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"Techno-economic Feasibility and Benefits of Hydrogen-based Steel Production"

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ABSTRACT

The steel industry is essential to global development but is also a major contributor to greenhouse gas emissions, accounting for about 7% of global emissions. To mitigate this impact, the industry must transition to more sustainable production methods. This study examines traditional steel production processes, such as Blast Furnace-Basic Oxygen Furnace (BF/BOF) and Electric Arc Furnace (EAF), alongside emerging technologies like Hydrogen Direct Reduction (H-DR). It analyses the challenges of retrofitting existing steel plants for hydrogen use compared to the construction of new facilities. Additionally, the different types and colours of hydrogen, their respective production methods, costs, and their role in making hydrogen-based steelmaking economically viable, are explored. The study highlights the central role of renewable energy in reducing the cost of green hydrogen and the potential for significant emissions reductions in steel production. By comparing carbon emissions, energy consumption, and production costs, the research outlines how hydrogen-based steelmaking can transform the industry. Furthermore, the impact of policy mechanisms such as carbon pricing and government incentives in accelerating this transition is discussed. The findings suggest that with strategic investments in technology, structure, and renewable energy, the steel industry can achieve significant reductions in its carbon footprint while maintaining competitiveness, providing a clear pathway to a cleaner and more sustainable steel production.

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1 Introduction

The production of steel is essential to modern society and many industries as it is a key material for building infrastructure like bridges, buildings, and roads. It is also essential in manufacturing cars, machinery, and appliances, enhancing technological innovation and economic development. As global economies increasingly focus on sustainability, the steel industry is required to adopt technologies and processes that reduce carbon emissions. These include cleaner production methods, such as Electric Arc Furnaces and hydrogen-based steelmaking to reduce emissions, and recycling practices to ensure that steel is repurposed effectively, minimizing waste and saving resources. In this changing environment, steel production not only supports the infrastructure and products we rely on daily but also plays a crucial role in the transition to a more sustainable production system.

By adopting new techniques and focusing on eco-friendly activities, the steel industry can keep up with the growing global demand while supporting sustainability goals that help both the economy and the environment.

Therefore, the steel industry is a priority sector to be decarbonized as it represents one of the most significant sources of CO_2 emissions across industries. The world's steel industry has accounted for approximately 5% of the world's total energy consumption and about 7% of the total human GHG emissions per year [1,2]. On average, the production of one ton of crude steel globally results in the emission of approximately 1.9 tons of CO_2 but, as it will be shown in this thesis, there is a large margin for reducing this figure replacing coal with hydrogen in the production cycle.

The present work is structured as follows. In Section 2, three different steel production processes are described, comparing the process steps, the materials and the CO_2 emissions. Section 3 analyses the costs of brand-new hydrogen-based steel production plants and possible retrofit of existing ones. Section 4 analyses the greenhouse gas emissions of different production types. Conclusions are reported in Section 5.

2 State of the art: steep production processes

Steel production is essential for modern industries, and different methods have been developed to meet the growing demand. In this chapter, steel production processes are compared:

- Blast Furnace – Basic Oxygen Furnace (BF/BOF)
- Electric Arc Furnace (EAF)
- H_2 Direct Reduction (H-DR)

These methods vary in how they work, the materials they use, and their impact on the environment, and must be carefully assessed in order to achieve a sustainable steel production.

2.1 Blast Furnace – Basic Oxygen Furnace (BF/BOF)

Globally, the blast furnace-basic oxygen furnace (BF-BOF) steelmaking process is the most widely used method, accounting for approximately 60% of crude steel production in the EU and about 70% in the world, despite being the most carbon-intensive, while the rest is produced in Electric Arc Furnaces (EAF), mostly from scrap metal with a small share from direct reduced iron (DRI) [3].

As shown in Figure 1, the steelmaking process begins with the preparation of materials, specifically through two key steps: sintering and coking.

- Sintering: fine iron ore particles are combined into larger pieces known as sinter. This is done by mixing iron ore fines with coke breeze and limestone, then heating the mixture in a sintering machine [4]. This process improves the strength and permeability of the ore, making it suitable for the Blast Furnace.
- Coking: coal is converted into coke by heating it in the absence of air. This results in a carbon-rich material suitable for the reduction of iron ore in the Blast Furnace.

After the materials are prepared, they are charged into the Blast Furnace (BF) along with coke and limestone. Inside the BF, the coke reacts with the iron ore to reduce iron oxides to molten iron. The key reaction is expressed in Eq. 1.

$$\boldsymbol{Fe_2O_3 + 3C \rightarrow 2Fe + 3CO} \qquad \text{Eq. 1}$$

The produced molten iron is then conveyed into the Basic Oxygen Furnace (BOF), where oxygen oxidizes the impurities thus refining the iron into steel. The main reaction in the BOF is:

$$\boldsymbol{C + O_2 \rightarrow CO_2} \qquad \text{Eq. 2}$$

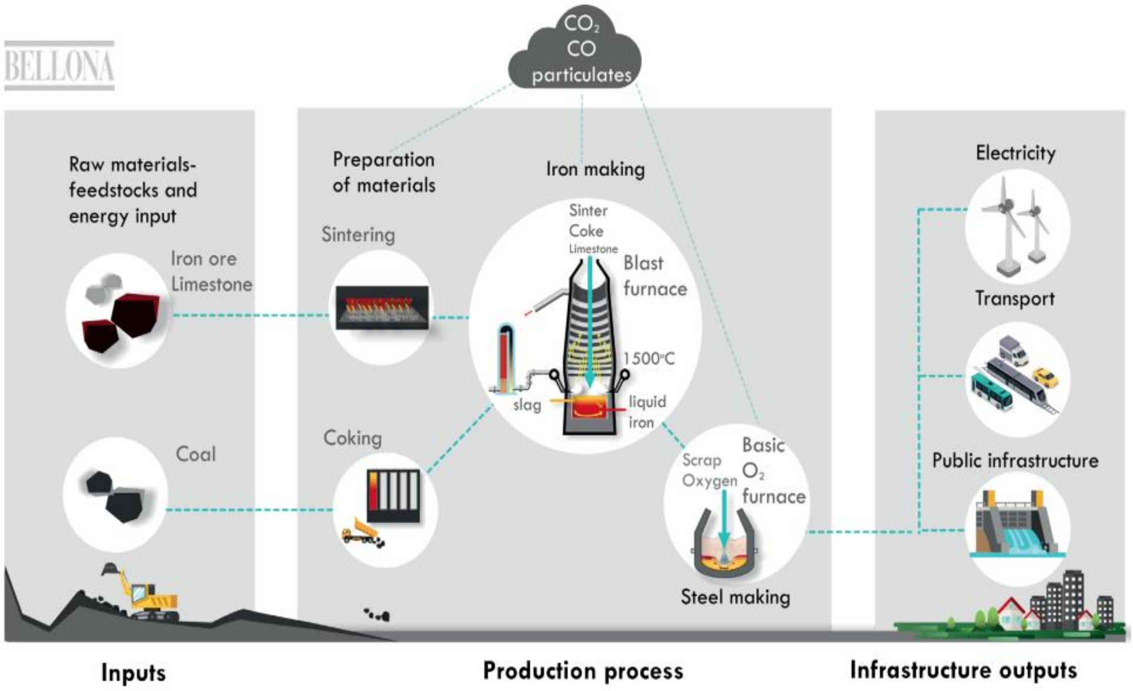

Figure 1. The steel making process creates emissions both during preparation of materials and iron and steelmaking [4]

Moreover, several more reactions take place during the BOF process to form slag, such as:

Silicon oxidation:

$$\boldsymbol{Si + O_2 \rightarrow SiO_2} \quad \text{Eq. 3}$$

Manganese oxidation:

$$\boldsymbol{Mn + O_2 \rightarrow MnO} \quad \text{Eq. 4}$$

Phosphorus oxidation:

$$\boldsymbol{2P + O_2 \rightarrow 2P_2O_5} \quad \text{Eq. 5}$$

As it is clear, the BF/BOF steel making process is highly CO and CO_2 intensive. The steel and iron production with traditional technologies requires large amounts of coal and releases about 1.85 tCO_2/t on average [5].

2.2 Electric Arc Furnace (EAF)

While the traditional processes involve the use of the Blast Furnace (BF) and Basic Oxygen Furnace (BOF) to produce steel from iron ore, the Electric Arc Furnace (EAF) offers an interesting alternative. Nowadays, EAF is experiencing a significant growth worldwide, thanks to its flexibility, lower carbon emissions and the possibility to use scrap steel as its feedstock, allowing for the recycling of existing materials rather than relying on virgin iron ore (Figure 2) [6–8]. A ladle furnace is essential in steelmaking, particularly after the electric arc furnace (EAF), to enable secondary refining of molten steel, allowing for precise control over temperature and chemical composition, and produce high-quality steel.

In the ladle furnace, molten steel is heated using electric arc or induction heating to maintain or raise its temperature. Alloying elements are added for composition adjustments, while impurities are removed through chemical reactions with fluxes. Mixing can be enhanced through the injection of inert gases. Advanced control systems monitor the process parameters in order to provide real-time adjustments and eventually ensure a final product of consistent quality.

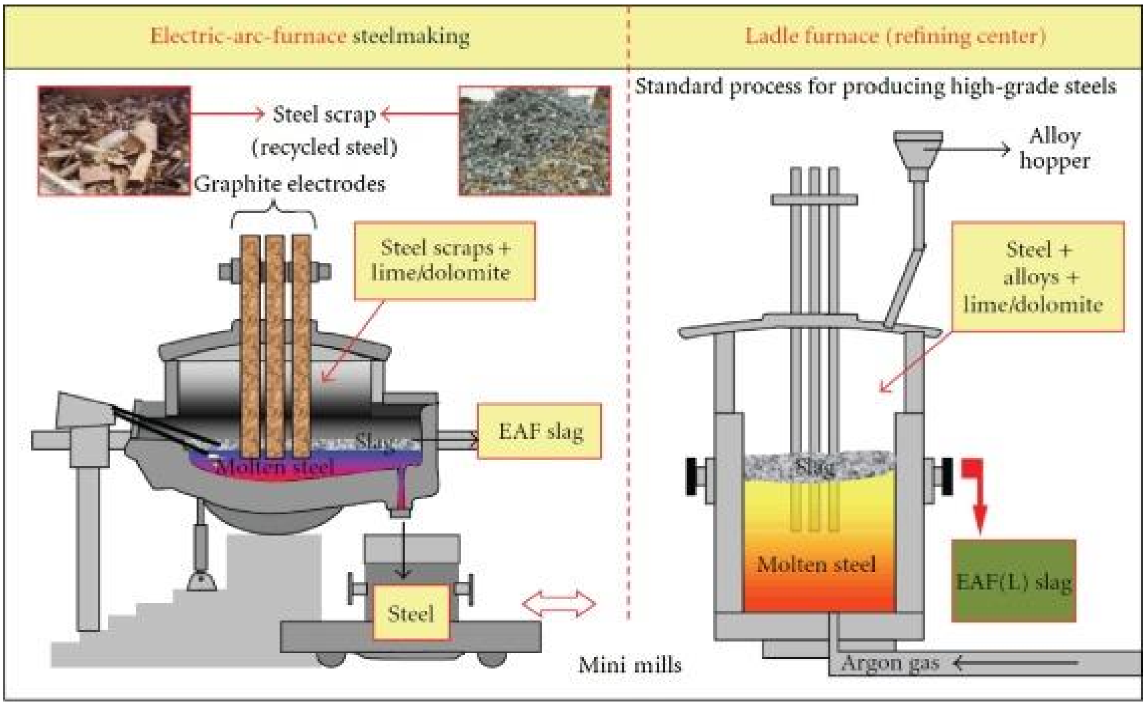

Figure 2. Schematic representation of electric-arc-furnace (EAF) steelmaking and ladle refining (LF) processes [9]

Currently, around 40% of steelmaking plants utilize Electric Arc Furnaces (EAFs), but they can encounter several challenges that affect their operations and product quality [3]. EAF operations are significantly dependent on the availability and pricing of scrap metal, which can be volatile due to market fluctuations. This reliance can create challenges in maintaining a steady supply of suitable materials, further impacting the overall quality of the steel produced.

2.3 H_2 Direct Reduction (H-DR)

On the other hand, one promising way towards the decarbonization of iron ore-based steelmaking is hydrogen (H_2) direct reduction (H-DR). In H-DR, iron ore is reduced by H_2, yielding only water (H_2O) as a byproduct. This process is called direct reduction as the produced iron, referred to as direct reduced iron (DRI) or sponge iron, remains in the solid phase (direct reduction without melting) [10]. The main advantage of hydrogen is that it can make the entire process almost carbon-free. The chemical reaction involved in this process is expressed by:

$$\boldsymbol{Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O} \quad \text{Eq. 6}$$

The H-DR steelmaking process is endothermic, requiring hydrogen to be preheated to temperatures above 800°C to provide sufficient heat for the reaction. This process is depicted in Figure 3, which outlines the material and energy flows. Firstly, an electrolyser splits water into hydrogen (H_2) and oxygen (O_2). H_2 is stored for subsequent use into a shaft reactor, where it reacts with iron ore pellets at 800°C to produce direct reduced iron (DRI) or sponge iron. Meanwhile, water vapor and unreacted hydrogen are separated in a condenser with heat recovery. The produced sponge iron (DRI) can be compacted to hot briquetted iron (HBI), which is more suitable for transportation and storage [11].

The next stage involves processing DRI/HBI in a conventional EAF, where it is combined with scrap metal (composed of 95% iron and 5% inert substances), carbon, and lime [12]. The EAF melts these inputs into liquid steel while generating slag and emitting CO_2 from lime calcination and carbon use.

Despite the CO_2 emissions generated from lime use and carbon in the EAF, the overall emission intensity of the H-DR process is significantly lower compared to the (BF/BOF) route. Specifically, lime and carbon use in the H-DR process result in just 53 kg of CO_2 per tonne of steel, which is only 2.8% of the emissions associated with the BF/BOF process [12].

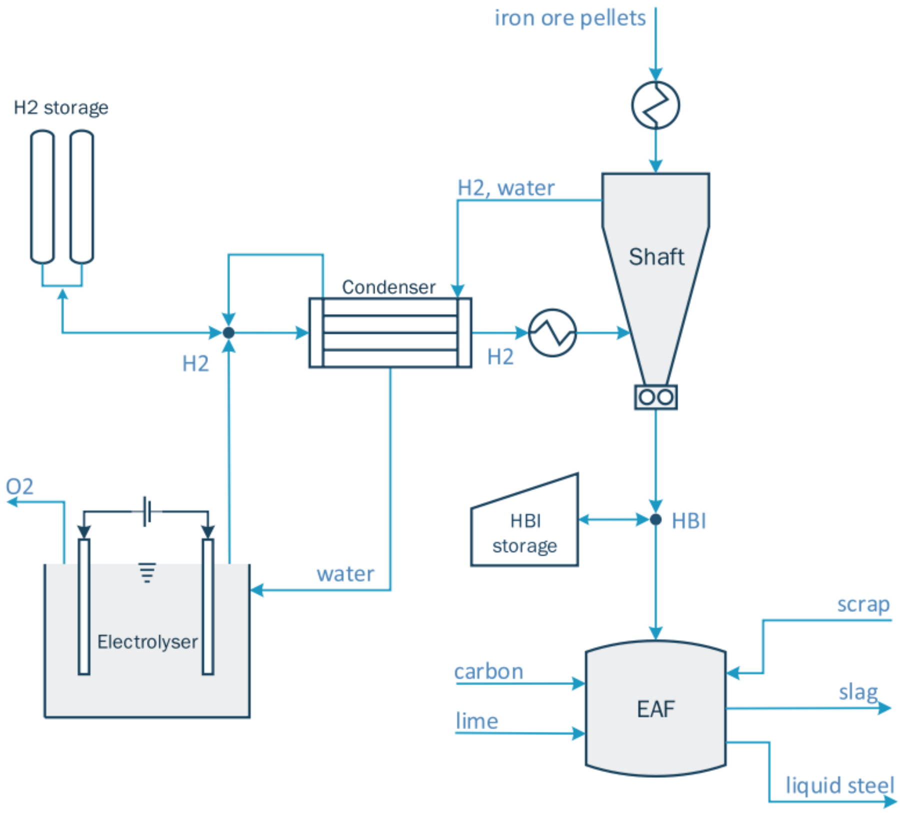

Figure 3. Proposed process design for hydrogen direct reduction (H-DR) process[12]

The main challenge for hydrogen direct reduction (H-DR) in steelmaking are hydrogen supply and production costs, as the availability of green hydrogen, produced through renewable energy sources, is currently limited and usually more expensive than traditional carbon-based methods. Currently, the production cost of steel is around €400/t, where approximately €50/t represents the cost of coal. The cost of replacing coal in the production process would be around €180 for the required hydrogen at today's best prices (€3.6 per kilogram), increasing the total cost of steel production by roughly one third, approximately €533/t [5]. However, as renewable energy sources continue to grow, the cost of green hydrogen is expected to decrease, lowering the costs for H-DR.

Furthermore, several large-scale projects, such as the Hybrit project in Sweden and the H_2Steel project in Germany, are already working to develop and demonstrate the commercial feasibility of hydrogen-based steelmaking technologies [11]. These initiatives show that with the right investments in technology, infrastructure, and energy production, H-DR can play a key role in achieving the steel industry decarbonization goals. Typically, around 94% of incoming iron (Fe_2O_3) is fully reduced in commercial DR processes based on natural gas; this would yield a H_2

consumption of around 51 kg/t DRI [13,14]. So, H-DR demands a large supply of H_2, and understanding the hydrogen production methods is key to assess the sustainability of this steel production method. For this reason, the hydrogen production methods are described in Section 2.4.

2.4 Hydrogen production methods

As the production of hydrogen relies on different primary energy sources, hydrogen can be classified according to a colour scale depending on to the production process, the kind of energy used, the costs and the related emissions. There are several colour definitions but, according to the most comprehensive classification, they are green, blue, aqua, white, grey, brown or black, yellow, turquoise, pink and red [15]. As shown in Figure 4, that summarizes the main hydrogen colours next to their production method, each hydrogen colour is produced with a different energy source.

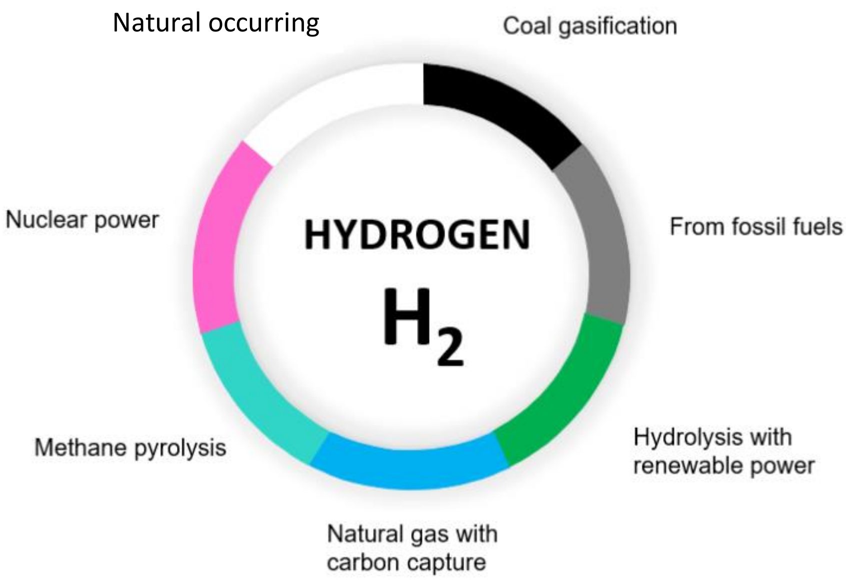

Figure 4. Main hydrogen colours with their respective production methods [16]

2.4.1 Green, Pink, and Yellow

Green hydrogen, often called "clean," or "renewable," is produced through water electrolysis using electricity from renewable sources as solar energy or wind energy, generating zero direct CO_2 emissions. In this process, about 80% of the electrical energy is transformed into chemical energy of hydrogen, taking about 55 kWh to produce 1 kg of hydrogen [5]. For these reasons, green hydrogen plays a crucial role in the transition to a sustainable energy and transport system. Currently, green hydrogen accounts for a small fraction of total hydrogen production due to excessive costs, but it holds great potential for the future as the cleanest hydrogen production option, supporting net-zero carbon goals. Over the past decade, the production cost of green hydrogen has dropped by 60%, now typically ranging between €3.6 and €5.3 per kilogram [5]. This price is expected to decrease more thanks to lower investment costs due to scale effects for production facilities and lower electricity prices from renewable sources like wind and solar. The price of green hydrogen could reach 1.8€/kg by 2030, making it a more competitive option for large-scale hydrogen production [5].

In addition, pink hydrogen is produced through water electrolysis using low-carbon electricity from nuclear power plants. Nuclear electricity is not widely included in the EU hydrogen strategies, but it could represent a viable option in other regions like Russia and China. Even if China has a significant renewable energy production, nuclear energy is still important for making hydrogen as it can offer steady and reliable supply. This is especially helpful during seasons or in areas where solar and wind are less available. By using both nuclear and renewables, China can meet its growing hydrogen needs, stay energy-secure, and lead in hydrogen and nuclear technology worldwide. France is actively aiming for this approach, suggesting that integrating hydrogen production facilities with nuclear plants could help minimize the limitation of nuclear energy output [15].

The costs, except for the electricity cost item, are comparable to those of green hydrogen. Electricity or heat from nuclear power is cheaper than electricity from green sources; thus, the pink hydrogen price is lower than green hydrogen. Even with the current low prices of PV panels, nuclear electricity can remain cost-competitive in the range of 2.7-5.4 \$/kg for pink H_2, as solar power require storage or backup systems, which lead to higher overall costs [17]. This makes pink hydrogen cheaper than green hydrogen in some cases. However, in regions with abundant and inexpensive solar energy, green and pink hydrogen can show similar costs.

Yellow hydrogen, moreover, is produced also with electrolysis but using electricity from energy grids. The carbon emissions involved can vary greatly depending on the energy sources supplying the grid at different times. The grid combines electricity from all available sources as shown in Figure 5, which vary by country and over time.

In Spain, for example, the electricity fed to the grid in 2021 came from a diverse mix of energy sources. Wind energy accounted for 23.3% of the total, making it the largest contributor, nuclear power followed closely with nearly 21%, combined cycle plants contributed 17.1%, while hydropower made up 12.4%, smaller shares came from cogeneration at 10% and solar photovoltaic at 8% [15].

Currently, in the U.S., the price of hydrogen from grid connected stands at 8.81$/kg, with a minimum price of 6.06$/kg. In the EU, the median price is 13.11$/kg, and the minimum price is 4.83$/kg [18], but these prices are supposed to decrease in the future years thanks to a reduction in electricity production costs.

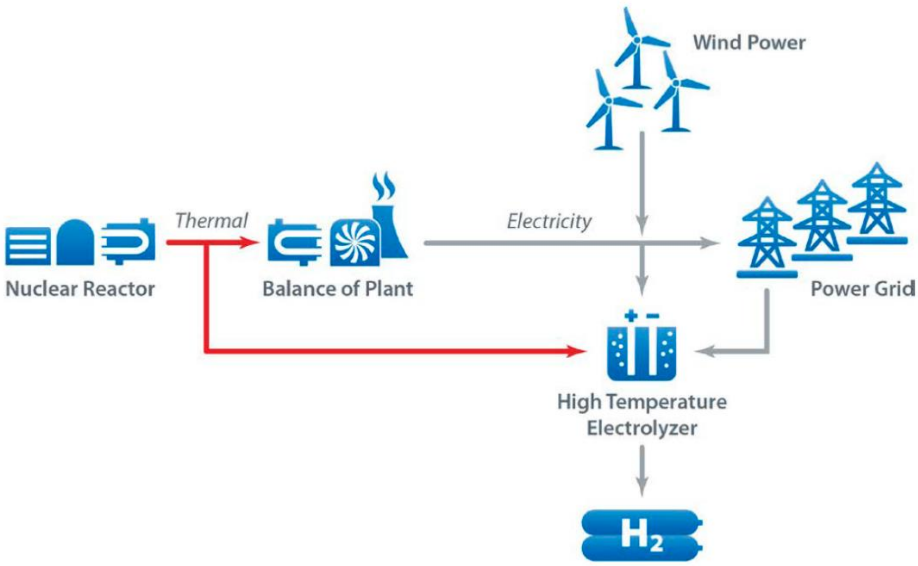

Figure 5. Energy sources for pink, green, and yellow hydrogen production [15]

2.4.2 Brown and Black

On the other hand, brown and black hydrogen are produced from fossil fuels, specifically lignite and coal, respectively. Figure 6 shows the four types of coal usually utilized: lignite and sub-bituminous coal (low rank), bituminous coals (medium rank), and anthracites (high rank) [15]. Both brown and black are among the least environmentally friendly forms of hydrogen due to their significant greenhouse gas emissions, making them less viable options in the transition to cleaner energy sources. Brown and black hydrogen are produced through the gasification of lignite and hard coal, respectively. These processes release around 20 t_{CO2}/t_{H2} [15], resulting in a much higher carbon footprint than other forms of hydrogen. For example, electrolysis typically requires about 55 MWh/t_{H2}. Considering the Italian electricity grid, which has an emissions factor of around 300 $kg_{CO2,eq}$/MWh, this would result in approximately 16.5 t_{CO2}/t_{H2}. In contrast, if the electricity comes from PV panels, which have an emissions factor of about 40 kg_{CO2}/MWh, the

CO_2 emissions drop significantly to around 2 t_{CO2}/t_{H2}. This makes green hydrogen from renewable sources more environmentally friendly compared to brown and black hydrogen. Currently, the cost of brown and black hydrogen ranges between 1.10€/kg and 2.10€/kg, depending mainly on the prices of brown and black coal respectively [16], which are cheap fossil fuels. However, brown and black hydrogen involve a high environmental price due to the significant CO_2 emissions generated during production, making it economically attractive but environmentally unsustainable in the long term.

As a result, these forms of hydrogen are being phased out or avoided in favour of cleaner alternatives like green and blue hydrogen, which help reduce the carbon footprint of hydrogen production.

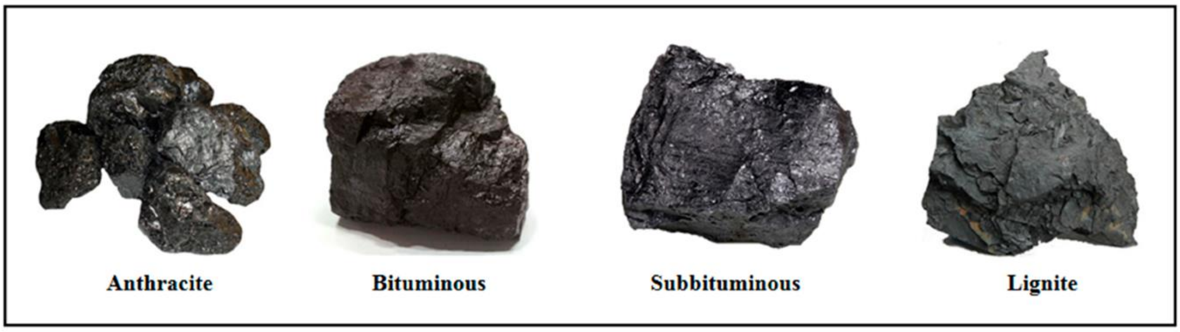

Figure 6. Different types of coal

2.4.3 Grey and Blue

Grey hydrogen is produced from natural gas through a steam methane reforming (SMR) process. In this method, high-temperature and pressure steam, ranging between 700–1,000°C and 5-20 bar, reacts with methane (CH_4) to produce hydrogen (H_2) and carbon dioxide (CO_2) [15], as shown in this equation:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad \text{Eq. 7}$$

This method results in significant CO_2 emissions, with approximately 10 t_{CO2}/t_{H2} [15]. While grey hydrogen releases greenhouse gases directly into the atmosphere, blue hydrogen employs carbon capture and storage (CCS) technology, offering a lower-carbon alternative while still relying on fossil fuels as its primary energy source.

The production costs of hydrogen from natural gas primarily depends on regional gas prices. In Europe, costs are typically around 1.5€/kg, with an increase to 2.0€/kg when including the expenses related to carbon emission reduction, transitioning it to blue hydrogen [5].

Blue hydrogen is considered a transition technology that could bridge the gap towards more sustainable hydrogen production methods, such as green hydrogen.

2.4.4 Turquoise

Turquoise hydrogen is produced through methane pyrolysis, a process that splits methane (CH_4) into hydrogen and solid carbon using high temperature heat typically between 800°C and 1,200°C, without emitting CO_2 if heat is powered by renewable energy. Turquoise hydrogen production offers a cleaner pathway compared to blue hydrogen. While turquoise hydrogen is a relatively innovative approach, it offers a promising way to produce hydrogen with minimal emissions, as the carbon byproduct is captured in solid form rather than released into the atmosphere. The price of turquoise hydrogen is expected to be 1.9 €/kg_{H2} and the emission released around 2.6 kg/$_{CO2}$/kg_{H2} [15].

Companies like Mitsubishi Heavy Industries are investing in turquoise hydrogen. They have partnered with Monolith Materials, the first U.S. manufacturer of turquoise hydrogen, and C-Zero, a startup focusing on hydrogen production and solid carbon sequestration [16].

2.4.5 White

White hydrogen refers to naturally occurring hydrogen. White hydrogen is a natural gas found in various parts of the Earth's crust. As clear in Figure 7, white hydrogen can be found under the ground, deep in the ocean, or in gases from volcanoes, hot springs, and hydrothermal vents. It seems to exist in many types of rocks and areas around the world, for example some of this hydrogen has been found in New Caledonia (group of islands in the southwest Pacific Ocean) and it is believed to have been formed by the reaction between water and the local rocks (ophiolites) and releasing hydrogen [15]. It is unique compared to other colours, as it represents hydrogen in its natural form, rather than a product of chemical or energy processes, but the limited research on the topic makes it challenging to accurately estimate global white hydrogen resources.

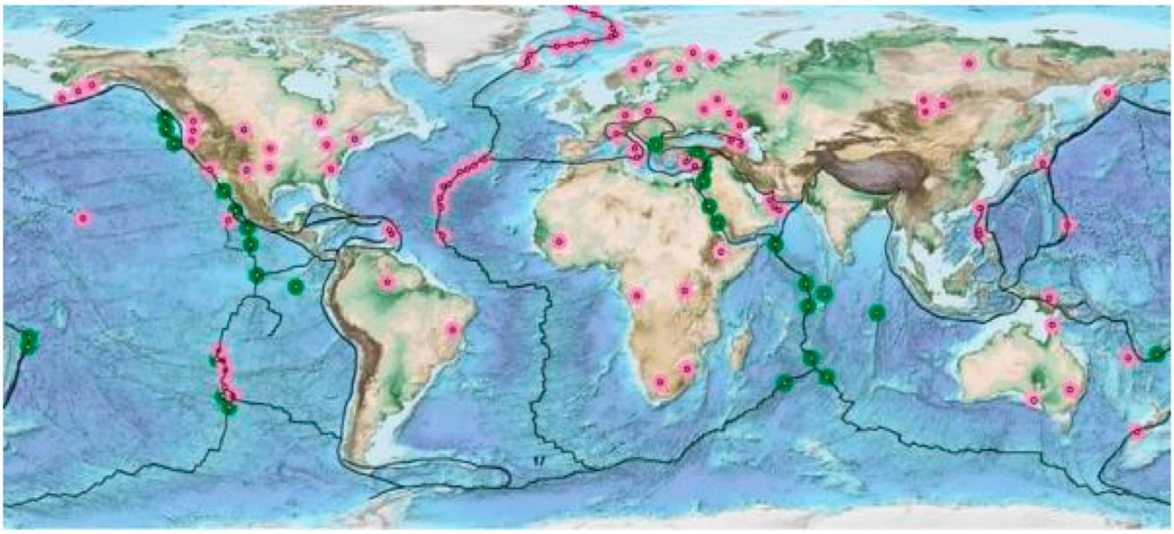

Figure 7. Spots where likely white H_2 can be found [15]

2.5 Future Trends in Hydrogen Production

As technology improves and stricter environmental regulations like carbon taxes for CO_2 emissions to industries and bans or restrictions on the use of coal and natural gas are introduced, the production of several types of hydrogen is expected to change. Green hydrogen, made from renewable energy through electrolysis, will likely grow the most. As the cost of renewable energy continues to decrease and electrolyser technology improves, green hydrogen will become more affordable and widely used, especially in industries like steelmaking and transport. This trend is clear by the significant drop in solar and wind electricity costs over the past decade to about 20-30 $/kg, with regions like the Middle East and Latin America achieving low energy costs that make green hydrogen cost-competitive [19]. However, regions like Europe still face higher production costs about 40-50 $/kg due to elevated electricity prices and limited access to low-cost renewable energy.

As mentioned before, as CCS technology improves and becomes cheaper, blue hydrogen will play a role in the transition to cleaner production, offering a lower carbon footprint compared to grey hydrogen, while still deriving from fossil fuels [15].

On the other hand, grey hydrogen is expected to decrease over time due to its high environmental impact and tighter regulations. New hydrogen types, like turquoise and pink hydrogen may also emerge as their technologies develop. The future of hydrogen will depend on technological advancements, market shifts, and global policies aiming for cleaner energy.

2.6 Hydrogen production as an electricity storage

Hydrogen is gaining attention as a crucial element for clean energy transition, particularly for its potential in energy storage. As an effective energy carrier, hydrogen allows to store and transport chemical energy in a gas or liquid form, offering a solution for long-term energy storage that can be scaled without geographical restrictions and can solve the challenges posed by variable renewable energy sources like solar and wind.

By examining the shape of the so-called "duck curve" (Figure 8), which represents the daily fluctuations in electricity demand compared to supply from solar energy, it is visible how solar generation reaches the peak during the day, while demand remains relatively low, while solar production drops and demand rises in the evening, so that a significant spike in the need for additional power occurs. This leads to an excess of energy production with respect to consumption, making it difficult to balance the mismatch between energy production and consumption and resulting in inefficiencies, such as wasted energy from solar production.

Given the challenges highlighted by the duck curve, converting surplus electricity into hydrogen presents a viable solution for energy storage and management. Hydrogen allows huge quantities of clean energy to be stored for long durations to be used in peak demand and seasonal energy balancing [20]. The storage method is particularly appealing due to its low rates of self-discharge and consistent performance over time, making hydrogen a reliable option for effective energy management in the shift towards cleaner energy solutions.

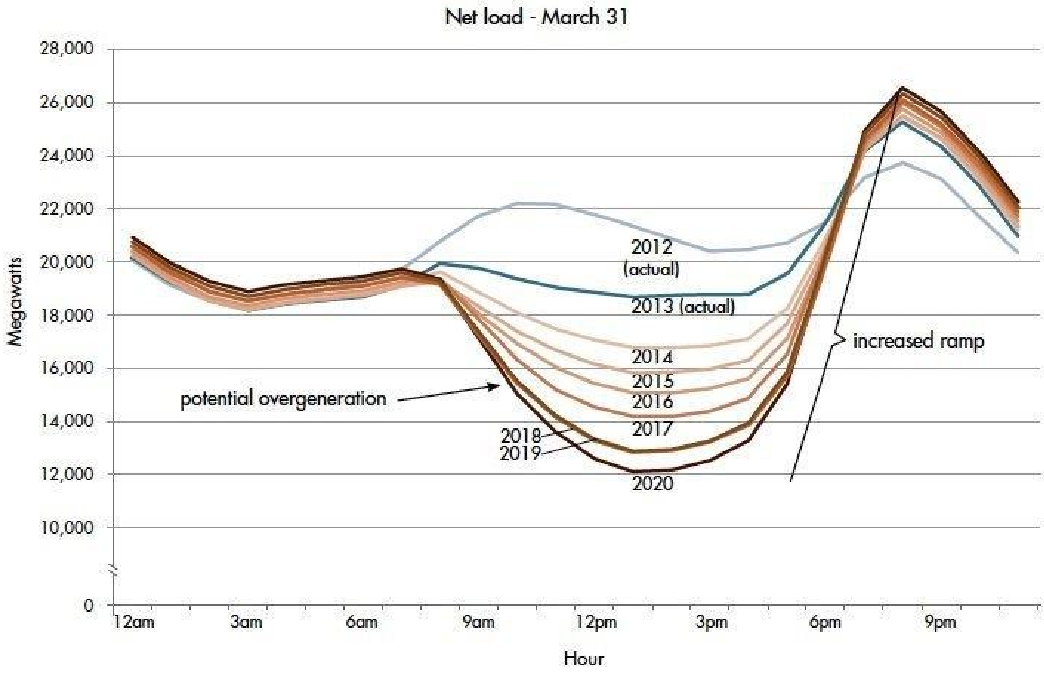

Figure 8. The effect of renewable energy sources on the electrical grid [21]

2.6.1 How Hydrogen Energy Storage System Works

The main component of a hydrogen energy storage system (HESS) is the electrolyser, which transforms electrical energy, often from renewable sources, into hydrogen, that can be stored as compressed gas, in solid-state metal hydrides, or in liquid containers. Storage options include compressed hydrogen tanks, liquid hydrogen reservoirs, and underground storage in geological formations [22].

To retrieve the stored energy, typically a fuel cell is used to transform the stored hydrogen back into electricity, producing only water and heat as by-products without carbon emissions. A schematic representation of the fuel cell is shown in Figure 9.

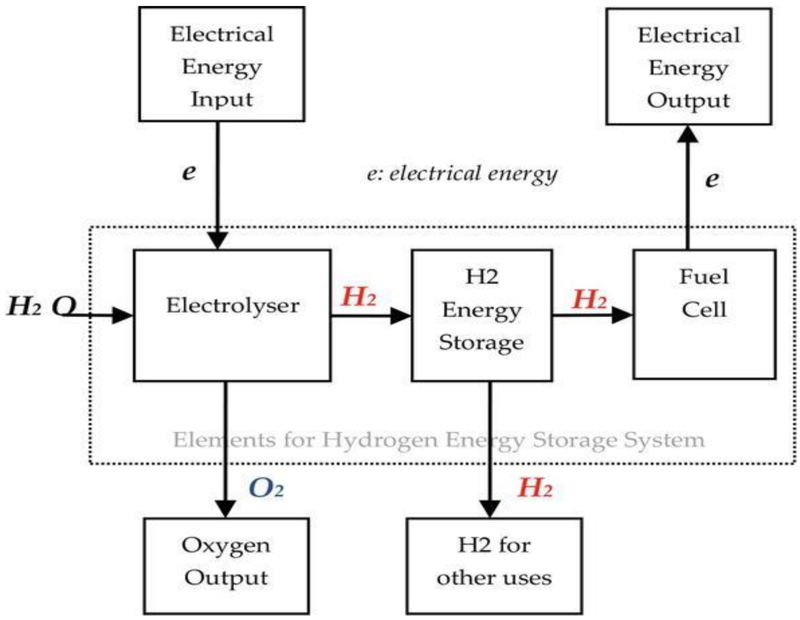

Figure 9. Basic elements of a hydrogen energy storage system (HESS) [22]

Fuel cells can achieve an electrical efficiency around 40%-50%, higher than the maximum efficiency of 37% typical of small combustion engines [22].

In addition to providing backup power to balance the grid, hydrogen storage systems can be integrated with other energy storage systems like batteries to create hybrid energy storage solutions, optimizing both short-term and long-term energy needs [22].

2.6.2 Challenges and Future Outlook for Hydrogen Energy Storage

While hydrogen energy storage offers many promising benefits, its integration into the global energy system still tackles several challenges. One major issue is the cost of hydrogen production, particularly for green hydrogen, due to the energy required for electrolysis, as well as the need for infrastructure development for storage and distribution. Additionally, hydrogen storage systems require specialized materials and technologies, such as high-pressure tanks or cryogenic storage systems, which add to both the financial and technical complexity [22].

Despite these challenges, the future outlook for hydrogen energy storage is optimistic. As renewable energy generation grows and economies of scale are realized in both hydrogen production and storage technologies, the costs are expected to decrease. Governments around the world are already supporting hydrogen initiatives through subsidies, research grants, and policy frameworks.

3 Hydrogen-based steel: retrofitting feasibility, economic analysis, influence of renewable energy power

As the world pushes towards a carbon-neutral future, one of the largest industrial sources of carbon emissions, the steel industry, faces immense pressure to reduce its carbon footprint. Hydrogen-based technologies are at the forefront of efforts to decarbonize steel production, offering a potential pathway to reduce the industry reliance on coke and coal. However, retrofitting existing steel mills with these new hydrogen-based technologies presents substantial technical, financial, and logistical challenges, that will be outlined in the following sections.

3.1 Challenges of Retrofitting Existing Steel Mills

The retrofitting of existing steel mills to integrate hydrogen-based technologies requires the overcoming of significant challenges to pursue the transition to more sustainable production methods in the steel industry.

3.1.1 Retrofitting Blast Furnaces

Blast furnaces have been the most used technology for steel production for centuries. Retrofitting a blast furnace to use hydrogen in place of coke is a massive task that requires changing the fundamental chemical processes of the furnace, the furnace design and thermal management. In fact hydrogen, unlike coke, does not produce carbon monoxide, which is traditionally used to reduce iron ore, but water vapor (H_2O) through the reaction with iron ore, a completely different byproduct [23]. The replacement of the blast furnace and basic oxygen furnace with a direct reduction shaft, an electric arc furnace, and supporting technologies such as an electrolyser, hydrogen storage, and heat exchangers, will be essential to facilitate this shift [11]. In hydrogen-based steel production, the downstream processes following the Electric Arc Furnace (EAF) largely the same as those used in traditional integrated steelmaking. After liquid steel exits the EAF, it undergoes secondary metallurgy treatments, where its composition is fine-tuned by adding or removing specific elements. This is followed by casting, where the steel becomes a semi-finished product. Finally, these are rolled into final products in rolling mills. These steps remain mostly unchanged, ensuring compatibility with existing infrastructure, the main difference being the absence of off-gases typically produced in conventional processes. In integrated steelmaking, off-gases from coke ovens, blast furnaces and basic oxygen furnaces represent an energy source within the plant, as they are recycled to power various operations [11]. In the hydrogen-based process, alternative energy sources must replace these off-gases to maintain efficiency, for example renewable electricity and green hydrogen. Additionally, optimizing heat recovery systems will be important to minimize the plants overall energy consumption and enhance the economic feasibility of hydrogen-based steelmaking. This shift underscores the need for innovation and investment in clean energy technologies to support the industry's decarbonization journey.

These significant changes are not only technically challenging but also expensive, with the need for specialized equipment and advanced safety systems to accommodate the volatility of hydrogen as a fuel. Furthermore, current blast furnace infrastructures were designed with coke as the primary reductant, and their retrofitting to use hydrogen potentially means replacing parts of the furnace, implementing hydrogen injection systems, and adjusting gas handling to accommodate hydrogen physical properties [24].

3.1.2 Retrofitting Electric Arc Furnaces (EAFs)

While blast furnace retrofitting presents many difficulties, the retrofitting of Electric Arc Furnaces (EAFs) with the integration of H-DR technology appears more feasible, as EAFs have a more flexible structure and operate with electricity and do not rely on coke as a reducing agent. By replacing scrap steel with a direct reduction shaft that uses hydrogen to react with iron ore and produce Direct Reduced Iron (DRI), steel production can become much greener with lower carbon emissions. However, achieving zero-emission steel production presents challenges, particularly in addressing the CO_2 emissions associated with the use of lime (1 mole of CO_2 for each mole of calcium oxide (CaO) produced from $CaCO_3$) and carbon (50% of the supplied carbon absorbed into the steel while the remaining are converted into CO_2) in the EAF [12]. For instance, alternative materials could potentially replace lime for slag foaming and the carbon required in the process could be sourced from biogenic materials, such as biomass. But, the development and implementation of such solutions will require further research and innovation to ensure compatibility with existing EAF operations and to minimize overall environmental impact. [11].

Several major players in the steel industry, such as Thyssenkrupp and ArcelorMittal, are already experimenting with hydrogen in EAFs. For instance, ArcelorMittal has committed to using hydrogen in some of its European plants, with the goal of decarbonizing its operations by 2050 [25]. For steelmakers aiming to achieve zero-emission production, integrating hydrogen storage systems is a crucial measure, therefore companies will benefit from investing in advanced hydrogen storage solutions as part of their decarbonization strategies.

3.2 The Case for New Hydrogen-Based Steel Plants

Given the technical and logistical challenges of retrofitting old plants, some industry experts argue that building new hydrogen-based steel plants may be a more viable alternative [11], as new plants can be designed to optimize hydrogen-based production using hydrogen-compatible infrastructures, making them more cost-effective in the long run. Hybrit, a collaboration between SSAB, LKAB, and Vattenfall in Sweden, is an example. This project aims to build a carbon neutral fossil-free steel plant using green hydrogen produced via electrolysis by 2026 [26]. Additionally, these new plants can take advantage of government subsidies, carbon credits, and innovative financing models available to companies investing in sustainable technologies [23], useful to also sustain the initial costs and reduce the financial risks. In addition to direct funding, carbon tax reductions can provide an important financial benefit, like tax breaks or exemptions. Moreover, new plants can be built in places with abundance of renewable energy, like areas with strong solar or wind power, to maximize the local production and consumption of energy. These plants can further use technologies, including advanced electrolysers characterized by higher efficiency and systems driven by artificial intelligence to ensure real time monitoring and optimization of energy usage. Another aspect to pay attention to is the integration of reliable short and long-term hydrogen storage systems for the balance of energy production and demand through the storage of surplus hydrogen produced during periods of high renewable energy output and its subsequent use during times of lower energy generation. This ensures consistent plant operation and energy security, even under fluctuating renewable energy conditions.

By designing modern facilities equipped with advanced technologies, energy-efficient systems, and robust hydrogen storage solutions, steelmaking companies can reduce carbon emissions and also attract investors and strategic partners who prioritize sustainability and innovation, reinforcing the industry commitment to decarbonization.

3.3 Construction and Retrofit Costs of Hydrogen-Based Steel Plants

As mentioned, transitioning to hydrogen-based steelmaking involves not only technical but also economic challenges. The costs of retrofitting existing facilities versus constructing new hydrogen-based steel plants must be carefully analysed to determine the most economically viable pathway. This section outlines the core cost components, comparing the two options and providing insights into which path is more advantageous in achieving a low-carbon steel industry.

3.3.1 Cost of Retrofitting Existing Steel Mills

Retrofitting existing steel mills, especially Blast Furnaces and Electric Arc Furnaces (EAFs), with hydrogen-based technologies requires significant capital and operational expenditures due to necessary technical modifications and hydrogen safety systems.

As for the Capital Expenditures (CAPEX), the costs include installation of pipelines, furnace modifications, i.e. re-engineering the furnace lining, implementing enhanced cooling and refractory materials to accommodate hydrogen distinct thermal and combustion characteristics [27], integrating storage facilities and updating gas-handling systems, adding hydrogen injection and safety systems to manage hydrogen high reactivity. Studies estimate that modifying a blast furnace for hydrogen compatibility can cost up to 25% of building a new hydrogen-compatible facility [28]. In comparison, retrofitting EAFs tends to be less complex, as EAFs are more flexible in their operation and can more easily integrate hydrogen as a reducing agent without major structural changes.

As for the Operational Expenses (OPEX), the replacement of fossil fuels by electricity results in an increased cost of energy supply [29]. Studies estimate that the operational expenditures would be responsible for at least 80% of the increased costs based on low-carbon technologies [30]. However, while both BF and EAF systems face similar OPEX challenges, the higher energy demands and complexities of hydrogen injection systems in Blast Furnaces make their operational transition more costly compared to EAFs.

For perspective, if we consider China's steel production in 2023, which reached 901 million tonnes/year using the traditional BF process [31]. The increased operational costs from adopting low-carbon technologies would amount to approximately €178 per tonne of steel which is around €160 billion/year [30]. This value highlights the significant financial impact that transitioning to green steelmaking could have on high-output producers like China.

This cost increase could have a big impact on the global steel market. Steel producers have two options to face these higher expenses: earning less profit or raising the prices, which could penalise the buyers. In countries like China, where the steel industry is a key sector, these extra costs might push the government to step in, offering financial support, like subsidies, or adjust carbon pricing to help low-carbon steel stay competitive in the market.

In conclusion, retrofitting Blast Furnaces is generally more challenging due to the extensive structural modifications and higher CAPEX involved in adapting them to hydrogen-based processes, although both systems face significant OPEX challenges related to energy supply and safety considerations.

3.3.2 Cost of Constructing New Hydrogen-Based Steel Plants

The construction of new hydrogen-based steel plants involves substantial CAPEX and OPEX. The CAPEX primarily includes the costs of the electrolyser, the shaft, and the EAF. The electrolyser is expected to cost 0.585 €/W of installed capacity by 2030, based on advancements in proton exchange membrane (PEM) and alkaline electrolysis technologies [12].

The OPEX consists of resource costs, electricity, and maintenance. Raw materials include iron ore pellets at 100 €/t, scrap at 180 €/t, and lime at 100 €/t. Graphite electrodes, essential for the EAF, cost 4 €/kg and are consumed at a rate of 2 kg/t of steel produced. Labour costs are estimated at 53.2 €/t of steel and maintenance costs are assumed to be 3% of total CAPEX. Electricity costs are a significant operational cost, while the sale of byproduct oxygen can partially offset expenses.

It is estimated that 60% of the produced oxygen can be sold for 60.8 €/t, provided there are nearby customers [12].

As an example, the HYBRIT project in Bodon, Sweden (Figure 10), a green steel plant that will start working around 2025, is analysed from an economic point of view. The H_2 Green Steel has secured nearly €6.5 billion in funding for its large-scale green steel plant in Northern Sweden: this includes €4.2 billion through debt financing, an additional €300 million in equity raised, and a €250 million grant from the EU Innovation Fund, bringing the total equity to €2.1 billion [32]. The project aims to be the world's first facility to produce steel at a large scale using hydrogen, achieving a steel production rate of 5 million t/y by 2030 and onward, and to reduce of over 14.3 million tonnes of CO_2 over the first 10 years of operation [33,34].

Initially, the total cost was estimated at around €2.5 billion, but this cost has more than doubled due to increased costs that have emerged from new economic projections and higher funding needs for technologies and infrastructures [28]. This substantial increase reflects both the project expanded scope and the rising costs associated with developing such a pioneering facility.

Figure 10. The H_2 Green Steel plant in Boden, Sweden [32].

3.3.3 Comparative analysis: retrofit vs. new construction

According to the European Steel Association (EUROFER), the construction of new hydrogen-based steel plants in Europe could require high initial investments, at a regional scale in the major steel-producing regions, while the exact cost of constructing a single hydrogen-based steel plant remains unclear, as it depends on various factors as plant size, energy supply, location and subsidies [36].

In comparison, retrofitting existing plants appears more feasible, at least in the short term. Partial retrofits that blend hydrogen with traditional fuels, such as natural gas, can help reduce emissions without requiring a full-scale renovation. On the other hand, the operational costs for retrofitted plants may escalate over time, due to periodic maintenance and required further upgrades [27].

Moreover, retrofitting existing steel mills may result in lower emission reductions compared to newly built hydrogen-based plants, which are designed specifically for green hydrogen integration with optimized plant layouts, reducing long-term operating costs, improving production efficiency and achieving greater reductions in carbon emissions by eliminating the dependency on carbon-based fuels entirely [37].

Another issue is the excess production capacity, particularly in western countries: retrofitting existing steel plants avoids adding new production capacity, which could potentially damage the already oversupplied steel market. By focusing on retrofits rather than new construction, the industry can transition to greener technologies without facing the problem of overcapacity.

3.4 Impact of Electricity Costs for Producing (Green) Hydrogen

Hydrogen can be produced through various methods; however, most of these processes release harmful emissions into the atmosphere to some degree, which poses environmental risks. Green hydrogen, produced using renewable energy sources (RES), stands out as the most environmentally friendly option due to its clean production process.

Figure 11 illustrates the schematic of green hydrogen production using an electrolyser. Water is first processed at a treatment station, where it undergoes purification before being directed to the electrolyser. Powered by renewable energy sources like wind or solar, the electrolyser then splits the purified water into hydrogen and oxygen.

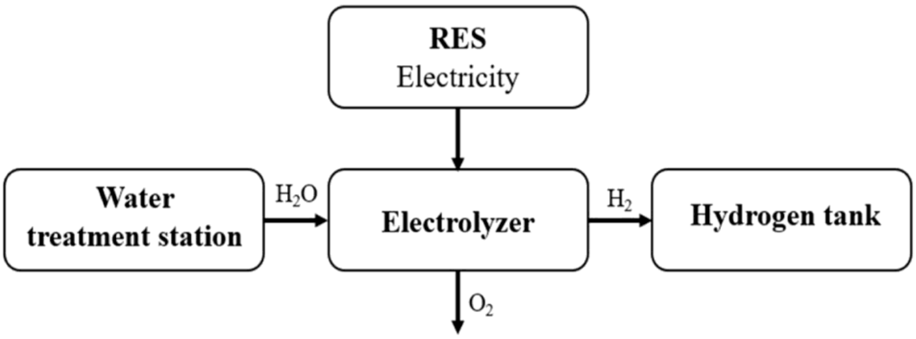

Figure 11. Diagram of green hydrogen production using an electrolyser [38].

The economic feasibility of green hydrogen production is heavily affected by the cost of electricity from RES. Electricity accounts for most of the production cost in this process. For green hydrogen to be competitive with fossil fuel-based alternatives such as grey or blue hydrogen, renewable electricity must be both abundant and inexpensive.

The calculations, based on key assumptions and formulas [38], yielded an average Levelized Cost of Hydrogen of 5.321 €/kg_{H2}, which takes into account all the costs of hydrogen production, including capital investments, operational costs, water and energy required and a cost of electricity from PV equal to 0.053 €/kWh).

A notable result is the sensitivity of the LCOH to changes in the cost of electricity from renewable sources, that shows how the LCOH is highly influenced by fluctuations in electricity prices (which is consider to range 0.035 €/kWh to 0.24 €/kWh, reflecting pre-crisis and post-crisis conditions), with the cost increasing or decreasing by 0.059 €/kgH_2 for every 0.001 €/kWh change in electricity costs.

In Figure 12, the linear relationship between electricity costs and LCOH is visually represented, showing a clear upward slope as electricity costs rise. The red line in the graph marks the boundary between pre- and post-crisis energy prices, showing how the energy crisis has shifted the cost dynamics for green hydrogen production and the critical role that energy prices play in determining the economic viability of hydrogen production projects. In fact, the results highlight the potential for hydrogen production costs to be significantly reduced with a decrease in electricity prices. Overall, the results indicate that while green hydrogen production can be economically important, its competitiveness is closely tied to the cost of renewable electricity.

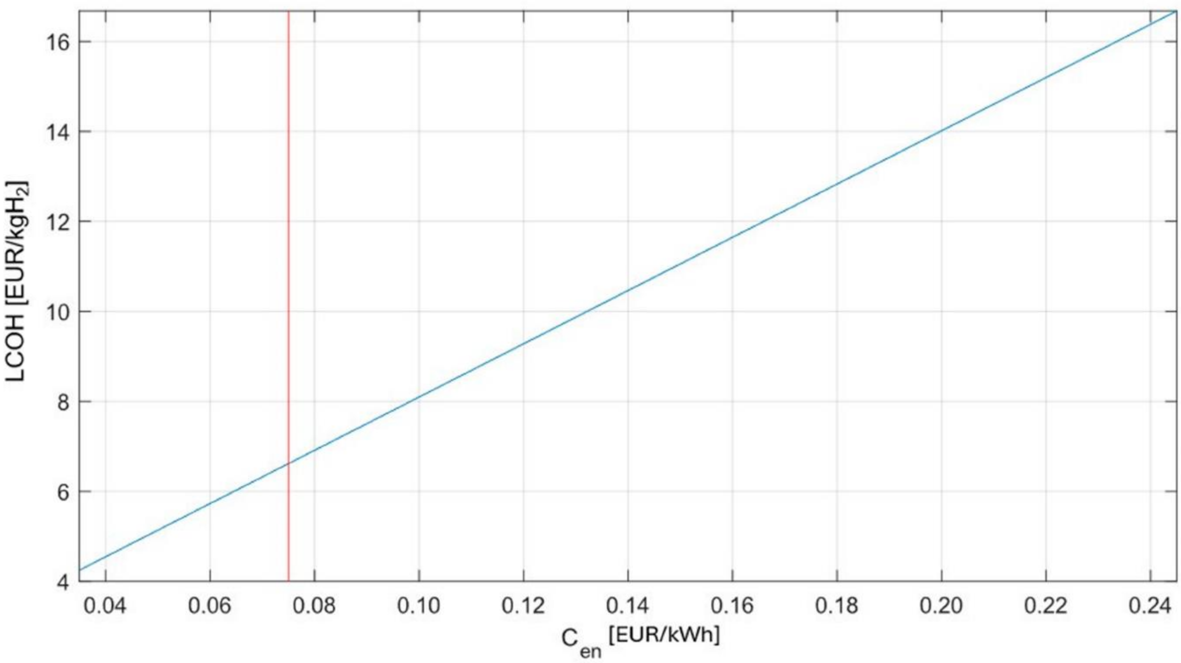

Figure 12. The impact of changing the cost of electricity from a RES on the average cost of green hydrogen production [38].

3.4.1 Renewable Energy Cost Range

Over the past decade, renewable energy has seen rapid deployment growth and cost reduction, and, if this trend continues, it could substantially lower green hydrogen production costs in the coming years [38]. As shown in Figure 13, the solar photovoltaic cost decreased significantly between 2010 and 2018 from 0.371 $/kWh to 0.08 $/kWh, also the onshore wind cost decreased from 0.085 $/kWh to 0.05 $/kWh (32). These numbers shows that the cost of renewable power generation has fallen dramatically in recent years.

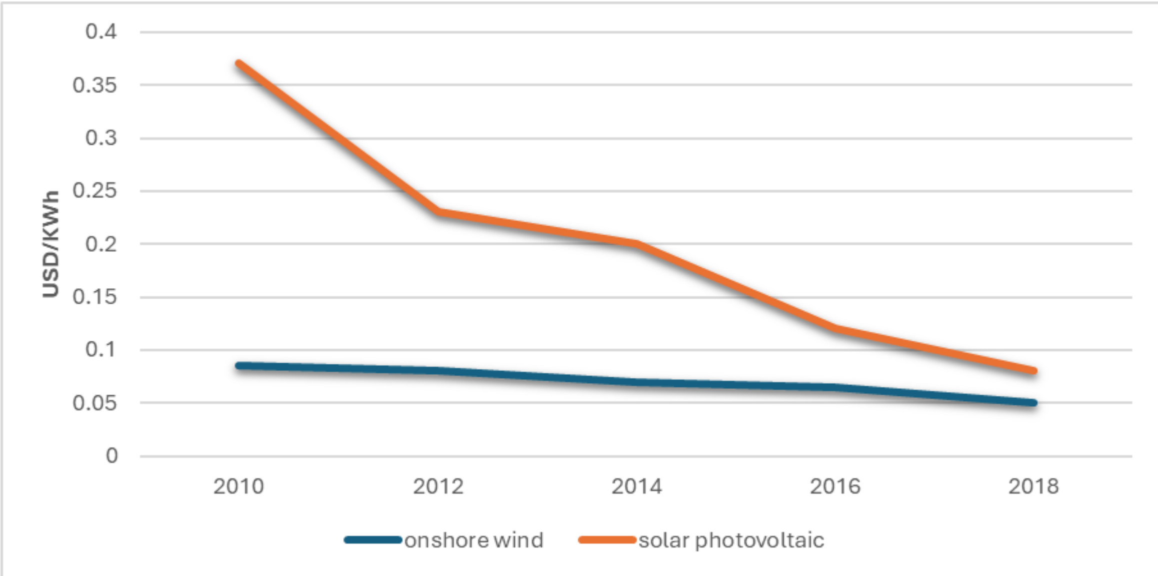

Figure 13. Global cost trends for onshore wind and solar PV [39].

However, these values are not the same across the globe. So nowadays, regions as the Middle East and Latin America have lower Levelized Cost of Energy (0,02-0,03 $/kWh) than Europe (0,04-0,05$/kWh) [19]. This is mainly caused by the elevated grid electricity prices and also the limited access to low-cost renewable energy in Europe.

3.4.2 Production Cost of Green Hydrogen

Beyond the need for hydrogen with a low carbon footprint, the high cost of green hydrogen remains a significant challenge. Currently in Europe green hydrogen is priced at around 5 €/kg is still twice as expensive as blue hydrogen and three times the cost of grey hydrogen [40].

As the green hydrogen production depends on the electricity prices, the cost of green hydrogen will show a decrease with respect to the decrease of the renewable energy costs. So, as it is reported in Figure 14, in 2020 the cost of H_2 produced from solar farms was 6.5 €/kg, while the cost of H_2 produced from wind farms was 4.15 €/kg. Projections shows that it will decrease gradually, reaching 1.92 and 1.5 €/kg respectively as approaching 2050 [38].

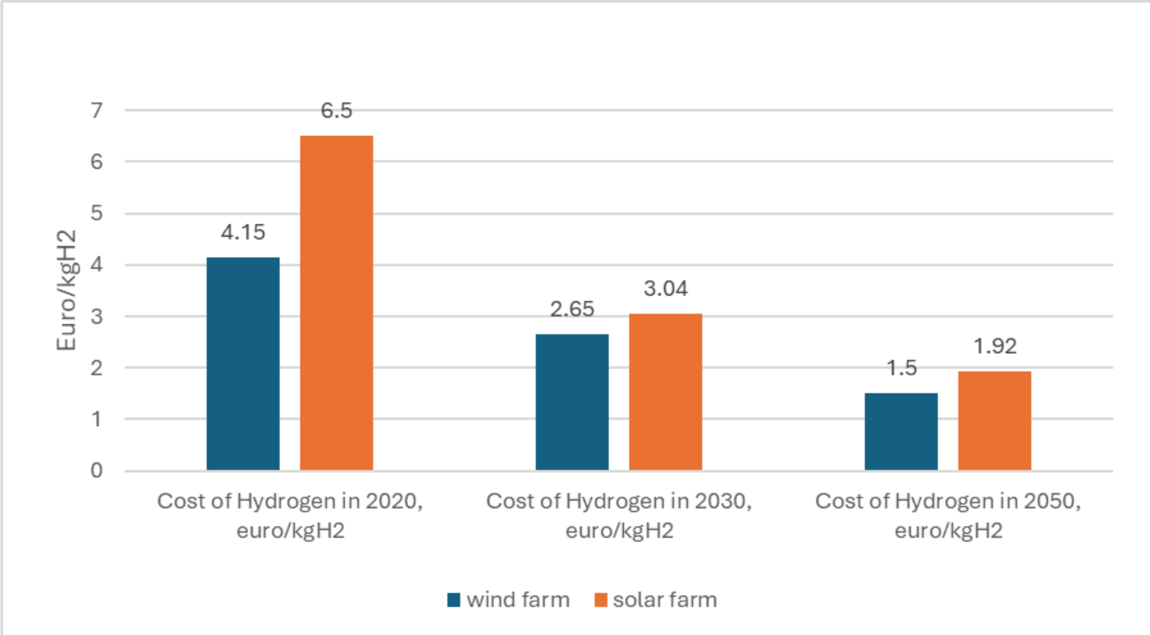

Figure 14. Average production cost of green hydrogen for 2020,2030 and 2050 [38].

The possibility to scale up green hydrogen production depends on having access to low-cost electricity from renewable energy sources, like wind and solar, coupled with a storage system, possibly a hydrogen storage technology, to ensure electrolysis continuity.

Moreover, CAPEX for electrolysers remain a major cost contributor to the LCOH of green hydrogen, as it can be around 1-2 $/kg of the green hydrogen cost [19]. So rapid innovation and manufacturing scale-up is needed in the electrolysers production. By 2040, the electrolysers costs are seen to be halved with respect to the current prices, which will cause a big reduction in the LCOH [19].

Green hydrogen is mentioned to play a significant role in the future, with its adoption becoming more feasible and economically attractive as renewable energy technologies advance and the cost of hydrogen produced from PV and wind power is expected to decrease reaching costs lower than the cost of hydrogen produced from fossil fuels with CCS in 2050 [39].

3.4.3 Economies of scale effects

As the green hydrogen industry grows, the cost of production is expected to decrease significantly due to economies of scale. Right now, producing green hydrogen through electrolysis can be quite costly because of the expensive equipment, like electrolysers, and the infrastructure needed for renewable energy sources. However, as production increases and more hydrogen plants are built, the cost per unit of hydrogen will naturally go down. This is due to the possibility for companies to buy materials and equipment in larger quantities and, at the same time, improve their technology and processes, making them more efficient and lowering overall operational expenses. Alkaline electrolysers (AEL), which are the most widely used worldwide due to their efficiency and lower initial costs, are a prime example. Their cost is expected to drop significantly, from €242–388 per kW in 2020 to as low as €52–79 per kW in the coming years reaching 2030 [41]. This reduction will further enhance the economic feasibility of green hydrogen production, driving its adoption across industries.

3.5 Composition of the Total Cost for Levelized Cost of Green Hydrogen Production

The levelized cost of hydrogen (LCOH) is an important tool for understanding the feasibility of an investment, as it is the total cost of producing hydrogen over the lifetime of a facility, divided by the total hydrogen output [42]. To study the cost of green hydrogen production, it is essential to break down the total cost into three main categories: Capital Costs (CAPEX), Operation and Maintenance Costs (OPEX), and Other Costs.

The CAPEX is the initial expenditure needed to build the green hydrogen production facility. As shown in Figure 15, these costs are split into depreciable costs and undepreciable costs. Depreciable costs are spread over the facility lifetime and include the cost of electrolysers, the core equipment used to produce hydrogen from water through electrolysis. Other depreciable costs include mechanical and electrical systems, installation costs, the cost of replacing equipment during the facility operation and the hydrogen storage systems and batteries. Undepreciable costs, such as the cost of purchasing or leasing land, are fixed and not spread across the facility lifetime. Moreover, Figure 15 shows the annual OPEX, divided into fixed and variable costs. Fixed costs include labour and administrative expenses, property taxes, and the cost of materials for regular maintenance. Variable costs depend on the level of hydrogen production and include water and electricity costs, that can be particularly significant for green hydrogen production as electrolysis relies heavily on renewable electricity.

As well as the other costs that include expenses that are not part of CAPEX or OPEX but still affect the total cost of production like decommissioning cost, which cover the safe shutdown and dismantling of the facility at the end of life, depreciation costs and salvage value.

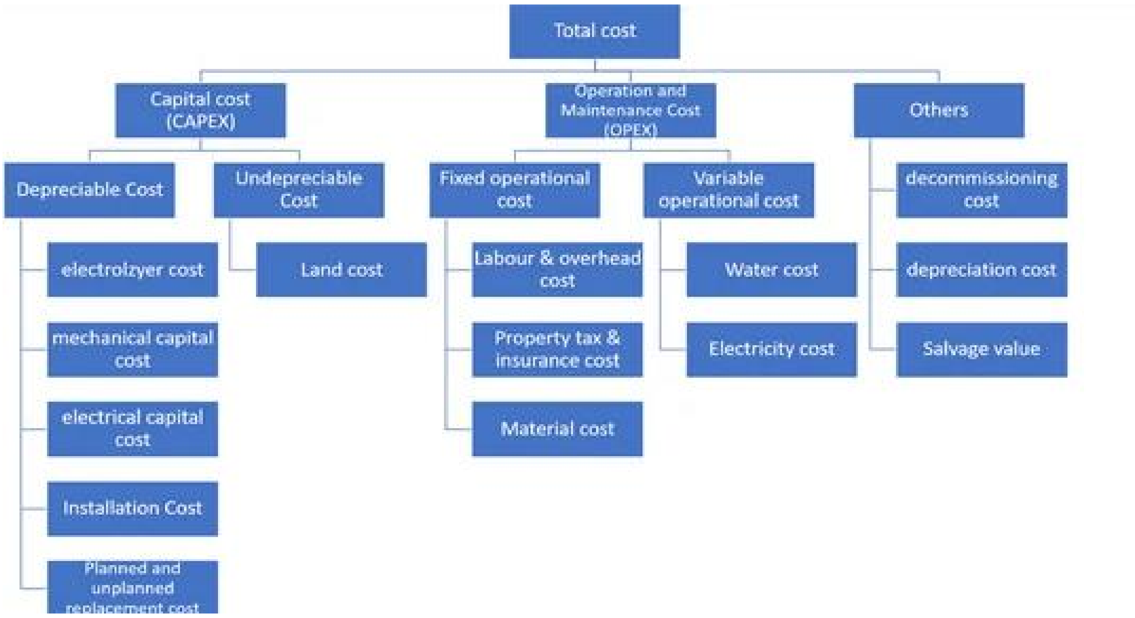

Figure 15. Composition of the total cost for levelized cost of hydrogen (LCOH) calculation [42].

4 Assessment of Carbon Footprint and Energy

Understanding the environmental impact of traditional processes, such as the blast furnace (BF) route, and comparing it with newer technologies like the Electric Arc Furnace (EAF) and hydrogen-based steelmaking (H-DR), is crucial for identifying pathways to decarbonize the sector.

4.1 Emissions Scopes

The "Greenhouse Gas Protocol, a Corporate Accounting and Reporting Standard" categorizes the emissions into three main scopes, also by the United States Environmental Protection Agency [43], that are outlined in the following paragraphs.

4.1.1 Scope 1: Direct Greenhouse Gas (GHG) emissions

Direct greenhouse gas emissions are generated from sources that are either owned or directly controlled by the company. The pie chart in Figure 16 illustrates the distribution of emissions across different stages of BF-BOF steel production. The traditional Blast Furnace process is the largest contributor, accounting for 69% of total emissions, since the combustion of coke and coal results in a significant release of CO_2.

The sintering process follows, contributing to 13% of emissions. During sintering, iron ore fines are heated to create the sinter, that is then used in the blast furnace, and CO_2 emissions due to the combustion of fuels and the chemical reactions involved in creating the sinter.

Steelmaking itself, which includes methods like the Basic Oxygen Furnace (BOF) used to convert molten iron into steel, accounts for 11% of emissions. While this stage is less carbon-intensive than the blast furnace, it still generates significant emissions due to the high energy consumption and CO_2 released from the oxidation of carbon in the molten iron.

The coke ovens contribute to 5% of the emissions. In this stage, coal is carbonized to produce coke, which is essential for the blast furnace, but the carbonization generates CO_2 as a byproduct.

Lastly, pelletization represents the smallest source of emissions, accounting only for a 2%, as converting iron ore fines into pellets for use in the blast furnace still requires and results in some CO_2 emissions. Pelletization offers a more uniform product, while sintering is better for processing various ore types.

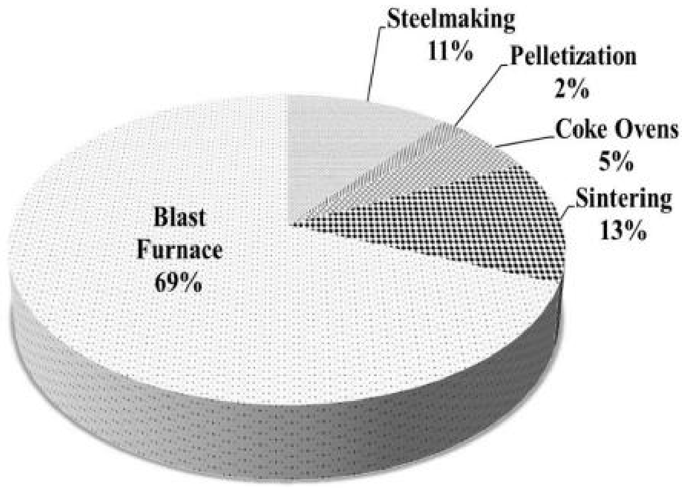

Figure 16. The CO_2 emissions in primary steelmaking (BF-BOF) [44]

In conclusion, in the traditional blast furnace process, which includes iron making by blast furnace, BOF steel making, casting and hot and cold rolling, direct emissions are primarily the result of the combustion of coke.

4.1.2 Scope 2 and Scope 3: Indirect Greenhouse Gas (GHG) Emissions

Scope 2 refers to indirect GHG emissions that occur as a result of the generation of purchased electricity consumed by a company. These emissions are not directly produced by the company operations but arise from the electricity that is bought and used within the company operations. Importantly, Scope 2 emissions physically occur at the facility where the electricity is generated, so the company itself is not responsible for the emissions but its operation is more or less sustainable according to the share of renewable and non-renewable electricity.

Scope 3, on the other hand, refers to other indirect emissions that are a consequence of a company activities but originate from sources that the company does not own or control, therefore occurring outside of the organization boundaries. As shown in Figure 17, Scope 3 emissions include the extraction and production of materials and equipment, the transportation of fuels and the use of products and services. These emissions are often more difficult to track and manage, as they occur across the entire supply chain [43].

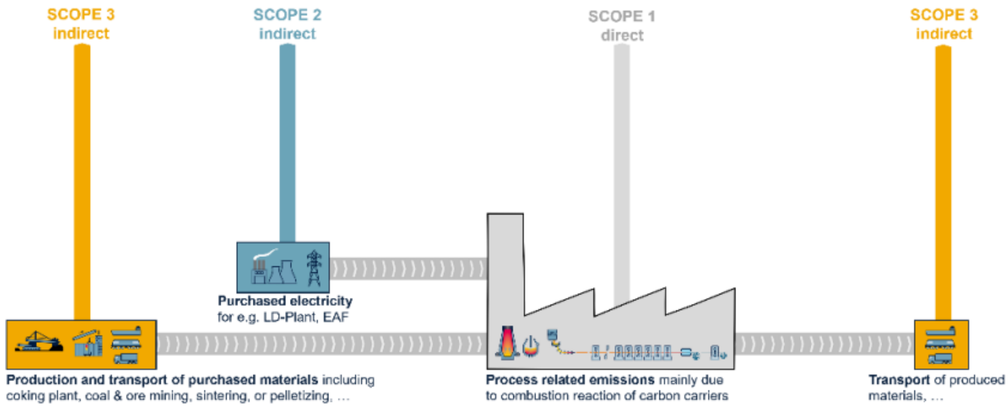

Figure 17. Scope division of production emissions of a steel-making plant [43]

4.2 CO_2 value comparison in steel production processes

Figure 18 highlights the impact of various steel production methods on specific CO_2 emissions, comparing the traditional integrated process with the optimized scrap-based Electric Arc Furnace (EAF) – Electric Steelmaking Process (ESP) process. The transition from traditional integrated steel production to the EAF-ESP process results in a reduction of CO_2 emissions by 95%, from 2555 kg_{CO2}/t of steel to just 123 kg_{CO2}/t [43]. When producing liquid steel with the scrap-based EAF process, emissions decrease from 1960 kg_{CO2}/t to 117 kg_{CO2}/t.

The ESP process brings even greater environmental benefits, reducing CO_2 emissions from 312 kg_{CO2}/t to just 2 kg_{CO2}/t, nearly achieving zero-carbon steel production. This method also facilitates direct application of cold band substitutes, further reducing CO_2 emissions from 283 kg_{CO2}/t to just 4 kg_{CO2}/t. Additionally, the continuous, ultra-thin material eliminates the need for cold rolling and annealing processes, further reducing the carbon footprint.

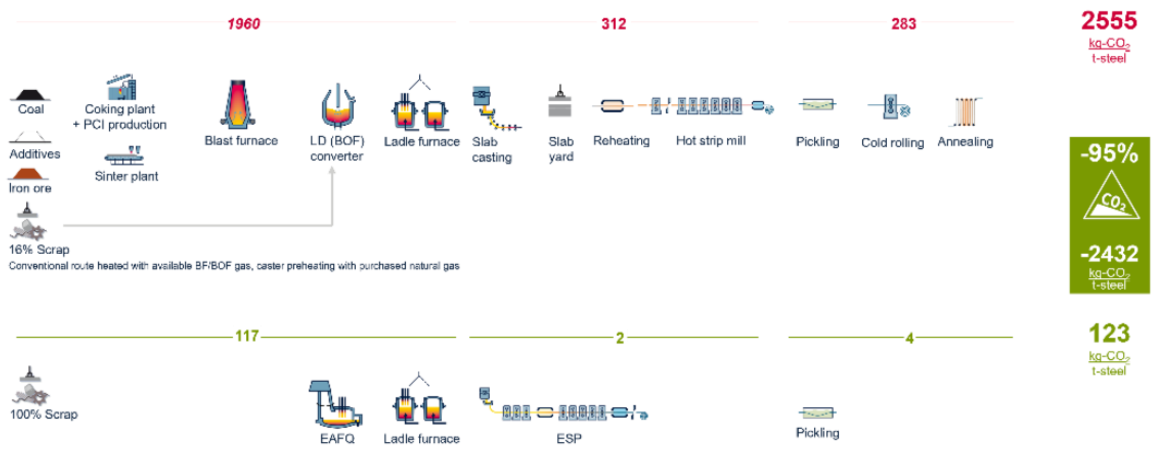

Figure 18. Comparison of Scope 1 CO_2 Emissions: Integrated vs. EAF-ESP Steel Production [43]

The Hydrogen-based Direct Reduction (HDR) EAF process, which employs hydrogen as a reducing agent instead of carbon and replaces percentage of the scrap used in EAF, is developing as a cleaner alternative to traditional methods. The HDR-EAF process depends largely on the power grid emission intensity (GEI). A cleaner power grid with a higher share of renewables significantly increases the emissions reduction potential when replacing the traditional (BF/BOF) route. However, hydrogen production, if not fully green, can still contribute to Scope 1 emissions depending on the energy mix used for its production. In scenarios where green hydrogen is used, the HDR-EAF process can approach near-zero emissions [12]. Apart from reducing the carbon emissions, the HDR-EAF also shows energy consumption levels comparable to traditional BF methods, with the specifics of this energy usage detailed in section 4.3.

4.3 Energy Consumption in Steel Production Processes

The specific energy consumption (SEC) for producing liquid steel through the HDR-EAF is 3.48 MWh/t, approximately similar to the BF process, which consumes 3.68 MWh/t, primarily from coal and coke. In the HDR-EAF, two-thirds of the energy is used by the electrolyser to produce hydrogen, although the EAF and ore heating processes consume significant amounts of energy [12]. However, the energy consumption of the reduction shaft remains minimal thanks to the heat recovery from the condenser.

Pushing HDR-EAF to replace the current BF/BOF production would lead to a significant rise in electricity demand from renewable sources. For example, replacing Germany's 29.5 Mt/year primary steel production with the HDR process would require approximately 103 TWh of electricity, while Sweden's 3.1 Mt/year output would need 10.8 TWh. At the same time, fossil fuel usage would see dramatic reductions of 108.8 TWh in Germany and 11,4 TWh in Sweden [12]. These figures account for iron and steelmaking alone and exclude additional energy demands for pelletizing, secondary metallurgy, casting, and rolling. The pelletizing and rolling steps would require an extra 2.2 GJ of fuel per ton and 140 kWh of electricity per ton, regardless of the production method.

Moreover, as shown in Figure 19, the SEC of HDR-EAF is highly sensitive to the proportion of scrap steel added to the EAF. Increased scrap usage significantly reduces energy consumption because less iron ore is needed, which lowers the energy demands in all preceding process steps. For instance, an EAF charge containing 50% scrap halves the electrolyser's energy consumption. Producing steel purely from scrap is also more efficient, consuming 0.667 MWh per ton compared to 0.753 MWh per ton for direct reduced iron (DRI).

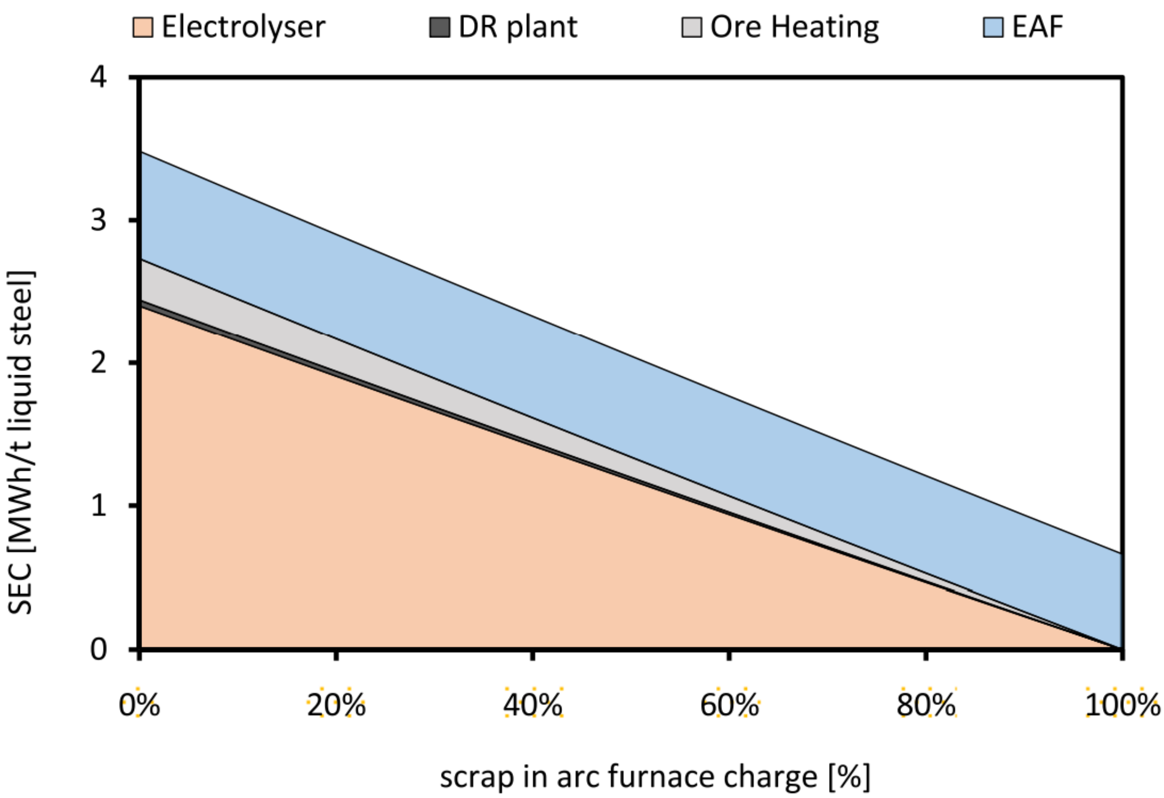

Figure 19. Impact of scrap charge on H-DR process energy consumption [12]

4.4 CO_2 Price Development

The development of CO_2 prices in the EU Emissions Trading System (EU ETS) has been widely analysed and it is mainly influenced by political frameworks and market dynamics. Although the interaction between fossil energy prices and CO_2 prices can be described by correlations based on historical data, this relationship is not universally consistent, as it heavily depends on the investigated period. Additionally, methodologies such as regression analysis, uncertainty modelling and artificial neural networks have been applied to predict CO_2 price paths, yet significant variations remain due to uncertainty and changing market dynamics [45].

4.4.1 Impact of CO_2 Prices on the Economic Feasibility of Hydrogen-Based Steel

Current steel production, especially in blast furnaces that use coal and coke, generates high CO_2 emission and faces rising costs under systems like the EU Emissions Trading System (EU ETS). When CO_2 prices increase, low-emission processes become economically more appealing than traditional methods, which are more carbon-intensive. To make hydrogen-based steel production competitive with conventional methods, carbon allowances need to reach at least 62 €/t_{CO2}, while electricity prices should remain below 40 €/MWh [46]. While the higher carbon taxes can encourage companies to invest in greener infrastructures, such as hydrogen production facilities, these thresholds demonstrate the critical role of policy incentives and governmental subsidies in supporting the transition to low-carbon steel production. The cost of green hydrogen, currently high due to expensive electrolysis and renewable energy infrastructure, is also an important factor. If CO_2 prices keep increasing and green hydrogen becomes cheaper, hydrogen-based steel is set to become a more promising technology. Rising CO_2 costs may also change how businesses and consumers view steel, as industries might prefer low-carbon steel to meet sustainability goals, even if it costs more, giving hydrogen-based steelmakers an edge in the market.

In the long run, high CO_2 prices combined with cheaper green hydrogen could reshape the steel industry. Hydrogen-based steelmaking would not just be better for the environment—it could also become the more cost-effective choice, helping the industry cut emissions while staying competitive globally.

4.4.2 Phases of the EU ETS and Price Fluctuations

The EU ETS has undergone four phases, as shown in Figure 20, reflecting the evolving regulatory frameworks, market mechanisms, and external economic factors that have influenced the CO_2 price dynamics over time:

- Phase I (2005–2007): trial phase where the EU ETS was established to cover CO_2 emissions from power plants and certain industries, most allowances were given for free and companies couldn't bank them for future use. Prices began at €10/t_{CO2} but spiked to €30/t_{CO2} before dropping to near zero by the end of the phase. This drop happened because too many allowances were issued, leading to oversupply and no incentive to reduce emissions further.
- Phase II (2008–2012): stricter rules were applied, including a lower cap on emissions and new countries joining the system (Iceland, Liechtenstein and Norway). Companies could bank allowances for use in future phases to prevent another price collapse, but prices fluctuated again due to the global financial crisis, the reduced industrial activities and a surplus of allowances, with prices falling from €30/ t_{CO2} to around €10/t_{CO2}.
- Phase III (2013–2020): significant changes were introduced, including a single EU-wide cap and a shift to auctioning allowances instead of giving them away for free. Due to a surplus of allowances from Phase II, prices remained low until they began to rise reaching €30/t of CO_2 by 2020, after the EU announced more ambitious climate goals and introduced the Market Stability Reserve (MSR) to manage excess allowances.
- Phase IV (2021 onward): this phase focuses on achieving the EU's long-term climate targets of net-zero emissions by 2050. The emissions cap continues to tighten, and the MSR is adjusted to remove surplus allowances from the market more effectively. Although this phase aims to keep prices rising steadily, creating stronger incentives for low-carbon investments, price fluctuations still occur due to factors like energy demand and political decisions.

Looking ahead, the EU ETS is expected to continue evolving as part of the EU's broader climate goals. With the increasing tightening of emission caps and the strengthening of mechanisms like the Market Stability Reserve, CO_2 prices are likely to rise, showing more investments in clean technologies. Building on the historical analysis of CO_2 price fluctuations, the next section will delve into future CO_2 price scenarios.

Figure 20. CO_2 price development for Phase I to IV [45]

4.4.3 Future Scenarios of CO_2 Prices

For predicting future CO_2 price paths, several scenarios are analysed. The reference scenario assumes a steadily increasing CO_2 price from 87 €/t of CO_2 in 2023 to 200 €/t by 2030 to meet the EU's climate goals, as shown in Figure 21, [45]. Other scenarios include:

- Scenario DISC (Discounted Scenario): this scenario assumes that market participants anticipate a significant rise in CO_2 prices in the future. As a result, companies and investors begin to adjust their behaviour early, leading to an initial surge in the supply of allowances. The CO_2 price increases steeply, reaching the target price of 200 €/t_{CO_2} for 2030 ahead of schedule, but with a discounted progression due to inflation and interest rates (the European Central Bank refinancing rate is assumed to be 3.5%). After this rapid initial increase, the price stabilizes and rises more slowly.
- Scenario LOWEST'25 (Lowest Price in 2025): In this scenario, the CO_2 price is projected to drop in 2025, followed by a gradual recovery to the reference price path. The decline in 2025 could be due to a variety of factors, such as an economic slowdown, changes in policies, or market oversupply, which lead to reduced demand for allowances during that year. After this dip, the price is expected to rise slowly, eventually aligning with the expected price trend. This scenario reflects the possibility of a temporary setback in CO_2 pricing before the market stabilizes.

- Scenario PEAK'25 (Price Peak in 2025): Scenario PEAK'25 envisions a sharp, short-term price spike in 2025, where the CO_2 price increases by 110% over the reference price. This sharp peak could result from market imbalances, speculative trading, or unexpected economic events causing a temporary surge in prices. After reaching this peak, the price would normalize, returning to the reference trajectory. This scenario is inspired by historical price behaviour observed during Phase III of the EU ETS,
- Scenario FLUCT (Fluctuating Scenario): CO_2 prices are expected to slightly fluctuate around the reference price, with variations of ±20%. This suggests a relatively stable market where prices experience minor ups and downs, possibly due to non-fundamental factors such as market speculation, uncertainty in policy implementation, or external economic shocks. The fluctuations are based on historical market behaviour, where prices moved within a certain range due to these unpredictable elements but remained largely stable over time.

Each of these scenarios represents a different outlook on how the CO_2 market might behave in the future, based on assumptions about market participants reactions, economic conditions, and policy changes.

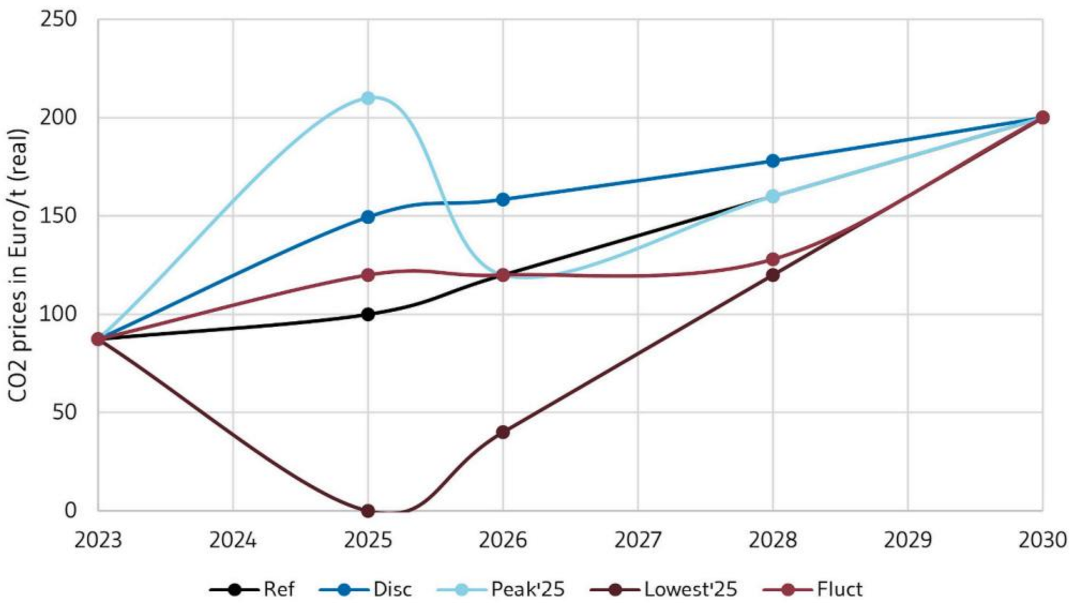

Figure 21. Proposed and analysed CO_2 price developments based on assumptions from historical studies [45]

4.4.4 Impact of CO_2 Price Scenarios on the Economics of H_2

Future CO_2 price scenarios have a direct impact on the cost comparison between hydrogen-based and conventional coke-based steel production.

- Reference Scenario: With a steadily increasing CO_2 price from 87 €/t in 2023 to 200 €/t by 2030, hydrogen-based steel production becomes more attractive, as the cost of carbon allowances for coke-based production rises sharply and continuously. This could encourage a faster change to hydrogen-based methods, reducing long-term production costs for H_2-based steel.
- Scenario DISC: The quick rise in CO_2 prices, reaching 200 €/t earlier than expected, increases the cost of traditional coke-based steel production. This early jump would push the steel industry to adopt hydrogen-based production to avoid higher carbon costs. However, once the price return stable it would allow hydrogen steel to remain competitive in the long term.
- Scenario LOWEST'25: The temporary drop in CO_2 prices in 2025 could make coke-based steel cheaper for a while. However, as prices rise again, the cost of conventional production will increase, making hydrogen-based steel production a better long-term option.
- Scenario PEAK'25: The sharp price increase in 2025 would result in a cost problem for coke-based steel production, making hydrogen-based production much more attractive. After the peak, as CO_2 prices return to the trajectory, the cost difference between H_2 and coke-based steel production would remain significant, reinforcing the economic case for investing in hydrogen technologies.
- Scenario FLUCT: CO_2 prices fluctuating within a ±20% range suggest a stable but uncertain market. While production costs for steel may vary, hydrogen-based steel production would likely stay cost-competitive as long as CO_2 prices trend upwards, encouraging a shift to greener technologies.

We conclude that rising CO_2 prices, whether steadily or through sudden movements, generally create a good environment for hydrogen-based steel production, as the increasing cost of carbon allowances for steelmaking becomes a stronger financial problem.

5 Conclusions

The steel industry is a key part of modern life, but it also produces a significant amount of carbon emissions. The aim of this study is therefore to highlight the urgent need to adopt greener production methods, gradually abandoning highly polluting traditional processes like BF/BOF that release nearly 1.85 t_{CO2} for every ton of steel. An alternative is represented by hydrogen-based methods, such as H-DR, that have the potential to cut emissions by up to 95% when combined with renewable energy. Upgrading old steel plants to use hydrogen is possible but comes with big challenges, such as high costs and the need for new equipment. Building new plants specifically designed for hydrogen use is a better long-term solution, as new plants can take full advantage of hydrogen and renewable energy, making them more efficient and sustainable. Some hydrogen-based steel production plants can be found around the world: for example, the HYBRIT plant is a demonstrative project in Sweden aiming at showing how green hydrogen can make steel production cleaner. Renewable energy is a critical factor in this transition, as the cost of green hydrogen depends on affordable and reliable renewable electricity. Although solar and wind power are continuing to grow, challenges like storing hydrogen and balancing energy supply remain. However, continued investment in renewable energy and improved technology will help overcome these issues. This study also highlights the importance of policies and financial support. Carbon taxes, government funding, and partnerships between industries and governments can lower the financial risks of adopting hydrogen-based technologies, encouraging investments in innovation and speeding up the transition to greener steel production.

In conclusion, the path towards the decarbonization of the steel sector has many challenges, first of all the high costs, but it also offers opportunities to modernize and lead in sustainability. By investing in hydrogen-based methods and renewable energy, and with strong global cooperation, the steel industry can significantly reduce its emissions, achieve climate goals, and ensure long-term sustainability. This transition not only offers a cleaner future but also opens up new opportunities for innovation, job creation, and leadership in global sustainability efforts.

References

1. Hasanbeigi, A.; Arens, M.; Price, L. Alternative Emerging Ironmaking Technologies for Energy-Efficiency and Carbon Dioxide Emissions Reduction: A Technical Review. *Renewable and Sustainable Energy Reviews* **2014**, *33*, 645–658, doi:10.1016/j.rser.2014.02.031.
2. Kushnir, D.; Hansen, T.; Vogl, V.; Åhman, M. Adopting Hydrogen Direct Reduction for the Swedish Steel Industry: A Technological Innovation System (TIS) Study. *Journal of Cleaner Production* **2020**, *242*, 118185, doi:10.1016/j.jclepro.2019.118185.
3. European-Steel-in-Figures-2021.
4. BELLONA Hydrogen in Steel Production: What Is Happening in Europe – Part 1 Available online: http://tiny.cc/bellona1 (accessed on 21 September 2024).
5. Kurrer, C. The Potential of Hydrogen for Decarbonising Steel Production Available online: https://bit.ly/3zpASgY (accessed on 21 September 2024).
6. Kirschen, M.; Badr, K.; Pfeifer, H. Influence of Direct Reduced Iron on the Energy Balance of the Electric Arc Furnace in Steel Industry. *Energy* **2011**, *36*, 6146–6155, doi:10.1016/j.energy.2011.07.050.
7. Lee, B.; Sohn, I. Review of Innovative Energy Savings Technology for the Electric Arc Furnace. *JOM* **2014**, *66*, 1581–1594, doi:10.1007/s11837-014-1092-y.
8. Kerimov, R.I.; Shakhov, S.I. Use of Metallized Raw Materials in Electric Furnace Steelmaking. *Metallurgist* **2020**, *64*, 128–135, doi:10.1007/s11015-020-00974-1.
9. Yildirim, I.Z.; Prezzi, M. Chemical, Mineralogical, and Morphological Properties of Steel Slag. *Advances in Civil Engineering* **2011**, *2011*, 1–13, doi:10.1155/2011/463638.
10. Andersson, J. Application of Liquid Hydrogen Carriers in Hydrogen Steelmaking. *Energies* **2021**, *14*, 1392, doi:10.3390/en14051392.
11. Åhman, M.; Olsson, O.; Vogl, V.; Nyqvist, B.; Maltais, A.; Nilsson, L.J.; Hallding, K.; Skåneberg, K.; Nilsson, M. Hydrogen Steelmaking for a Low-Carbon Economy. A Joint LU-SEI Working Paper for the HYBRIT Project Available online: https://bit.ly/47BxMTJ (accessed on 21 September 2024).
12. Vogl, V.; Åhman, M.; Nilsson, L.J. Assessment of Hydrogen Direct Reduction for Fossil-Free Steelmaking. *Journal of Cleaner Production* **2018**, *203*, 736–745, doi:10.1016/j.jclepro.2018.08.279.
13. Battle, T.; Srivastava, U.; Kopfle, J.; Hunter, R.; McClelland, J. The Direct Reduction of Iron. In *Treatise on Process Metallurgy*; Elsevier, 2024; pp. 89–149 ISBN 978-0-323-85373-6.
14. Liu, B.N.; Li, Q.; Zou, Z.S.; Yu, A.B. Discussion on Chemical Energy Utilisation of Reducing Gas in Reduction Shaft Furnace. *Ironmaking & Steelmaking* **2014**, *41*, 568–574, doi:10.1179/1743281213Y.0000000168.
15. Arcos, J.M.M.; Santos, D.M.F. The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production. *Gases* **2023**, *3*, 25–46, doi:10.3390/gases3010002.
16. Souvik Sen; Mani Bansal; Syed Razavi; Abdul Saboor Khan The Color Palette of the Colorless Hydrogen. *The Way Ahead* **2022**.
17. Francesca Gabriel Understanding Hydrogen: How Is It Made, How Is It Scaled, and What Challenges Does It Bring? *Capgemini* **2024**, 7.
18. ADAM CHRISTENSEN Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe. *International Council on Clean Transportation* **2020**, 73.
19. Eliseo Curcio Hydrogen Production Costs: Analyzing LCOH, LCOE, and Market Implications. *Eliseo Curcio* 12.
20. Hydrogen as Energy Storage 2013.
21. California ISO What the Duck Curve Tells Us about Managing a Green Grid 2016.

22. Mahmoud Morsi Ali, D. Hydrogen Energy Storage. In *Energy Storage Devices*; Taha Demirkan, M., Attia, A., Eds.; IntechOpen, 2019 ISBN 978-1-78985-693-4.
23. IEA for the G20, Japan *The Future of Hydrogen*; Japan, 2019; p. 203;.
24. Bloomberg New Energy Finance (BNEF) *Hydrogen in Steelmaking: Opportunities and Challenges*; 2020;
25. ArcelorMittal *Hydrogen-Based Steelmaking to Begin in Hamburg*; 2019;
26. Fossil-Free Steel Production Ready for Industrialisation 2024.
27. Guevara Opinska, L.; Mahmoud, M.; Bene, C.; Rademaekers, K. Moving towards Zero-Emission Steel. Technologies Available, Prospects, Timeline and Costs Available online: https://bit.ly/3TDR8lr (accessed on 21 September 2024).
28. *Economic Assessment of Hydrogen-Based Steel Production.*; 2022;
29. Green Steel for Europe Technology Assessment and Road Mapping 2021.
30. Green Steel for Europe Investment Needs 2021.
31. Dr Edwin Basson *2024 World Steel in Figures*; 2024; pp. 1–30;.
32. Stegra *H2 Green Steel Raises More than €4 Billion in Debt Financing for the World's First Large-Scale Green Steel Plant*; 2024;
33. Michael Kavanagh Steelmakers Look to Hydrogen to Green Heavily Polluting Sector. *FINANCIAL TIMES* 2024.
34. Grzegorz Pawelec; Joana Fonseca *STEEL FROM SOLAR ENERGY*; 2022; p. 90;.
35. Mitchell Killer US Firm Selected for Work at 'World's First' Renewable Hydrogen-Based Steel Mill. **2024**, 4.
36. EUROFER *European Steels In Figures 2021*; 2021; p. 72;.
37. Sun, M.; Pang, K.; Barati, M.; Meng, X. Hydrogen-Based Reduction Technologies in Low-Carbon Sustainable Ironmaking and Steelmaking: A Review. *J. Sustain. Metall.* **2024**, *10*, 10–25, doi:10.1007/s40831-023-00772-4.
38. Kotowicz, J.; Baszczeńska, O.; Niesporek, K. Cost of Green Hydrogen. *Energies* **2024**, *17*, 4651, doi:10.3390/en17184651.
39. *Hydrogen: A Renewable Energy Perspective*; International Renewable Energy Agency: Abu Dhabi, 2019; ISBN 978-1-5231-5202-5.
40. Majewski, P.; Salehi, F.; Xing, K. Green Hydrogen. *AIMSE* **2023**, *11*, 878–895, doi:10.3934/energy.2023042.
41. Krishnan, S.; Koning, V.; Theodorus De Groot, M.; De Groot, A.; Mendoza, P.G.; Junginger, M.; Kramer, G.J. Present and Future Cost of Alkaline and PEM Electrolyser Stacks. *International Journal of Hydrogen Energy* **2023**, *48*, 32313–32330, doi:10.1016/j.ijhydene.2023.05.031.
42. Zun, M.T.; McLellan, B.C. Cost Projection of Global Green Hydrogen Production Scenarios. *Hydrogen* **2023**, *4*, 932–960, doi:10.3390/hydrogen4040055.
43. Jungbauer, A.; Preuler, L.; Schwarz, G.; Lengauer, T.; Kradel, B. Zero-Carbon-Emission Hot Rolling of Direct Application Sheet with Real Endless Strip Production Available online: https://bit.ly/3XRcazl (accessed on 21 September 2024).
44. *Ironmaking and Steelmaking Processes: Greenhouse Emissions, Control, and Reduction*; Cavaliere, P., Ed.; Springer International Publishing: Cham, 2016; ISBN 978-3-319-39527-2.
45. Tekin, E.; Gillich, A.; Hufendiek, K. Impact of Different CO2 Price Paths on the Development of the European Electricity System. *Energy Strategy Reviews* **2024**, *55*, 101499, doi:10.1016/j.esr.2024.101499.
46. Bailera, M.; Lisbona, P.; Peña, B.; Romeo, L.M. A Review on CO2 Mitigation in the Iron and Steel Industry through Power to X Processes. *Journal of CO2 Utilization* **2021**, *46*, 101456, doi:10.1016/j.jcou.2021.101456.