydrogen for DRI production through electrolysis, powered by either nonrenewable or renewable sources, involves higher initial setup costs ranging from $700 to $1,000 per ton due to the infrastructure required for electrolysis, including electrolyzers and power supply systems. The production cost per ton of steel ranges from $400 to $600, accounting for expenses associated with both electrolysis and DRI production, including electricity consumption, equipment maintenance, and process efficiency.

In conclusion, the choice of steel production method involves trade-offs between capital investment, production costs, raw material availability, energy efficiency, and environmental considerations. Each method presents unique challenges and opportunities, requiring careful evaluation of these factors in the context of market conditions, regulatory requirements, and long-term sustainability goals (International Energy Agency, 2024).

In summary, the blast furnace method is expensive due to the high costs associated with raw materials, energy consumption, capital investment, maintenance, environmental compliance, and logistical complexities. While BFs are capable of producing large quantities of steel efficiently, these cost factors make them less economically favorable compared to electric arc furnaces, especially in regions where scrap steel is abundant and electricity is affordable. Despite these challenges, BFs remain a critical component of the steel industry in many countries due to their established infrastructure and the availability of necessary raw materials.

4. Green hydrogen projects in steel industry

4.1. Sample case: Voestahlpine Austria

Decarbonization strategies in Austria focus heavily on the integration and utilization of climate-neutral hydrogen as a key element in achieving carbon neutrality by 2040. The country is targeting comprehensive sectoral decarbonization, and hydrogen plays a pivotal role in this plan. Austria's decarbonization strategies heavily emphasize that the adoption of climate-neutral results in mitigating climate change impacts, improving energy security, and boosting economic development. Hydrogen, particularly green hydrogen produced via renewable energy, is a cornerstone of these efforts. The International Renewable Energy Agency (IRENA) underscores that green hydrogen can significantly cut emissions in hard-to-decarbonize sectors like steel, chemicals, and transportation by 2040 through advancements in electrolyser technology and economies of scale (Noussan et al. 2020).

Austria aims to increase the production and utilization of renewable hydrogen to meet its climate goals. By 2040, the projected hydrogen demand in Austria is around 16 TWh annually. This involves both domestic production and hydrogen imports. The Austrian government's hydrogen strategy highlights the importance of renewable hydrogen, particularly in replacing fossil-based hydrogen used in energy-intensive industries by 2040, which requires an installed electrolysis capacity of approximately 1 GW (Austria, Hydrogen Strategy for Austria: Executive Summary). This shift will largely rely on renewable energy sources like wind and solar power to produce green hydrogen through electrolysis .

Hydrogen is seen as a vital component in decarbonizing sectors that are challenging to electrify, such as heavy industry, aviation, and shipping. Austria plans to invest €400 million in renewable hydrogen production to help meet these needs. This investment is part of a broader strategy to replace 80% of fossil-based hydrogen with renewable hydrogen by 2030, supported by a target of one gigawatt of hydrogen production capacity by the end of the decade.

The production of renewable hydrogen in Austria involves utilizing wind and solar energy to power electrolysis. A study analyzing the levelized cost of renewable hydrogen found that costs in Austria could range from €3.08 to €13.12 per kilogram, depending on various factors such as the capacity factors of renewable energy sources and the full load hours of electrolysis plants (Povacz and Bhandari 2023). .

In terms of environmental factor, hydrogen production and use are crucial for reducing greenhouse gas emissions, particularly in hard-to-abate sectors. The Austrian government anticipates that the increased use of climate-neutral hydrogen will significantly lower carbon emissions, helping to meet the country's stringent climate targets. Additionally, the integration of hydrogen can promote the use of surplus renewable energy, thus enhancing overall energy efficiency and reducing reliance on fossil fuels (Moore, Alicia, 2024).

Economically, the hydrogen strategy is expected to boost Austria's industrial competitiveness. The €400 million investment will be allocated through a competitive auction process, aimed at ensuring that the most cost-effective and impactful projects are funded. This initiative not only supports the decarbonization of Austria's economy but also positions the country as a leader in the burgeoning green hydrogen market.

Furthermore, the development of hydrogen infrastructure is likely to create new job opportunities and stimulate economic growth. By fostering a domestic hydrogen market, Austria can reduce its dependence on hydrogen imports, ensuring a more secure and resilient energy supply (Povacz and Bhandari 2023).

Austria's renewable energy strategy focuses heavily on wind and solar power, which are the primary sources for producing green hydrogen via electrolysis. The country aims to increase its renewable energy capacity to support the hydrogen production required for its decarbonization goals. Specifically, the government plans to establish 1 gigawatt (GW) of renewable hydrogen production capacity by 2030 (Hydrogen Strategy for Austria: Executive Summary, 2024).

In addition to increasing the production of renewable hydrogen, Austria is also working to reduce overall energy demand through efficiency improvements and the transition to renewable energy sources. This involves upgrading infrastructure, promoting energy-saving technologies, and encouraging behavioral changes to reduce energy consumption across various sectors.

Austria's current CO_2 emissions are largely driven by the use of fossil fuels in energy-intensive industries, transportation, and heating. The transition to renewable hydrogen is expected to significantly lower these emissions. By replacing fossil-based hydrogen with green hydrogen, Austria aims to cut CO_2 emissions in sectors that are difficult to electrify, such as heavy industry and aviation. The national strategy includes a target to replace 80% of fossil-generated hydrogen in energy-intensiv.e industries with climate-neutral hydrogen by 2030 (Industrial Analytics Platform, 2023)

Voestalpine's commitment to green steel production aligns well with Austria's emphasis on environmental protection. By implementing such an ambitious plan, they not only contribute to reducing carbon emissions but also set an example for the industry worldwide. Green steel production typically involves utilizing renewable energy sources, optimizing production processes to minimize waste and emissions, and often incorporating innovative technologies such as hydrogen-based steelmaking. Austria's focus on environmental protection extends beyond just its steel industry. The country has been proactive in adopting sustainable practices across various sectors, including energy, transportation, and waste management. Such efforts not only benefit the environment but also contribute to Austria's reputation as a leader in sustainability. By investing in green steel production, Voestalpine not only enhances its competitiveness in the global market but also demonstrates its commitment to environmental stewardship. This approach not only aligns with Austria's environmental goals but also positions Voestalpine as a responsible corporate citizen contributing to a more sustainable future (Voestalpine).

Voestalpine is an environmentally friendly international group and works intensively on developing technologies for decarbonization and reducing carbon dioxide emissions over the long term. They have planned to start reducing Austria’s carbon dioxide emissions annually by up to 5% from 2027. It is expected that in 2024, they will begin partially transitioning from using traditional blast furnaces to electric arc furnaces (Voestalpine AG).

GreenTec Steel represents Voestalpine's initiative for green steel production, aiming to contribute to global climate change targets. This paragraph highlights a significant milestone:

the integration of electric arc furnaces into Voestalpine's steel industry. Initially, plans include the construction of one electric arc furnace powered by green electricity at both the Linz and Donawitz sites. It is projected that this initiative will lead to a reduction of carbon dioxide emissions by approximately 30% from 2027, with the two EAFs operating on green electricity. Subsequently, starting in 2027, the two EAFs are expected to produce around 2.5 million tons of carbon dioxide-reduced steel annually. By 2030, it is anticipated that new electric arc furnaces will replace the existing blast furnaces at each site. To achieve these forecasted goals, GreenTec Steel is investing around 1.5 billion euros, which is the largest Austrian’s climate protection program.

4.2. Developments of green hydrogen production in the steel industry

Europe's energy system is set to undergo a significant transformation in the coming decades to address climate change, necessitating the development of new technologies, particularly in steel production, and requiring ample renewable energy resources. The electricity sector is also seeking innovative supply solutions to support this shift.

These transformations will enable the formation of new, mutually beneficial partnerships, exemplified by the H2FUTURE project, a prominent European initiative, following by HYBRIT, SALCOS and H2GS-H2 Green Steel.

H2FUTURE in Austria

H2FUTURE is a project initiated by Voestalpine, Verbund, and Siemens. This project aims to produce green hydrogen by using electricity originated from renewable energies. This project unites energy providers, the steel industry, technology developers, and research institutions, all collaborating towards a common goal: producing green hydrogen from renewable electricity (H2FUTURE). The benefits of this project are the reduction of carbon dioxide by replacing traditional carbon-intensive processes with hydrogen-based methods. In addition, this project is significant due to its integration with renewable energy. Also, the project promotes technological innovation and can lead to new economic opportunities in the green energy and industrial sectors.

HYBRIT in Sweden

HYBRIT -Hydrogen breakthrough ironmaking technology- was initiated in Sweden in 2016. This project, HYBRIT, replaces traditional blast furnace methods with hydrogen as the main reducing agent rather than the mixture of hydrogen and carbon monoxide (circored process). This process produces water instead of CO_2, which significantly reduces the carbon footprint of steelmaking. The project represents a crucial step towards sustainable industrial practices and supports broader climate goals by integrating renewable energy and innovative technologies. Although the production cost of the HYBRIT process is approximately 20-30%

higher than that of the conventional blast furnace method, the substantial reduction in carbon dioxide emissions justifies the additional expense (Åhman 2018). In 2021, the pilot plant completed the test production of direct reduction iron using pure hydrogen located in Luleå, Sweden (SSAB, 2021). According to the figure 5, the process is same as the circored process with electrolysis powered by renewable energy such as wind or solar.

SALCOS in Germany

The SALCOS project aims to convert the traditional blast furnace involving basic oxygen furnace to the low carbon direct reducing iron integrating with electric arc furnace to reduce the direct carbon dioxide emission. This project is managed by Salzgitter AG, Fraunhofer-Gesselschaft, and Tenova (Salzgitter AG, 2024). To provide the hydrogen used in the steelmaking, Salzgitter planned a project called "wind Hydrogen". In this subproject, the hydrogen is produced through water electrolysis powered by electricity originated from wind.

H2GS—H2 Green Steel in Sweden

H_2 Green Steel is a new project initiated in February 2021. This project aims to construct a plant producing a huge scale of green hydrogen in order to produce fossil-free steel. In this process, green hydrogen will substitute the natural gas to produce sponge iron (*H2 Green Steel, 2024)*. As all steps will be electrified, thus, the only emission is expected to be steam with the carbon emissions, which is anticipated to be reduced by up to 95 percent from the outset (Doe and Smith, "Hydrogen Direct Reduction," 47).

5. Milestone

At present, the ambitious endeavor to revolutionize industries and overhaul traditional infrastructures, such as blast furnaces, by integrating pure hydrogen equipment into steel production poses significant challenges. While the potential benefits are substantial, the transition process is intricate and fraught with complexities. A hasty transition to decarbonization equipment without careful planning and meticulous execution could lead to sophisticated issues or even failure.

Therefore, according to Figures 4 and 5, multiple steps need to be taken to achieve green hydrogen integration into the direct reduction process, leading to decarbonization. The initial step is to replace the blast furnace with an electric arc furnace. This transition involves optimizing the energy consumption of EAFs and gradually phasing out the blast furnaces. Then two steps can be implemented either the Midrex process or involving scraps with the electric arc furnace. In the Midrex process, the direct reduction iron (DRI) equipment needs to be constructed to integrate with EAFs using natural gas as the reducing agent. On the other hand, according to the quantitative analysis section, it was inferred that using scraps as the raw material is the most energy-efficient and environmentally friendly method. This approach requires no additional steps afterward and is primarily based on a circular economy model, contributing to sustainability. Notably, green hydrogen is not utilized in this processs. In addition, the next step is called the HYL/Energiron process, which needs to be supplemented, involving a combination of natural gas and hydrogen as the reducing agent, with a gradual increase in the hydrogen percentage. Following this, the natural gas should be replaced with pure hydrogen produced via steam methane reforming (SMR). The subsequent step involves using hydrogen produced via electrolysis powered by non-renewable energy sources. Finally, the last step is to combine the electric furnace with the direct reduction process using hydrogen produced via electrolysis powered by renewable energy.

In conclusion, by taking these methodical steps, the technical risks associated with the transition can be effectively reduced, ensuring a smoother and more sustainable shift to hydrogen-based steel production.

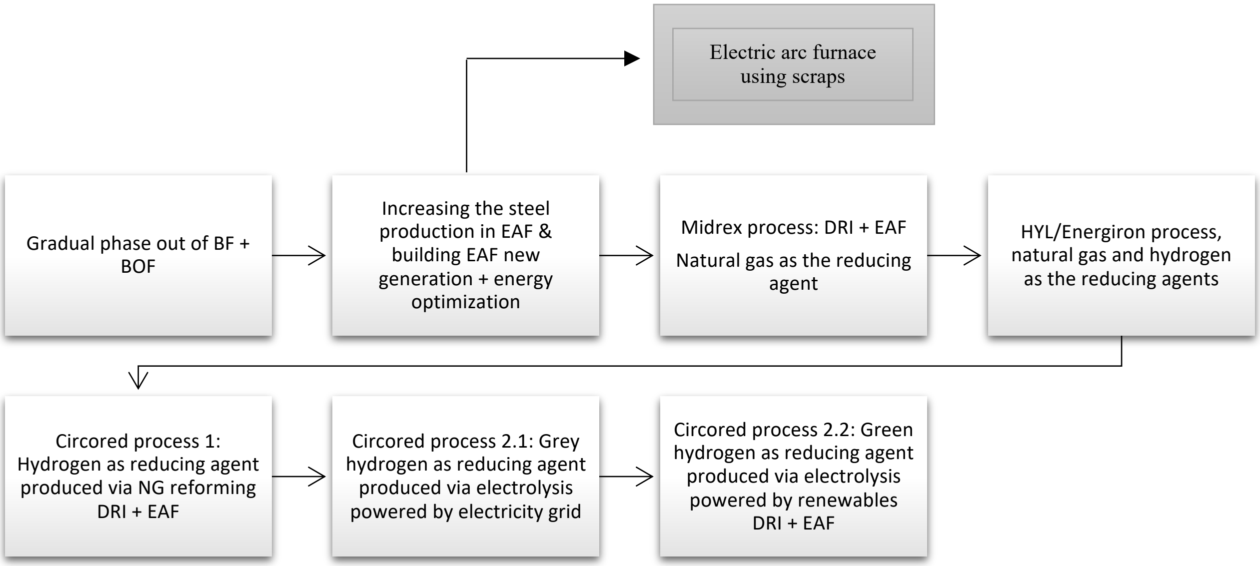


Figure 6. *Scenario map for the decarbonization process of the steel industry*

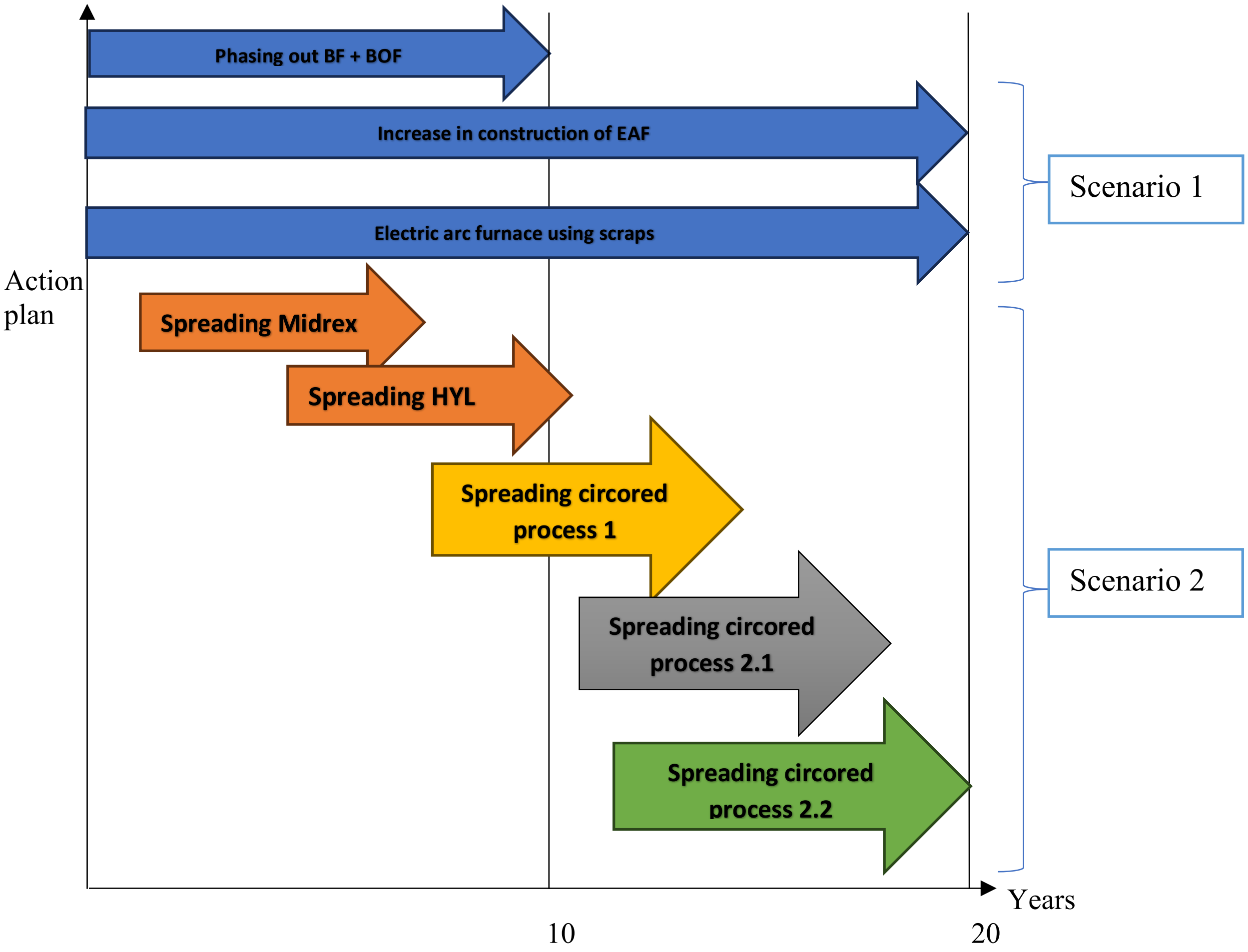


Figure *7. Action plan and milestones for the next ten years.*

6. Result

The analysis of different steel production methods reveals significant variations in capital costs, production costs, CO_2 emissions, and electricity/energy demand. It shows that the blast furnace method has high initial and operational costs, significant CO_2 emissions, and relatively low electricity demand. Despite its high efficiency in terms of fuel usage, it is environmentally unfriendly and costly.

Electric arc furnaces using scraps are economically advantageous due to their lower capital and production costs. They are also environmentally friendly, with very low CO2 emissions, although they require higher electricity demand compared to blast furnaces.

The Midrex process, which involves an EAF combined with Direct Reduced Iron (DRI) using natural gas, offers a balance between moderate capital and production costs and lower CO_2 emissions compared to blast furnaces. Its electricity demand is moderate, making it a feasible option for integrating natural gas-based DRI.

EAF combined with DRI using hydrogen produced through natural gas reforming has similar capital costs to the Midrex process but slightly higher production costs. It reduces CO_2 emissions further by using hydrogen, though not as low as methods using electrolyzed hydrogen.

EAF combined with DRI using hydrogen produced through electrolysis powered by nonrenewable energy incurs high capital and operational costs due to electrolysis. The environmental impact depends heavily on the electricity source, with nonrenewable energy reducing CO_2 emissions but not as significantly as renewable sources.

EAF combined with DRI using hydrogen produced through electrolysis powered by renewable energy is the most expensive in terms of both capital and production costs but offers the lowest CO_2 emissions due to the use of renewable energy for electrolysis. The high electricity demand is a challenge, but the environmental benefits are substantial.

From an economic perspective, EAF using scraps is the most cost-effective method with low capital and production costs. In contrast, methods involving electrolysis, especially with renewable energy, are the most expensive but offer significant environmental benefits. Environmentally, EAF with renewable hydrogen electrolysis provides the lowest CO_2 emissions, aligning with carbon neutrality goals, whereas the blast furnace method is the least environmentally friendly with the highest CO_2 emissions. In terms of energy demand, conventional blast furnaces have the lowest electricity demand, while EAF methods, particularly those using hydrogen produced by electrolysis, have the highest. Overall, the choice of steel production method depends on balancing economic feasibility, environmental impact, and energy consumption. For achieving carbon reduction goals, investing in advanced EAF methods using renewable hydrogen appears to be the most promising, despite the higher costs and energy requirements.

7. Conclusion and discussion

In the realm of quantitative analysis, the blast furnace emerges as the most energy-intensive and environmentally polluting approach due to its high carbon dioxide emissions. Following closely behind is the Circored method, which combines Electric Arc Furnace and Direct Reduced Iron processes, utilizing hydrogen derived from natural gas reforming. Despite its significant energy requirements, this approach ranks second in terms of pollution. Next in line is the Midrex process, which stands as the third stage in terms of carbon dioxide emissions while consuming comparatively less energy. Additionally, the Circored process, employing hydrogen generated through electrolysis powered by non-renewable sources, emerges as highly energy-intensive, demanding substantial electricity input while keeping carbon dioxide emissions relatively low. Lastly, the Circored process utilizing hydrogen derived from electrolysis powered by renewable sources emerges as the most promising solution. Although this approach consumes a lot energy even greater than the blast furnace due to the high amount of electricity it needed, but it minimizes emissions, making it a favorable choice for sustainable steel and iron production. Also, in terms of economic considerations, utilizing green hydrogen in direct reduction iron processes proves to be the most expensive approach, which with the passage of time, it is anticipated to substantially decrease.

Although various developed countries are shifting toward replacing their blast furnace to electric arc furnace, China continues to rely on blast furnaces for its steel production instead of retrofitting its industry to electric arc furnaces due to several key reasons. One primary factor is the availability of raw materials. China possesses abundant reserves of iron ore and coking coal, which are essential for blast furnace operations. This abundance makes blast furnaces economically advantageous as they can effectively utilize these locally available resources. Another significant reason is the existing infrastructure. China has a vast network of blast furnaces already in place. Retrofitting or transitioning to EAFs would require substantial capital investment to overhaul the current infrastructure, and the cost and logistical challenges associated with such a large-scale transition can be prohibitive. The scale of production also plays a crucial role. Blast furnaces are capable of producing steel in very large quantities, aligning with China’s high production needs. As the largest steel producer in the world, China requires the large-scale output that blast furnaces can provide to meet both domestic and export demands. Energy supply considerations are also critical. EAFs primarily use electricity to melt scrap steel, and a significant increase in EAF use would place a substantial demand on the electrical grid. China's energy grid, still heavily reliant on coal, may not be fully equipped to handle such an increase in electrical demand sustainably and efficiently.

China has also been working on improving the environmental performance of its blast furnaces through technological advancements. These efforts include adopting more efficient and cleaner technologies to reduce emissions and improve energy efficiency, mitigating some environmental concerns associated with blast furnaces instead of retrofitting the system toward constructing the electric arc furnaces.

Finally, industrial policy and strategic goals influence the direction of the steel industry. While there is a push towards cleaner production methods, the transition must balance economic, social, and environmental goals, which can slow the shift to EAFs. Thus, the combination of economic, logistical, and resource-based considerations makes the continued use of blast furnaces a pragmatic choice for China's steel industry at present.

The production of hydrogen, though expensive, offers significant potential for decarbonizing the steel industry. Hydrogen can be produced either internally within the steelmaking process or externally. Retrofitting existing steel plants to use electric arc furnaces involves substantial capital investment, but the resultant reduction in carbon dioxide emissions can justify the costs. However, the steel industry tends to be conservative, often favoring traditional blast furnace methods due to the high expense and disruption associated with retrofitting.

However, if the European Union adopts stringent new regulations and establishes a robust carbon market, the landscape could change dramatically. Such regulations might include setting stringent emission baselines and implementing policies that cap greenhouse gas emissions, which would drive the industry towards adopting more advanced and sustainable technologies. Under these conditions, companies would face penalties and carbon taxes for exceeding emission caps, making the transition to hydrogen-based processes more economically viable.

The shift towards hydrogen will require significant infrastructure development, which cannot happen overnight. Developing the necessary facilities for hydrogen production and distribution will take time. Nevertheless, industries that begin this transition early will be better positioned to succeed in a future with higher carbon costs. If the EU increases the price of carbon to reflect the impacts of climate change, companies that have already integrated hydrogen technologies will have a competitive advantage.

At present, the European Union's Emissions Trading Scheme (EU ETS) sets the carbon price at approximately €71 per metric ton. This pricing mechanism aims to incentivize reductions in greenhouse gas emissions by making it more costly to emit carbon dioxide. However, significant changes are anticipated in the coming years. Due to market reforms aimed at tightening the supply of carbon credits and making the system more stringent, the price is expected to rise sharply. Projections indicate that by 2030, the carbon price could reach around €149 per metric ton. This increase reflects efforts to strengthen climate policies and encourage industries to adopt more sustainable practices, ultimately contributing to the EU's goal of achieving carbon neutrality by mid-century (BloombergNEF, 2024).

Therefore, the earlier the steel industry adopts hydrogen production, the more advantageous it will be in the long run. It's important to consider that scaling up hydrogen production will take time, making it crucial to start planning and investing in internal hydrogen production systems now. This approach will ensure that industries are prepared for future regulatory changes and can benefit from reduced carbon emissions and associated costs. In conclusion, although the initial costs of retrofitting and developing hydrogen infrastructure are high, the long-term benefits in terms of reduced emissions, compliance with future regulations, and economic viability make it a necessary step for the steel industry.

Hydrogen-based steel production via Electric Arc Furnace is now technically feasible and is considered a promising long-term solution for decarbonizing the steel industry on a large scale. The critical question is not whether this transformation will happen, but when and to what extent. Several interdependent factors will determine the tipping points for decarbonization in the steel industry.

The main drawback of using electric arc furnaces with green hydrogen is the substantial amount of renewable energy required and the high cost of electricity for electrolysis. The availability of renewable energy sources is unevenly distributed globally, and their intermittency, such as variations in sunshine across hours and seasons and wind speeds, poses a challenge. This unpredictable nature of renewable energy makes it difficult for regions to plan for the long term.

Hydrogen-based steel production requires a significant increase in electricity from renewable sources. Producing two million tons of hydrogen-based steel requires about 8.8 Terawatt-hours of energy, equivalent to the output of 300 to 1,100 wind turbines. Therefore, the availability, reliability, and cost of renewable energy are crucial for this technological shift.

A reliable supply of green hydrogen is essential for large-scale hydrogen-based steel production. Producing two million tons of steel requires 144,000 tons of green hydrogen, which necessitates substantial electrolysis capacity. The economics depend on decreasing green hydrogen prices, closely tied to renewable electricity costs. Competition from other industries for green hydrogen will also affect its availability.

Transitioning from BF/BOF to DRI/EAF using hydrogen will increase demand for Direct Reduced (DR) pellets. The security of DR pellet supply and potential price increases could impact the economics of hydrogen-based steel production. Ensuring carbon neutrality throughout the value chain requires close collaboration with raw material suppliers.

The DRI/EAF method using natural gas is already established in some markets. Transitioning to hydrogen-powered processes is technically feasible but currently costly and unproven on a large scale. However, converting from natural gas to hydrogen in DRI/EAF is considered straightforward

The success of green hydrogen-based steel hinges on customer acceptance and willingness to pay for carbon-neutral products. Industries are increasingly interested in decarbonized steel to reduce their own carbon footprints. Legislative measures, like carbon pricing or eco-labeling, could also drive demand.

Political support for decarbonization, including carbon pricing and border taxes, is crucial for the economic viability of hydrogen-based steel. Start-up capital and subsidies will be needed to offset significant capital expenditure requirements. Collaboration among regulators, governments, and industry stakeholders is essential.

The shift towards hydrogen-based steel cannot happen overnight. Future availability of affordable renewable energy and favorable regulation are key drivers. Despite Europe's goal of carbon neutrality being 30 years away, immediate action is essential due to the long lifetimes of industrial sites and the extended planning horizons for investments. Current decisions must follow a clear decarbonization roadmap, combining long-term goals with short-term actions to ensure a gradual transition. In Europe, green hydrogen-based steel production is likely to play a crucial role in reducing emissions. This may involve initially optimizing BF/BOF processes, then switching to EAF using scrap and DRI powered by natural gas or imported HBI, and ultimately adopting carbon-neutral EAF production with a mix of scrap and hydrogen-based DRI. The balance between scrap and DRI will depend on future product requirements. Hydrogen-based DRI will be vital for producing high-purity steel grades without CO_2 emissions, securing the future of steel production in Europe (Mc Kinsey & Company, 2020).

The future of renewable energy, particularly solar and wind power, indeed holds promise for reducing electricity costs as technology advances and economies of scale kick in. The projection of a 1 terawatt (TW) global capacity for electricity production from photovoltaic panels underscores the growing importance of solar energy in the global energy mix.

However, it's crucial to acknowledge that while this capacity can potentially supply a significant portion of today's electricity demand, it's just one piece of the puzzle. Meeting future energy needs sustainably will likely require a diverse portfolio of renewable sources, energy storage solutions, and advancements in energy efficiency. Continued innovation, investment, and policy support are essential to realizing the full potential of renewable energy and achieving a more sustainable and affordable energy future.

The commercialization of electricity generation from solar energy began in the mid-20th century, but its impact on cost was initially limited by the low efficiency of early solar cells and high manufacturing expenses. However, as technology advanced and economies of scale were realized, the cost of solar energy steadily declined. Breakthroughs in materials science, manufacturing processes, and system design, coupled with increasing global production capacity, contributed to significant cost reductions. Today, solar energy has become increasingly competitive with conventional sources of electricity, thanks to continuous innovation, economies of scale, supply chain optimization, policy support, and increased competition. This decreasing cost has facilitated the widespread adoption of solar energy, accelerating the transition to a more sustainable and renewable energy future.

Indeed, the trajectory of the cost of green hydrogen derived from renewable sources mirrors the pattern observed in the solar energy sector. Initially, high technology costs posed barriers to widespread adoption. However, with advancements in technology and the establishment of markets for green hydrogen, particularly in industries like steel production, where it can significantly reduce CO_2 emissions, incentives and policies aimed at promoting its use can catalyze cost reductions. As industries embrace green hydrogen and governments incentivize its adoption through measures such as carbon pricing or subsidies, the investment in converting technologies like electric arc furnaces can pay off, further driving down costs and accelerating the transition to a cleaner, more sustainable energy economy.

In conclusion, the incorporation of green hydrogen into steel manufacturing processes represents a pivotal step towards reducing carbon emissions and promoting sustainability within the industry. With its production reliant on renewable energy sources through electrolysis, green hydrogen offers a carbon-neutral alternative to traditional methods. By integrating green hydrogen into various steel production techniques, such as direct reduction and electric arc furnaces, the sector can significantly advance decarbonization efforts. This review has examined the technical feasibility, economic viability, and environmental benefits associated with adopting green hydrogen in steel production, emphasizing the importance of infrastructure development, investment, and supportive policy frameworks. Despite potential challenges proactive measures can ensure a successful transition towards a more sustainable steel industry, by making technological progress with environmental imperatives to effectively tackle climate change.

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List of Abbreviations

GHG	Greenhouse gas emissions
WHO	World health organization
COP	Conference of parties
RE	Renewable energy
	Environmental innovations
UN	United Nations
SDG	Sustainable development goal
IPCC	Intergovernmental Panel on Climate Change
EAF	Electric arc furnace
BF-BOF	Blast furnace-basic oxygen furnace
DRI-EAF	Direct reduced iron-electric arc furnace
Scrap-EAF	Scrap-based electric arc furnace
CS	Crude steel
EJ	Exajoules
H-DR	hydrogen direct reduction
CCUS	Carbon capture, usage and storage
IEA	International energy agency
NG	Natural gas
SMR	Steal methane reforming
HBI	hot briquetted iron

HYBRIT	Hydrogen Breakthrough Ironmaking Technology
ISI	Iron and steel industry
EU ETS	European Union's emissions trading schemes
SOEC	Solid oxide electrolysis cell
PEMEC	Proton exchange membrane electrolysis cell
AEC	alkaline electrolysis cell

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