A Comparative Analysis of Hydrogen and Natural Gas as Reducing Agents in Steelmaking

To

Bart Skarzynski

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By

Dara Safe, Travis Thyes, Dylan Gessert, Daniel O'Brien

College of Engineering

University of Wisconsin - Madison

Executive Summary

Rising greenhouse gas emissions from increased human activities involving fossil fuels are a global concern. The global steel sector is the second-largest industrial contributor to greenhouse gas emissions, with roughly eight percent of total carbon dioxide emissions from fossil fuels (Muslemani et. al, 2021). More specifically, the most energy-intensive process within steelmaking is reducing raw iron ore material into crude iron, requiring 13.5 gigajoules per tonne of crude steel (Martelaro, 2016). The UNFCCC's Paris Agreement was declared to combat climate change globally in 2015 (UNFCCC, 2015). The agreement incentivized the steel industry to become carbon neutral by 2050. This ambitious effort requires breakthrough technologies in the reduction process of primary steelmaking to replace standard coal-based methods. In the analysis of German researchers, green hydrogen as a reducing agent is the most promising solution to achieving a carbon-free steel industry (Arens, 2017). The following report starts with a background on the steel industry, including environmental concerns and production methods, then compares green hydrogen and natural gas in the steelmaking process. Finally, this report concludes with a recommendation of which technology is currently most feasible and the outlook on green hydrogen.

The steel industry is considered an energy-intensive industry that largely contributes to the global climate crisis. Despite being a significant polluter, the steel demand continues to rise in the 21st century, forcing the industry to seek process changes to lower the number of greenhouse gasses (Fischedick et al., 2014). Green steel replaces the blast furnace with a shaft furnace that takes in a reducing agent, hydrogen or natural gas, and produces water vapor instead of carbon dioxide. There are large incentives for steelmakers to pursue green steel for major industries, such as automotive. Customers want green steel to achieve their emission goals, providing steel makers with pricing power. Steel companies project to lose an estimated 14% of their potential value if they fail to reduce carbon emissions (Hoffmann et al., 2020).

The production of steel can take two routes, primary and secondary. Primary steel production is any process that turns raw iron ore into steel. In contrast, secondary steel production melts recycled scrap steel to create new, usable steel. While both processes are crucial to meeting current steel demand, globally, 70% of all steel manufactured is the result of the primary steel production process, while about 29% of all steel production is the result of the secondary steel process (Quader et al., 2015). Primary steel production uses one of two methods, coke-based steel production or direct reduced iron (DRI) steel production. Coke-based steel production uses iron ore, burned down carbon concentrated coal called coke, and limestone in a blast furnace to reduce the iron oxides into iron and then uses oxygen gas in a basic oxygen furnace to remove the remaining carbon. The amount of burning in these two processes makes this a carbon-intensive production method and the blast furnace alone accounts for 70% of coke based steel production carbon dioxide emissions (Peplow, 2021). The DRI process typically uses natural gas and, more recently, hydrogen gas to reduce the iron ore to iron before liquid steel conversion in an electric arc furnace. While natural gas accounts for 92% of the DRI process (L. Lu et al, 2015), hydrogen is considered more appealing because water vapor is the only byproduct of the reduction process. While hydrogen gas and natural gas offer a greener future in steel production, neither come without their respective challenges.

Evaluating hydrogen and natural gas as reducing agents is determined through fuel production efficiency, the feasibility of large-scale implementation, and environmental impact. Preparing natural gas for steel production involves two steps: extraction from the ground and reformation into hydrogen and carbon monoxide. Although this seems less efficient than hydrogen, which uses water electrolysis, the reformation of natural gas is 20% more efficient than producing hydrogen via electrolysis (Otto, 2017). This inefficiency contributes to outcomes such as increased costs. Based on current electricity and natural gas prices, steel production with hydrogen is 40% more expensive than when using natural gas (Conde, 2021). This price difference, however, can be reduced and even eliminated by the anticipated "carbon tax" and varying electricity prices. A major limiting factor for hydrogen-based production is building the infrastructure to produce the hydrogen required to fulfill the world's steel needs. However, hydrogen gas is appealing because the gas produces zero carbon dioxide emissions (Otto, 2017). On the other hand, less than 50 years of known natural gas reserves are left in the world today, making natural gas a limited resource.

After analyzing the feasibility of natural gas and green hydrogen as the reducing agent for DRI, natural gas is the most effective fuel source in the short term as the industry moves toward carbon-neutral. Despite minimal infrastructural changes needed for green hydrogen in DRI shaft furnaces, sourcing green hydrogen is the key limitation in this comparison. Green hydrogen requires further development of renewable energy systems and electrolyzers to be considered an efficient and cost-effective alternative fuel. Even though natural gas is the best solution to start implementing currently, natural gas is not considered a sustainable option in the long term.

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1. Introduction and Objectives

This research project serves to analyze greener alternatives to the traditional steel making process. Specifically we want to look at the use of the two major fuels, natural gas and hydrogen, in steel making furnaces for the production of green steel. We will give an introduction to the effects of carbon dioxide emission on our world. Then we'll talk about how steel contributes to emissions and describe the incentives for the industry to explore green steel. After that there will be a technical background on the steel making process, both traditional processes and green processes. With the knowledge from the technical background at hand, we will analyze efficiency, cost of implementation, and carbon dioxide production for the two aforementioned fuels - natural gas and hydrogen. Finally, a decision matrix will be used to quantify the analysis and a recommendation will be made along with some closing thoughts about the future of green steel.

2. Background on Greenhouse Gas Emission Problem

2.1 *Energy-intensive Industries*

Greenhouse gasses are a pressing problem due to the negative externalities associated with their production and it's critical that we explore ways to mitigate their production. Rising greenhouse gas emissions from increased human activities involving fossil fuels are a global concern. Greenhouse gas accumulation in the atmosphere leads to the greenhouse effect or trapping of heat within the Earth's atmosphere, leading to extreme climate conditions, respiratory disease, and intensified natural disasters (Kweku et al., 2018). Global temperatures are expected to increase by at least 3 degrees fahrenheit by the end of the century, and that's not the worst of it, by the end of the century it is projected that 83 million people will die due to climate change (Krajick, 2021). We must look for ways to lower emissions otherwise there will be dire consequences for the human race. One of the more compelling places to explore greener alternatives is industry. The industrial sector consumes roughly one-quarter of global greenhouse gas emissions and one-third of primary energy consumption (EPA, 2018) (EIA, 2016). Energy-intensive industries, such as iron and steel, paper, cement, and aluminum, are more challenging to decarbonize than other sectors, like electricity generation and transportation, because of the need for fossil fuels for combustion in industrial processes (EIA, 2016). The energy-intensive industries require novel process technologies to replace existing ones or applications of carbon capture and usage to current technology, using renewable energy sources instead of current industrial energy sources. It is critical that we pursue routes to reduce emission within these energy-intensive industries as these efforts will go a long way in reducing the effects of climate change. The challenges of decarbonizing the industrial sector means that the pathways forward aren't fully defined, making it a valuable topic for analysis.

2.2 *Steel Industry's Impact on Carbon Emission*

The steel industry is a major industrial polluter and it needs to use process changes to improve. The global steel sector is the second-largest industrial contributor to greenhouse gas emissions, accounting for roughly eight percent of total carbon dioxide emissions (Muslemani et al., 2021). In fact, for every ton of steel produced 1.85 tons of carbon dioxide is produced (Hoffmann et al., 2020). Steel is the most commonly used metal in the world with 1864 million tons produced in 2020 ("About steel", n.d.). Due to its high strength and relatively low cost steel is an incredibly popular choice of material in infrastructure, transportation, appliances, and more. The amount of steel produced has more than tripled in the past 50 years, and the demand for the metal is expected to continue to increase until the end of the twenty-first century (Conte, 2021) (Fischedick et al., 2014). This isn't an industry where a greener alternative to the end product is expected to eat up market share. Unlike the auto industry where electric vehicles pose a green alternative to traditional internal combustion engines. Steel is here to stay and for the industry to reduce emissions it must make changes in the production processes.

Though the steel industry has used recycling to dramatically improve sustainability, it needs to find new methods to reduce pollution. Historically speaking the steel industry has made significant progress in improving efficiency and reducing pollution. Today, one ton of steel can be produced using just 40% of the energy needed in 1960 ("About steel", n.d.). A big driver of sustainability and efficiency has been recycling. Utilizing steel's magnetic properties, it has been easy to recover old steel and recycle, and the real kicker is that the properties of recycled steel are unchanged ("About steel", n.d.). Currently, 30 percent of new steel products contain recycled material (Conte, 2021). Unfortunately, the process of repurposing recycled steel, known as secondary steel making, is restricted by scrap availability. Therefore, the increase in demand for steelmaking in the future must be fulfilled by primary steelmaking. Primary steelmaking is a process where you start with raw iron ore mined from the earth instead of recycled scrap. The industry must look to primary steel making for potential reductions in emissions.

Luckily, there are alot of opportunities in primary steel making to reduce emissions. Figure 1 shows the traditional steel production process.

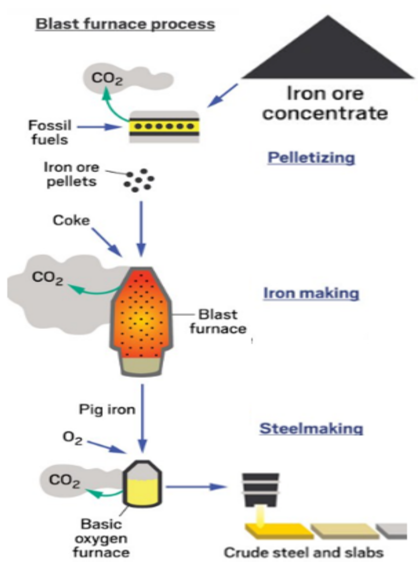

Figure 1: Traditional steelmaking process. Here's a visualization of where carbon dioxide is being produced during traditional steel production. Note that all three major processes - pelletizing, ironmaking and steelmaking produce carbon dioxide (Peplow, 2021).

There's a lot to process in Figure 1 and Section 3 will explain it more in depth. What I want you to note is the product from pelletizing, iron making, and steel making is carbon dioxide. The three major processes in traditional steel production all produce carbon dioxide. The blast furnace alone accounts for 70% of emissions. There's also a lot of emissions not shown on Figure 1. Coke is created from coal, and the coke making process accounts for 20% of emissions in steel making (Sohn, 2016). Then you also have pollution from the mining of coal and iron ore. Mines are typically in remote locations, so operators need to have their own large diesel generators in order to supply reliable power, unfortunately these are fairly dirty ways to produce power ("Powering the Mining Industry", 2019). Green steel on the other hand has the same three processes, but the approach is much different. For instance, green steel can eliminate the use of a blast furnace, which accounts for the most of the carbon dioxide, and replace it with a shaft furnace. A shaft furnace takes in iron ore pellets and a reducing agent, hydrogen, and produces water vapor as a byproduct instead of carbon dioxide. Therefore the only carbon dioxide from the iron making stage would come from the procurement of the hydrogen. Again, we are going to analyze two reducing agents, pure hydrogen and natural gas, which is reformed to hydrogen and carbon monoxide. Hydrogen is made from water using energy intensive electrolysis, but the process is carbon free if you use renewable energy as a power source. Natural gas is typically collected from the ground using fracking. Fracking is lower in carbon dioxide production than coal mining, but it creates a lot of methane which warms the earth 80 times more than equivalent carbon dioxide (Leahy, 2019).

2.3 *Global Incentives of a Carbon-Neutral Society*

Steel producers must explore green steel making to prepare themselves against potential effects of global climate initiatives. The introduction of the Paris Climate Agreement completely changed the landscape in the effort to mitigate climate change. "For the first time, a binding agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects."(UNFCCC, 2015) The major aim of the Paris Climate Agreement is for net-zero emissions by the mid 21st century (Gerres et al., 2021). As a result, steel production is directly in the crosshairs. An analysis of the effect of the agreement on steel production suggested that carbon dioxide produced would have to fall to 500 million tons annually in order to achieve that goal. Which would be one-sixth of the amount of carbon dioxide currently produced (Peplow, 2021). Due to the high amounts of carbon dioxide emitted from steel production countries are very timid about the expansion of production. For instance, China is the dominant producer of steel, making ten times as much steel as the second largest producer (Conte, 2021). China plans to reduce steel production in order to reach their goal of carbon neutrality by the year 2060 (Tang, 2021). This report is not going to analyze green steel regulations. How entities choose to achieve climate goals will vary greatly, but the economic impacts stemming from a global push for greener industries can not be entirely ignored. It's estimated that a failure to reduce carbon emissions would cost steel companies 14% of their potential value (Hoffmann et al., 2020). In order for the industry to align with both local and global climate goals there needs to be a significant change in the production of our steel in order to make the process more environmentally friendly.

Emissions regulations are directly pressuring many in the steel industry toward greener steel, but they also create financial incentives for producers to make the switch. Purchasers of steel are looking for cleaner alternatives in order to achieve their own emissions goals. One of the major industries that are currently demanding clean steel is the auto industry. The auto industry purchases 12% of the steel produced and this dirty industry is looking for ways beyond electric motors to clean up their business. Volvo, who intends to be climate neutral by 2040, announced that they would be partnering with a green steel company in Sweden and that would be used to produce vehicles which will be delivered starting in 2022 (Soderpalm, 2021). This demand gives steelmakers a chance to price green steel at a premium to traditional steel and it also enhances marketability for the product (Gerres et al., 2021). This represents a significant incentive for steel makers to make the switch. Steel producers are in a commodity based business where there's little product differentiation and all that matters is price. Buyer interest in green steel changes that. Which gives steel makers willing to make the change an opportunity to offer a highly sought after product.

3. Introduction of Steelmaking Processes

3.1 *Primary and Secondary Steelmaking*

Nearly all steel that is produced in the world today is made using one of two methods: primary steelmaking which uses a variety of processes including a blast furnace (BF) and basic oxygen furnace (BOF) to turn iron ore into usable steel, and secondary steelmaking which turns steel scrap into usable steel using an electric arc furnace. Primary steel production can come in many forms, but the two most popular methods of primary steel production are coke based steel production and direct reduced iron (DRI) steelmaking with natural gas or hydrogen as the reducing agent. Similarly to DRI primary steel production, secondary steel production utilizes an electric arc furnace rather than a BF and BOF combination. Secondary steel production begins with scrap steel, which comes in several different qualities. Scrap iron is molted in an electric arc furnace where all waste material is burned away, resulting in direct reduced iron, or sponge iron. From there, additives can be used to achieve the designed chemical composition (Quader et al., 2015). These processes vary widely in complexity, cost, and environmental friendliness, but a more in depth look at these processes will come later. Of the two processes, primary steelmaking makes up the majority of steelmaking. Globally, 70% of all steel manufactured is the result of the primary steel production process, while about 29% of all steel production is the result of the secondary steel process (Quader et al., 2015).

Secondary steel making takes advantage of the recyclability of steel, a product that is both 100% recyclable and infinitely recyclable, meaning it can all be recovered in a recycling process, no matter how many times it has previously been recycled (Muslemani et al., 2021). According to the National Material Company, in North America alone, over 80 million pounds of steel are recycled annually and for every ton of steel that is recycled “2,500 pounds of iron ore, 1,400 pounds of coal, and 120 pounds of limestone are conserved,” (National Material Company, 2021). Secondary steelmaking is a much simpler process than primary steel making, since it begins with recycled scrap steel, which has already been processed, rather than iron ore, which has to undergo extensive processing before it can become steel. This recycled scrap steel gets melted down in an electric arc furnace where it is typically combined with oxidation agents to help control the quality of the final product. Since this process uses an electric arc furnace, it is an easy path to green steel, assuming the power for the furnace is also green (Muslemani et al., 2021). Figure 3 below shows the difference in paths between primary and secondary steel production. Starting with scrap steel in the middle of the map, the scrap goes into an electric arc furnace, then on to be processed further, skipping several steps from the traditional BF and BOF process. Under environmental and political pressure, many steelmakers are looking for ways to decarbonize their steel production, and many are looking to recycling as a way to supplement primary steel production to further lower their carbon dioxide emissions. While this is a good start, the bulk of steel related carbon emissions come from the primary steel production process, reinforcing the importance of finding a greener solution in this space. While much cleaner methods of steel production are becoming more widely available and utilized, coke based steel production is still the most common method used to turn iron ore into steel.

3.2 Coke-based Primary Steel Production

Coke-based primary steel making starts with three ingredients: coal, limestone, and iron ore mined from the ground. Before the iron ore can be processed, coal must first be turned into coke, which acts as both a fuel and reducing agent in the blast furnace. The coal is fed into a coke oven where it is heated to over 2,000 ℉. During this process, the coal is liquified and resolidified, burning away all of the impurities found in the coal, and leaving behind the solid coke, which is nearly entirely carbon (KGS, 2019). Once the coke is formed, it is ready to be fed into the blast furnace with the iron ore and limestone. At this stage, raw iron needs to be extracted from the iron oxides that make up mined iron ore. In the blast furnace, the large carbon content of the coke is used as a fuel in the heating process as well as a reducing agent to reduce the iron ore into pure iron (Peplow, 2021). The products of this reaction are pure iron and carbon dioxide. Figure 2 below shows the reactions that occur in a blast furnace.

Traditional, coke-based steelmaking

$$2C + O_2 \rightarrow 2CO$$

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

Figure 2: Chemical equations of blast furnace reactions. This image shows the three main reactions that occur in a blast furnace, including the reaction that coke undergoes with iron oxide to produce iron and carbon dioxide (Peplow, 2021).

The second equation shows the carbon atoms from the coke bonding with the oxygen atoms in the iron oxides to produce pure iron, along with carbon dioxide. This process is a large contributor to the overall emission of carbon dioxide in this process. In addition to iron ore and coke, the limestone is added into the blast furnace during this process to bond with the other impurities found in a blast furnace, mostly sand and silica. These impurities solidify at furnace temperatures and form scag, which is a solid that forms at the top of the molten iron, making it easy to remove, leaving behind a much cleaner product. The end result of this blast furnace process is called pig iron. This iron has a high carbon content due to its exposure to the coke in the blast furnace, and is therefore quite brittle (Peplow, 2021). From this point, the pig iron needs to be processed further to become usable steel. The pig iron ingots formed from the blast furnace are then fed into a basic oxygen furnace (BOF) where the ingots are once again melted at a very high temperature, this time while being blasted with pure oxygen gas. Here the oxygen bonds with the remaining carbon in the pig iron to form carbon dioxide and steel (Quader et al., 2015). The steel that leaves the BOF can then be sent to be processed into whatever final product is desired by the customer. Figure 3 below shows the process of coke-based steel production.

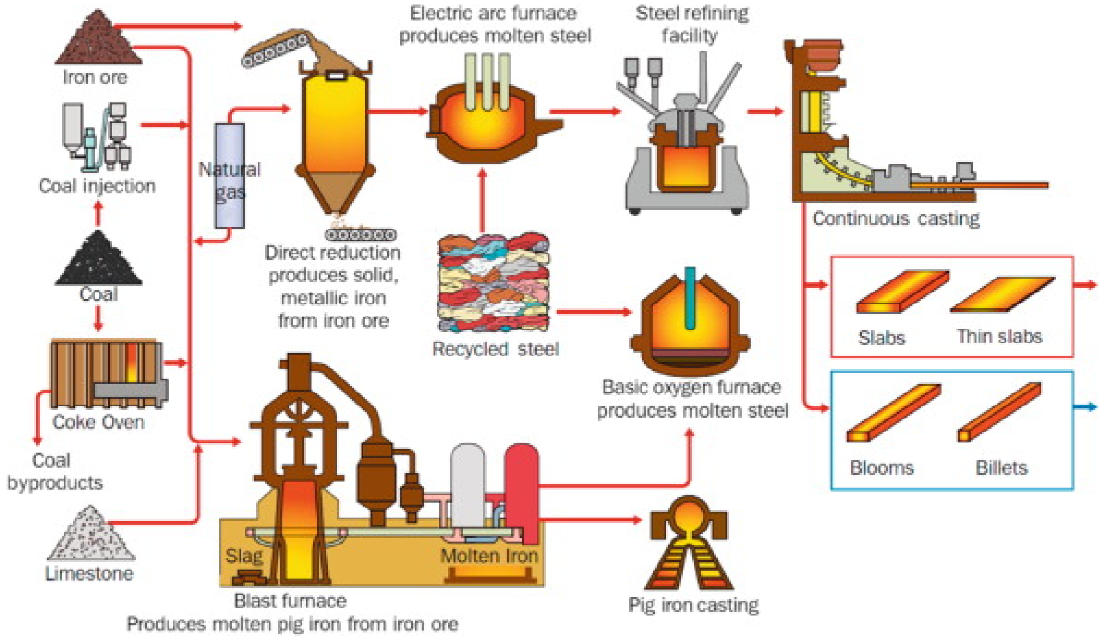

Figure 3: A steelmaking process map. This route shows the many processes of steel making in the order that they must occur to produce steel, including coke based steel production, direct reduced iron steel production, and secondary steel production (Yang, 2014).

Starting in the top left, the three main ingredients, coal, iron ore, and limestone, can be followed through the process, starting in the blast furnace where the first round of reduction occurs, into the basic oxygen furnace where the pig iron is melted again to lower the carbon content using oxygen gas, and finally onto refining the product into the desired type of steel. Figure 3 also highlights the amount of burning, and therefore the production of carbon emissions, that takes place throughout this process, starting in the coke oven, and continuing into the blast furnace and basic oxygen furnace. These processes are incredibly energy intensive while also producing large amounts of carbon dioxide. According to Peplow in an article for Chemical and Engineering News, "Processing iron ore into pellets and making coke are responsible for about 20% of this route's carbon dioxide emissions, with the blast furnace itself responsible for about 70%," (Peplow, 2021). These numbers emphasize the need to either reduce or eliminate these processes from steel production to reduce the industries carbon footprint in an effort to help ease the climate crisis The push to develop steel production processes that are cleaner than the traditional coke-based process has led to several advancements in the much cleaner direct reduced iron steel production process.

3.3 Direct Reduced Iron Process

While coke-based steel production is one of the most widely used steel production methods today, it is an outdated, energy intensive, and carbon emissive process. Recently, under the pressure of increased climate change and increased regulations, more steel producers are shifting to cleaner primary steel production methods, one of which is direct reduced iron (DRI). One of the main differences between coke based steel production and the DRI process is the use of blast furnaces and basic oxygen furnaces versus electric arc furnaces. A BF uses coal, coke, and iron ore to produce pig iron. A BOF uses a fuel, typically coal, and oxygen as the reducing agent, to remove carbon from pig iron in order to produce usable steel. In the furnace, the pig iron ingots are melted and blasted with oxygen gas, which bonds with the carbon to produce carbon dioxide and steel. The amount of carbon dioxide that is created by this process, both by the burning coal and the chemical reaction to remove the carbon from the pig steel, is the biggest problem with this technology. On the other hand, electric arc furnaces utilize electricity to melt scrap steel or already reduced iron from a DRI process. This process is both faster, as it involves far fewer steps, and can be much cleaner, depending on how the electricity for the furnace is produced. Unlike the traditional blast furnace to BOF route, the DRI process takes solid iron ore and introduces it to a reducing agent in its solid state, eliminating the energy intensive process of molting it. The two most popular reducing agents for DRI in industry today are reformed natural gas and hydrogen gas, with natural gas accounting for more than 92% of current DRI steel production (L. Lu et al, 2015). In order to use natural gas in this process, it must first be reformed, which results in a gas containing hydrogen and carbon monoxide, which is called syngas (Peplow, 2021). This syngas is then heated to 900 ℃ and blasted through the iron ore pellets in a shaft furnace, where it reacts with the iron oxides in the ore to remove the oxygen and leave behind a solid that is 90-94% pure iron. During the reduction process in the shaft furnace, the hydrogen gas and carbon monoxide from the syngas bond with the oxygen molecules in the iron oxides to produce water vapor and carbon dioxide. While this process is much cleaner than coke based steel production, carbon dioxide is still a byproduct of the reduction process, leaving further room for improvement for this process. From here, the reduced iron can be loaded into an electric arc furnace to be melted and alloys can be added to produce usable steel (L. Lu et al, 2015). The use of natural gas as a reducing agent and an electric arc furnace for melting results in a production process that produces far less carbon dioxide than the traditional BF and BOF route. Overall, the DRI process using syngas and an electric arc furnace produces 35%-40% less carbon dioxide than tradisional coke based steel production (Draxler, 2021). Figure 4 below shows the MIDREX process, currently the most common DRI process used in industry.

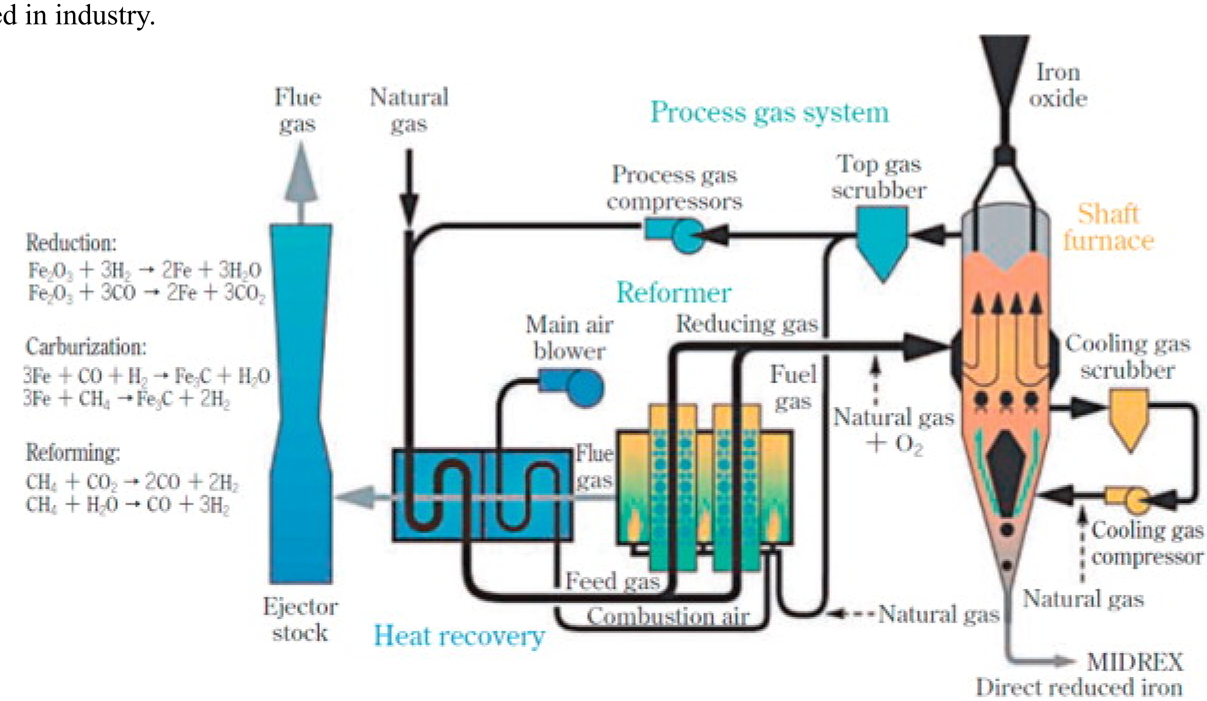

Figure 4: DRI process using natural gas. This image shows the DRI process in detail including the reforming process of the natural gas and the reduction of the iron ore in the shaft furnace (Yang, 2014).

Natural gas first gets reformed into syngas in the reformer before it can be used. From there, it is heated, and pumped into the shaft furnace where it is blasted against the iron ore pellets to cause the reduction reaction. The end product of this process is direct reduced iron that can be melted in an electric arc furnace and then processed into the end steel product. This final process in an electric arc furnace is very similar to what occurs in secondary steelmaking, and can also be seen in Figure 3. When comparing this process to the one shown in Figure 3, it is clear that the DRI process is much cleaner than the BF and BOF route.

While natural gas is currently leading the charge in DRI steel production, interest in hydrogen as a reducing agent has been increasing in recent years. This effort to produce steel with clean hydrogen is being led by project HYBRIT (Hydrogen Breakthrough Ironmaking Technology) in Sweden which kicked off in 2016. HYBRIT is a joint effort between steel maker SSAB, iron ore miner LKAB, and utility company Vattenfall, and they aim to utilize hydrogen, specifically green hydrogen, as the reducing agent in a DRI process rather than natural gas or coal (Blank, 2020). Figure 5 below shows the MIDREX process once again, but this time with hydrogen gas rather than natural gas.

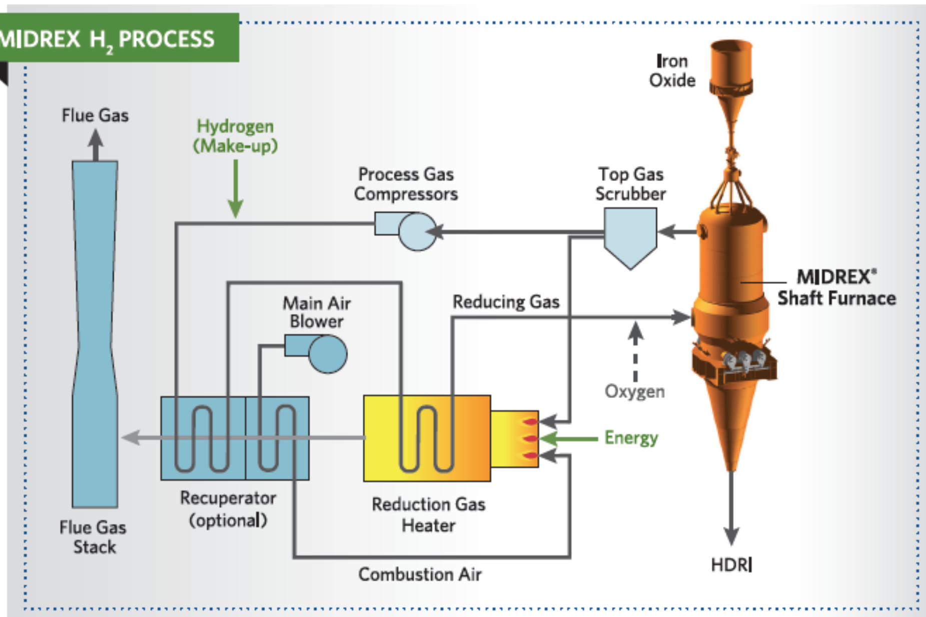

Figure 5: DRI process using hydrogen. This image shows the DRI process with hydrogen gas, outlining the simplicity of this process as well as its similarities to the natural gas DRI process (Ripke, 2017).

Figure 5 shows how similar this process is to that of natural gas, with the main difference being that the hydrogen gas does not need to be reformed in any way, it only gets heated and then sent to the shaft furnace. The primary benefit here is that the by-product of the reduction reaction with hydrogen is simply water vapor. With HYBRIT's efforts to eliminate the conventional blast furnace steelmaking process by utilizing hydrogen DRI, they will "single-handedly contribute to greenhouse gas reductions corresponding to more than 50 percent of Sweden's total footprint" (Blank, 2020) Furthermore, if the 18 million tons of crude steel that this plant is capable of producing were made using traditional methods, it would produce 28 million tons of carbon dioxide emissions (Blank, 2020). This push in green hydrogen steel production by HYBRIT will help to lower the price of hydrogen, and continues to put pressure on the industry to follow suit by proving the processes's feasibility and benefits. One of the biggest challenges currently facing the mass adoption of hydrogen based DRI is sourcing clean hydrogen gas. The best way currently to produce hydrogen gas is through electrolysis, which uses large amounts of electricity and water to produce hydrogen gas. In order to reap the environmental benefits of hydrogen in steel production, it's imperative that the electrolysis process uses renewable energy. Because of this, current prices of true green hydrogen are very high, but are expected to drop by almost 400% by 2050 (Hoffman, 2020), making hydrogen DRI a tough sell in present day, but the potential for abundant clean hydrogen makes for a very bright future in green steel production.

4. Comparative Analysis of Hydrogen and Natural Gas for Direct Reduced Iron

The use of direct reduced iron-electric arc furnace steel making setups (EAF) in place of the more traditional blast furnace-basic oxygen furnace (BF-BOF) setup is one big step that the world's steel industry can make to reduce their overall energy consumption as well as their greenhouse gas emissions. Electric arc furnaces do not rely upon carbon-based fuels that the traditional BF-BOF systems do and instead can be powered from renewable energy sources such as wind, solar and nuclear. While there are immediate benefits from moving to electric arc furnaces, the industry is looking for further methods to reduce its environmental footprint. Using hydrogen, instead of natural gas, during the steel production process has been shown on a small scale to be a possible solution for the steel industry to become carbon neutral. What follows is a comparison of using natural gas- and hydrogen-based iron ore reduction processes in conjunction with electric arc furnaces during the production of steel making. Specifically, these two different technologies will be compared on the basis of their energy efficiency, feasibility of large-scale implementation, and, finally, their environmental sustainability output.

4.1 Efficiency

In order to properly evaluate any industrial process it is important to consider the process' efficiency, or in other words, what are the process' inputs and outputs. In our current world, the industrial sector consumes over 50% of the world's energy supply. With steel making being an incredibly energy intensive process and the industrial sector already consuming a majority of the world's energy supply, it is important to keep efficiency in mind. Primary steel making with electric arc furnaces is a two part process. The iron ore must first be reduced via a chemical reaction into crude steel, then this crude steel is transferred over to the hot EAF where it is then purified and melted. The reduction process is where the two proposed solutions, hydrogen and natural gas, differ.

Natural gas or hydrogen gas can be used as an input to reduce the iron ore, however it is not just simply swapping the two gasses. Both hydrogen and natural gas have a few steps to go through before they can be useful in iron ore reduction. Comparing the amount of time and energy, as well as the number of steps in each path will prove valuable in evaluating each solution's efficiency. Natural gas, which is originally formed from decomposing organic matter that has been under heat and pressure from the Earth for thousands of years, requires two steps before it is ready for use. The natural gas needs to first be extracted from the ground. This is a complicated process, supported by its own industry, that boils down to drilling through earth's surface once a natural gas reserve has been found. Once the natural gas has been extracted, it must then go through a second process. Natural gas goes through a process called "reforming". Reforming takes natural gas and converts it into a mixture of hydrogen gas and carbon monoxide, often referred to as "syngas", and is now ready to be used (Office of Energy Efficiency and Renewable Energy, n.d.). This two step process for natural gas contrasts to the more direct approach that hydrogen allows.

Hydrogen gas can be used directly in steel making without any additional refinements or steps. The difficulty lies in getting the hydrogen, or more precisely making it. Pure hydrogen gas is not an abundantly available natural resource, and therefore it must be produced through a process called electrolysis. Electrolysis is an energy intensive process that takes water and splits the molecule into hydrogen and oxygen gas. (Office of Energy Efficiency and Renewable Energy, n.d.). Once the hydrogen has been produced, it is ready for use in the production line.

Despite the more streamlined process of water electrolysis, it does have its downfalls. In a report from the International Journal of Hydrogen Energy, it was shown that the efficiency of producing hydrogen through electrolysis is 70% (Schiebahn, 2015). This compares to academic research showing an 84% efficiency for the production of hydrogen through reforming of natural gas (Matos, 2009). While these both seem like reasonably high values of efficiency, this leads to 20% more energy required to produce hydrogen through electrolysis. These two paths for steel making can be seen in figure 6.

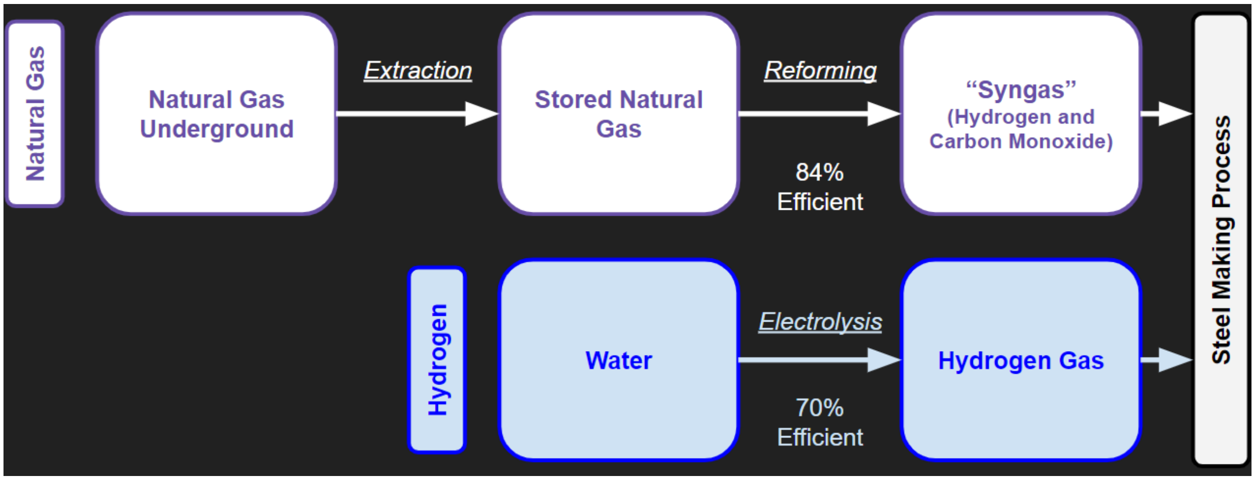

Figure 6: Paths to steelmaking flow chart. Hydrogen has less steps than natural gas, however it shows inefficiencies compared to natural gas' second step.

The simplified one step approach comes with a tradeoff of reduced efficiency during the production of hydrogen. This increased amount of electricity will not only impact the world's energy supply, it will also lead to increased costs that are passed down to the end users. The combined energy and economic inefficiencies, in an industry which has already been recognized for its extensive energy consumption and wastefulness, is a hard pill to swallow.

The success of both hydrogen and natural gas will be dependent on the sources that supply energy during production, specifically inefficient renewable energy sources. This is especially true for the direct production of hydrogen through electrolysis which has already been shown to require 20% more energy than the reforming step for natural gas. Looking at the energy requirements of the electric arc furnace, which will be paired with either of the proposed solutions, will provide a glimpse at what a 20% increase may truly mean. To produce one metric ton of steel, electric arc furnaces require approximately 2.4 gigajoules of energy (Fruehan, 2000) . To give this number some context, let us look at the requirements for a very common renewable energy source, solar. In order to produce the 2.4 gigajoules of energy to produce just one metric ton of steel, there would need to be 425 solar panels, or approximately 3,300 square feet of panel, operating at a standard power output of 20% of total capacity. (National Renewable Energy Laboratory, n.d.). If you would expand this analysis to the 2 billion tons of steel that is produced every year, the seemingly small difference in efficiency can scale to a major difference in energy needs that could impact how the world operates today. It also has impacts such as increased costs for consumers and increased land use to produce the said difference in energy requirements.

4.2 Feasibility of Large Scale Implementation

Evaluating each solution, hydrogen and natural gas, on their ability to be implemented on a large scale will be critical in determining which alternative should be utilized moving forward. There are many businesses in this world that can be highly effective at the small scale, however when they have grown beyond their current levels they can collapse and suddenly what originally made the business special has disappeared.. This can be seen all across the world in all sorts of industries including restaurants, hair stylists, and sales just to name a few. Any change to improve the steel making industry's carbon emissions can only be truly effective if it is scalable to cover the world's steel needs.

When scaling anything to a global scale, it is critical to evaluate the incremental cost associated with the process. A few dollars on the creation of a single metric ton of steel can add up to large sums in added costs over the course of a year. In a 2022 techno-economic evaluation of the decarbonization of the steel industry, a group of Austrian researchers compared hydrogen gas and natural gas as possible solutions to the steel industry's extensive carbon emissions. They estimated the costs of both solutions and compared it against traditional blast furnace-basic oxygen furnace (BF-BOF) technologies using current electricity and natural gas prices, and what they found was quite interesting. They calculated costs of 495, 491, and 675 $/ton of crude steel for BF-BOF, natural gas/EAF, and hydrogen/EAF, respectively. (Conde, 2021). Thus showing hydrogen as completely inferior to natural gas economically. The anticipated 40% cost increase would not only put steel makers in a tough position. Steel makers would be forced to pass these added costs onto consumers. The research team then added a twist to this calculation, they recognized the dependence of these calculations on their assumptions, specifically the cost of electricity and included anticipated penalties for carbon emissions. Figure 7 shows the cost per ton of crude steel as a percentage of the reference price of natural gas calculated above for each solution compared against electricity price, with the banded regions representing the expected carbon emission penalties each process should expect.

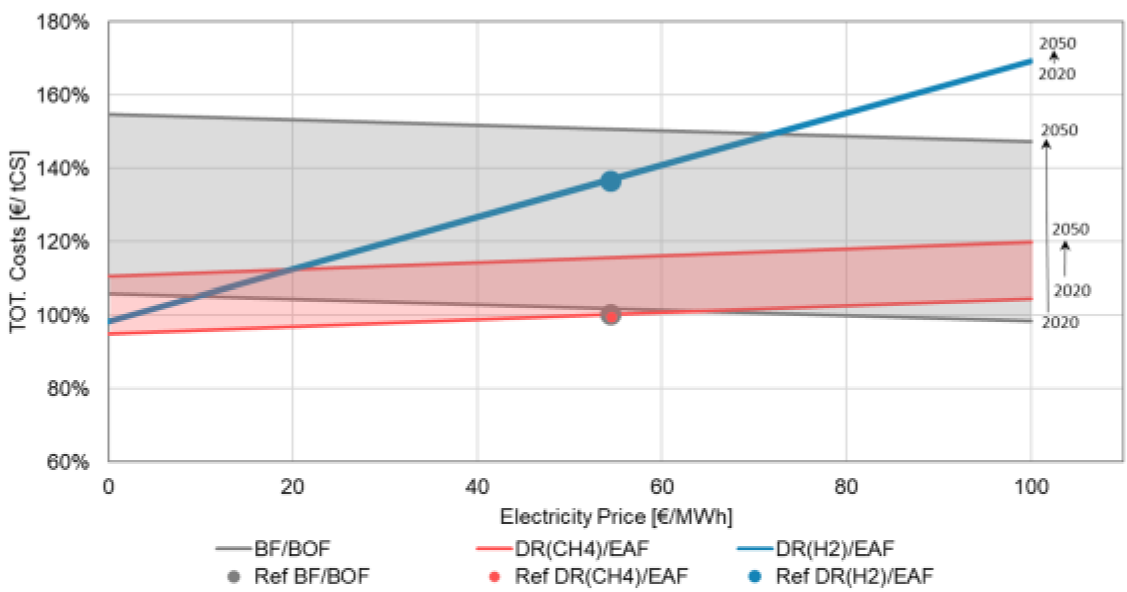

Figure 7: Production cost of steel diagram. The costs of three different types of steel making were compared based on the incremental cost for 1 ton of steel (Conde, 2021).

This plot shows us that while right now hydrogen is completely economically infeasible, by incorporating the expected penalties for natural gas and BF-BOF, hydrogen goes from by far the worst option to an average option. Additionally, as the price of electricity decreases the price gap between hydrogen and natural gas also decreases. It is important to note that, with everything else, electricity prices tend to increase over time which leads to a larger cost gap between hydrogen and natural gas. However, there is research that gives hydrogen some hope in terms of cost. Figure 8 gives the price of hydrogen gas over time.

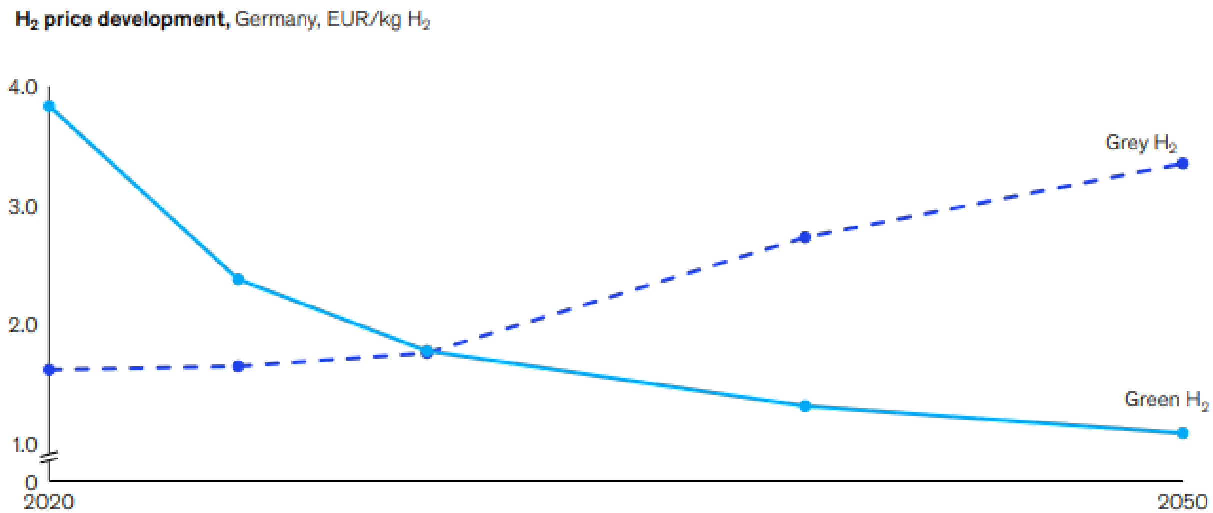

Figure 8: Cost of hydrogen production diagram. Varying hydrogen prices vary depend on how it is produced (Hoffmann, 2020).

This new research suggests that the cost of green hydrogen (hydrogen produced from renewable sources) is expected to cut in half by the year 2030 (Note: Grey hydrogen, which is produced from carbon-based fuels, is anticipated to increase in price due to expected penalties for carbon emissions) Putting an exact price tag on developing technologies is always a tough task, but hydrogen-based steel is especially difficult due to the number of things it is reliant upon including the development of the hydrogen manufacturing industry and the cost of electricity. Reducing these costs with hydrogen-based production to become more in line with other technologies will be critical for it to be considered a viable solution.

Not only is the incremental cost of each solution important to determine its viability to the carbon emission crisis, but it is important to evaluate the upfront costs and infrastructure requirements. When comparing the physical system to produce steel from either natural gas or hydrogen, they are quite similar. Both options utilize an electric arc furnace during the melting and refining of crude steel. They only slightly vary during the iron ore reduction process, where natural gas needs to be first reformed and the system needs to handle syngas (mixture of hydrogen and carbon monoxide) compared to 100% hydrogen gas. And, as a matter of fact, they are so similar that a natural gas system can be easily switched over to a purely hydrogen gas system. The secretary general of Gas Infrastructure Europe has been quoted as saying, “the existing gas infrastructure can be largely retrofitted and future-proofed to help transport and efficiently store hydrogen” (Collins, 2020). This leads to a few conclusions. Firstly, in practice, both hydrogen and natural gas require very little differences in terms of equipment during the actual steel making process. Secondly, even though there is already developed infrastructure to handle natural gas, if hydrogen was deemed the better alternative, there would be reduced time and capital requirements for the build out of new infrastructure. The one point where hydrogen falls well short is the production of hydrogen itself and the resources to produce clean energy.

Implementing either of these solutions involves moving from basic oxygen furnaces that use coal to provide the necessary heat towards electric arc furnaces that can use electricity in any form. Of course, the electric arc furnace starts to show out when it can pull its power from renewable sources. The type of electricity also matters when considering the 20% decrease in efficiency when moving from natural gas to hydrogen. Moving from carbon-based electricity to renewable energy will be vital in the success of either solution, however it is much more of a factor for hydrogen due to its increased energy requirements. The largest hydrogen production facility is planned in the German city of Hamburg. Assuming no interruptions or inefficiencies, the plant operating at its peak of 100 MW would produce less than 1TWh of hydrogen every year. This is just a drop in the bucket of the 70TWh requirement to convert just the

German steel market to purely hydrogen-based reduction processes. Taking this beyond just the shortcomings of hydrogen production, there is an additional 120TWh of energy that surrounds the steel production, coming to a total of approximately 200TWh (Roland Berger, 2020). What does this amount of energy really mean? Well, as of 2021, there is slightly over 3TWh of renewable energy capacity in the entire world (International Renewable Energy Agency, 2022). Not only would converting the German steel industry to hydrogen-based production take more than 70 of their largest electrolysis plants, but if renewable energy sources were used, it would nearly 70 times the current amount of renewable energy in the entire world. In order to do this, it would require large investments not only by the private sector, but also likely tax breaks and grants by the government. At the very least, building up the necessary infrastructure for hydrogen-based steel production would take a considerable amount of time. And time is something that our world, as we know it, seems to be running out of.

4.3 Environmental Impact

In order to achieve the primary goal and driving motivation of this entire analysis, it is essential that our proposed solution can produce the desired environmental impact in order to achieve the ultimate accomplishment of long-term carbon neutrality. It has already been shown that the implementation of electric arc furnaces alone can reduce the amount of carbon dioxide emissions by over 20% when compared to the more conventional blast furnaces (EUROFER: The European Steel Association, 2013). However, it is important to pair this technology with additional improvements for the steel industry to continue to reduce its emissions. Natural gas and hydrogen both have shown improvements upon conventional systems, however evaluating the solutions based on their environmental impact will allow for a more informed decision.

Both hydrogen and natural gas need to see improvements before they can be considered perfect solutions environmentally. Carbon gasses are some of the most common greenhouse gasses, and are a chronic pollutant resulting from steel making. In order for natural gas to be used in the production of steel, the methane, which is the primary chemical in natural gas, must first go through a separate process and be made into "syngas". Figure 9 shows the process, which is known as reforming.

Reforming (conversion of CH_4 to CO and H_2)

6. $CH_4 + CO_2 \longrightarrow 2CO + 2H_2$

7. $CH_4 + H_2O \longrightarrow CO + 3H_2$

Figure 9: Natural gas reforming chemical equations. Natural gas can be prepared for steel production through two different reactions (Midrex Technologies, Inc, 2022).

Syngas is a mixture of hydrogen gas and carbon monoxide that is formed through an endothermic reaction reforming process, which requires an input of energy and also creates an additional pollutant, carbon monoxide. Although it may seem like the answer to eliminating the pollution caused by this process would best be solved by just using hydrogen gas directly, it is important to remember that hydrogen gas is not an abundantly available resource. Hydrogen gas must be produced through its own separate process. On top of that, the current method to produce hydrogen gas, namely through the electrolysis of water, is incredibly energy intensive in its own right. In a study evaluating the reduction of carbon dioxide emissions in the German steel industry, the "carbon dioxide Emission Factor", which gives the amount of resulting carbon dioxide per a gigajoule of hydrogen gas, was calculated for various methods of producing the hydrogen gas to be used in steel manufacturing. The results of the study show that during the production of hydrogen through the reforming of natural gas there is 66.64 kg of carbon dioxide produced per a gigajoule of hydrogen gas. For the hydrogen gas produced through electrolysis, the study lays out two possible paths, one which uses strictly renewable energy sources and the other which uses electricity from the current German electrical grid. Hydrogen produced from the current electrical grid produced a whopping 119 kg of carbon dioxide per gigajoule of hydrogen, which is almost two times the emissions caused by natural gas, however hydrogen which was produced from strictly renewable energy sources is recognized to produce exactly 0 kg of carbon dioxide (Otto, 2017). The Austrian researchers had similar findings in their work. During the production of steel through direct iron ore reduction and EAF, the researchers determined there were 520 and 160 kg carbon dioxide per ton of crude steel produced while using natural gas and hydrogen, respectively. While both of these are impressive improvements over the BF-BOF's emissions of 1,830 kg carbon dioxide per ton, the reduced levels of emission from natural gas is insufficient to meet international carbon reduction goals (Conde, 2021). On the other hand, while there is promise for hydrogen to reduce carbon over BF-BOF by 90%, the potential environmental impact of using hydrogen in steel production is very dependent upon the source of electricity. While the world continues to develop, and energy requirements increase, it has yet to be seen if renewable energy sources will be able to satisfy the world's needs. Hydrogen gas has the potential to reduce the steel industry's pollution to international goals, something natural gas has been unable to prove to do, however it can also have the opposite effect if renewable sources are not able to provide sufficient electricity.

One aspect of having a positive environmental impact is having a small and maybe more importantly, sustainable carbon footprint. As already mentioned, the production of hydrogen through the electrolysis of water is an incredibly energy intensive process. The extent to which this process impacts the environment is dependent on the accessibility of renewable energy sources. This is in comparison to natural gas, which has a more well defined environmental impact. Regardless of one's fearfulness towards the unknown, or lack thereof, natural gas has another limiting factor that comes into play when considering its environmental sustainability. The United States Energy Information Administration estimated that as of January 1, 2020 there are approximately 205 trillion cubic meters of accessible natural gas reserves left in the world (US EIA, 2021). While this may seem like an almost unlimited supply of natural gas, it is important to realize our world's current dependence on this resource. Statista, which is a leading market and consumer data company, has tracked the annual global consumption of natural gas over the last 20+ years. Figure 10 shows the year by year trend of natural gas consumption in billions of cubic meters.

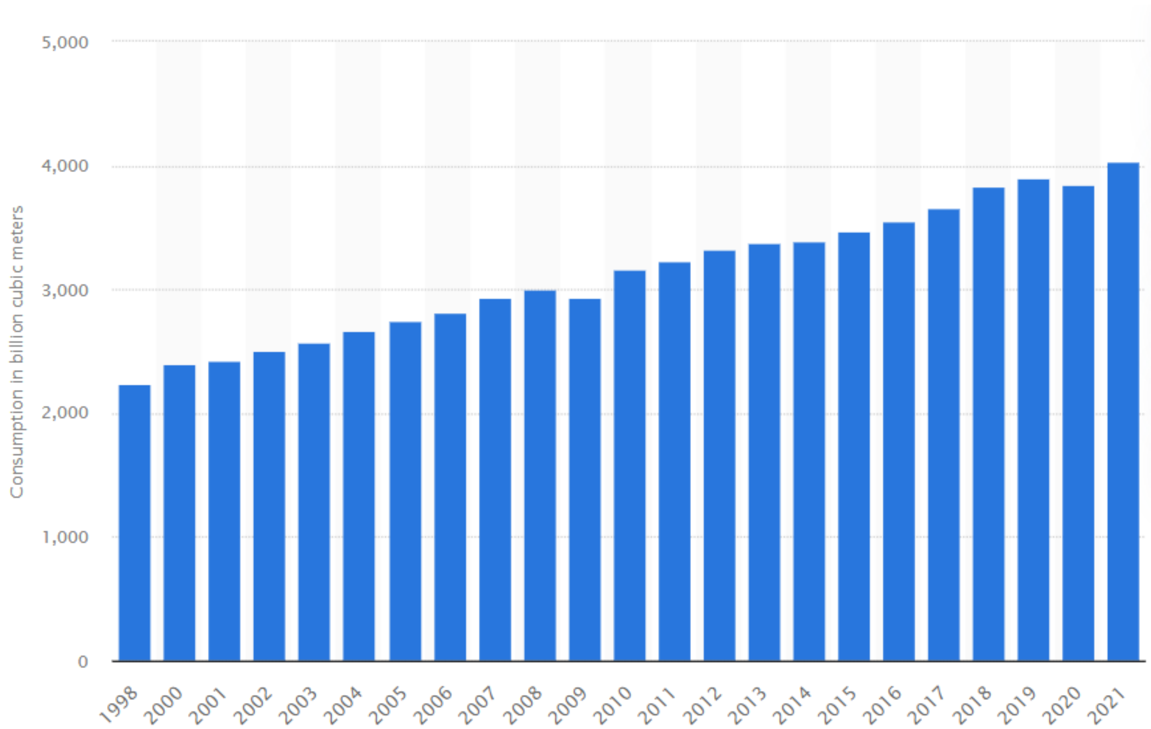

Figure 10: A global natural gas consumption bar chart. The annual global natural gas consumption steadily increases over time with a peak in 2021 of 4 trillion cubic meters (Sonnichsen, 2022).

The graph shows a linearly increasing trend of natural gas consumption with a peak use of 4.04 trillion cubic meters during 2021. By taking the estimated amount of natural gas reserves and dividing it by last year's usage, one finds that there are only 50 years left before we run out of natural gas. If one then decides to incorporate the increasing trend, which has shown incredible stability, the answer suddenly approaches the 30 year mark at which point the reserves will be emptied, and natural gas-based production is not even an option.

5. Recommendation

Based on the initial analysis of the fuel production efficiency, cost of large-scale implementation, and total carbon dioxide emissions associated with green hydrogen and natural gas in primary steelmaking, Table 1 describes the rankings of the observed technology for the chosen criteria. The rank scale ranges from one to three, with one being the least favorable and three being the most favorable option within the respective criteria. Criteria are ranked based on the quantitative and qualitative data from the comparative analysis in Section 4. Weight percentages accompany each criterion to account for the relative importance of the criteria towards the technology's overall feasibility and environmental impact.

Notably, the carbon dioxide emissions criteria hold the highest weight relative to other criteria due to the enormous economic and environmental incentive to address global climate change. The surplus of carbon dioxide is the main contributor to the greenhouse effect and is considered a negative externality of human activity with a high indirect social cost, as discussed in Section 1. Global powers recognize the impact of carbon dioxide emissions on current environmental systems and the destruction they can cause for generations if not addressed as soon as possible. Hence, the Paris Agreement created an incentive to become carbon neutral by 2050 (UNFCCC, 2015). Also, a key industry in the push for green steel is the automotive industry, as they strive for cleaner vehicle manufacturing (Muselmani, 2022). For these reasons, carbon dioxide holds the highest impact on the total rank in this comparative analysis. The winner in this respect is green hydrogen, which has practically zero carbon emissions per tonne of steel. On the other hand, natural gas produces 119 kg of carbon dioxide per gigajoule of syngas (Otto, 2017).

Furthermore, the cost of large-scale implementation has a thirty percent weighting because cost-effectiveness is a critical component of overall feasibility. Cost of implementation relates to all infrastructural adaptions required for each fuel to be implemented, along with considering fuel production costs. From Section 4.2, the research concludes that hydrogen in steelmaking plants is adaptable to the current shaft furnace infrastructure that is used with fossil-based fuels. Nevertheless, producing one tonne of steel made with green hydrogen is 675 dollars, whereas natural gas costs 495 dollars (Conde, 2021). The notable cost difference between hydrogen and natural gas arises in the production of the fuel itself. Green hydrogen availability is scarce and, therefore, far more expensive than natural gas because of inefficiencies in renewable energy systems and electrolysis powered by renewable electricity. With natural gas being roughly thirty percent cheaper than hydrogen currently, natural gas is the preferred option regarding the cost of large-scale implementation criterion.

Production efficiency is weighted identically to the cost of implementation because of the crucial need for the availability of fuel in an energy-intensive industry. This criterion entails the efficiency of fuel production and the number of intermediary processes from the fuel to the reducing agent. From Section 4.1, natural gas requires an additional reformation into syngas, a mixture of carbon monoxide and hydrogen, as the reducing gas before entering the shaft furnace, which creates the direct reduced iron. On the other hand, once hydrogen is produced, it can be applied directly into the shaft furnace. The fact that hydrogen requires fewer chemical processes before being used as a reducing agent makes the technology more efficient than natural gas in this respect. However, the efficiency of producing hydrogen through electrolysis is 70%, while the reformation of natural gas is 84% efficient. Although natural gas has an additional chemical process, the process is far more efficient than electrolysis when scaled, as mentioned in Section 4.1. Given these points, natural gas ranks most favorably in production efficiency due to higher availability when compared to green hydrogen.

Table 1: A decision matrix comparing natural gas and green hydrogen. The table compares natural gas and hydrogen as the primary reducing agent to produce direct reduction iron in the shaft furnace.

	Carbon dioxide emissions		**Cost of implementation**		**Production efficiency**			
	Weight	40%	**Weight**	30%	**Weight**	30%		
Energy source	**Rank**	**Wtd Rank**	**Rank**	**Wtd Rank**	**Rank**	**Wtd Rank**	**Total**	**Wtd Total**
Green Hydrogen	3	1.2	1	0.3	1	0.3	5	1.8
Natural Gas	1	0.4	3	0.9	3	0.6	**6**	**1.9**

After analyzing the feasibility of natural gas and green hydrogen as the reducing agent for DRI, natural gas seems to be the most effective fuel source in the short term as the industry moves toward carbon-neutral. Despite minimal infrastructural changes needed when switching from natural gas to hydrogen in DRI shaft furnaces, sourcing green hydrogen is the fundamental limitation in this comparison.

6. Conclusion

The race to neutralize carbon emissions in the steel industry by 2050 calls for the quick implementation of effective breakthrough technologies. Although recent advances have been initiated to significantly reduce emissions, such as recycling scrap steel and replacing coal-powered furnaces with electrically-powered electric arc furnaces, these advances fail to make the full leap to carbon-neutral production. That being said, green hydrogen is a top prospect in creating such deep emission reductions in the industry by eliminating carbon dioxide production. Green hydrogen is produced through electrolysis which uses electricity from renewable energy systems, such as wind and solar. Hydrogen fuel can be used as both a reducing agent and heat source in steel furnaces, replacing all functions of fossil-based fuels to produce green steel. The report proposes and analyzes the novel application of green hydrogen-based steel production as a potential route toward a carbon-neutral steel industry and draws a comparison with the natural gas alternative.

Based on Section 5, natural gas is the best immediate solution for carbon-free steelmaking. Despite the carbon dioxide emissions associated with natural gas, replacing the conventional method, coal in BF-BOF, with natural gas for DRI-EAF will decrease direct carbon dioxide emissions by 75% (Conde, 2022). While green hydrogen in steelmaking would theoretically reduce emissions entirely, implementing this technology is not feasible due to the related energy and cost challenges. The prerequisite of using green hydrogen within the vast steel industry is easy to access to green hydrogen via electrolysis. Therefore, the decarbonization of electricity must be addressed before considering the commercial implementation of hydrogen-based steelmaking so that net-zero carbon emissions are ensured. Additionally, the high costs associated with carbon-neutral electrolysis to fulfill the energy-intensive demands of the steel industry make green hydrogen technology prohibitive.

According to leading steel producers, the steel industry is set to transition to hydrogen-based production within the next decade. For instance, SSAB, a major North American steel supplier, is in the final years of Feasibility Study pilots and running pilot plants for hydrogen-based steelmaking. At this point, SSAB has already proven green hydrogen as an alternative fuel to reduce iron ore into crude steel and plans to make all operations carbon-free by roughly 2030, according to Figure 11 (SSAB, 2022).

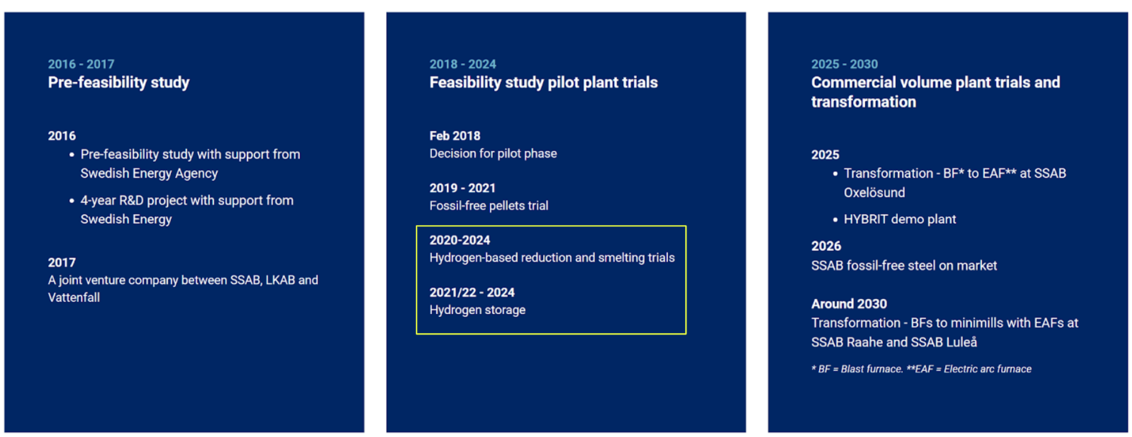

Figure 11: SSAB's timeline for fossil-free steelmaking. SSAB established the first green hydrogen-based direct reduction pilot plant in 2020 and a hydrogen storage facility in 2022. SSAB plans to produce fossil-free steel commercially by 2026 and fully transform their operations to green steelmaking by around 2030 (SSAB, 2022)

Based on this technical report, scaling green hydrogen steelmaking to meet the demand for the steel industry presents the most significant hurdle ahead. Therefore, prioritizing development and extensive research to make renewable electricity cheap and the up-scaling of electrolyzers is required to make commercial green hydrogen production economically viable. As the industry plans the transition into green steel production, intermediate solutions, like natural gas and electric arc furnaces, should be implemented in the meantime to allow greenhouse gas emission levels to improve significantly and a smoother shift to green infrastructure.

Alternatives involving readily available and cleaner fuels must be considered during the industry's transition stages to a fully decarbonized industry. Given coal's high carbon footprint on the steel industry, natural gas stands as a cleaner alternative. If natural gas or green hydrogen were not implemented, the greenhouse effect would continue to magnify, leading to global destruction, including a health crisis, food shortages, and more extreme natural disasters (Kweku, 2018). With that said, as hydrogen technology continues to develop to confront barriers to implementation, we must continue to consider the better alternative to address the ethical issue of global pollution. Even though natural gas is the best solution to implement today in quelling rising carbon emissions, natural gas is not a sustainable option in the long run as demand and energy needs are forecasted to increase. The long-term implications on carbon emissions, rising carbon tax, and relying on fossil fuels can make natural gas unfeasible in the future. In the end, reducing emissions in steelmaking is crucial to fight against the climate crisis.

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