McKinsey & Company

Decarbonization challenge for steel

Hydrogen as a solution in Europe

The steel industry decarbonization challenge

Steel is one of the core pillars of today's society and, as one of the most important engineering and construction materials, it is present in many aspects of our lives. However, the industry now needs to cope with pressure to reduce its carbon footprint from both environmental and economic perspectives. Currently the steel industry is among the three biggest producers of carbon dioxide, with emissions being produced by a limited number of locations; steel plants are therefore a good candidate for decarbonization. While the industry must adapt to these new circumstances, it can also use them as a chance to safeguard its license to continue operating in the long term.

In 2015, the global response to the threat of climate change took a step forward when 190 nations adopted the Paris Agreement. In 2019, the United Nations announced that over 60 countries – including the United Kingdom and the European Union (with the exception of Poland) – had committed to carbon neutrality by 2050, although the three principal emitters China, India, and the United States were not among that number.[1] Moreover, some nations have pledged to work toward earlier dates. Together, these agreements have led to growing pressure to pursue decarbonization across all industrial sectors.

Every ton of steel produced in 2018 emitted on average 1.85 tons of carbon dioxide, equating to about 8 percent of global carbon dioxide emissions.[2] Consequently, steel players across the globe, and especially in Europe, are increasingly facing a decarbonization challenge. This challenge is driven by three key developments that go beyond the Paris Agreement:

1. **Changing customer requirements and growing demand for carbon-friendly steel products.** A trend that has already been observed in various industries, including the auto industry where manufacturers such as Volkswagen or Toyota have the ambitious aim of eliminating carbon emissions completely from their entire value chains (including their suppliers) and taking on a full life cycle perspective.
2. **Further tightening of carbon emission regulations.** This is manifested in carbon dioxide reduction targets, as well as rising carbon dioxide emission prices as outlined in the European Green Deal.
3. **Growing investor and public interest in sustainability.** For example, the Institutional Investors Group on Climate Change, a global network with 250-plus investors and over USD 30 trillion in assets under management, has raised expectations for the steel industry to safeguard its future in the face of climate change. At the same time, global investment firm BlackRock has confirmed its commitment to environmentally responsible business development and sustainable investing.

1 Climate Action Summit 2019, *Report of the Secretary-General on the 2019 Climate Action Summit and the Way Forward in 2020*, UN.org.
2 World Steel Association.

Recent studies estimate that the global steel industry may find approximately 14 percent of steel companies' potential value is at risk if they are unable to decrease their environmental impact.[3] Consequently, decarbonization should be a top priority for remaining economically competitive and retaining the industry's license to operate. Moreover, long investment cycles of 10 to 15 years, multibillion financing needs, and limited supplier capacities make this issue even more relevant and lock in significant lead times for addressing the decarbonization challenge.

In response, decarbonization measures such as establishing or switching to hydrogen-based (H_2) steel production can be implemented either in forthcoming (greenfield) sites or existing (brownfield) facilities.[4] The latter opportunity requires existing equipment to either be retrofitted or for the facility to possibly be completely rebuilt in order to implement a decarbonized production process. The optimal steps to decarbonization will differ by location and site, depending on the likes of technical feasibility, existing infrastructure, market demands, operating costs (i.e., the price of renewable electricity, the price of scrap), and the regulatory environment.

14%

of steel companies' potential value is at risk if they are unable to decrease their environmental impact

3 Study of 20 global steelmakers. The weighted average value at risk for the sample is 14 percent of net present value under a 2°C scenario, where global carbon prices rise to USD 100 per ton of carbon dioxide. Results range from 2 percent to 30 percent for individual companies.

4 For example: retrofitting existing EAF plants for hydrogen-based steel production.

Technology landscape for decarbonization in steel production

Going forward, steel producers need to assess, evaluate, and decide on a technologically and economically viable way to decrease their carbon footprint.

Steel can be produced via two main processes: either using an integrated blast furnace (BF)/basic oxygen furnace (BOF) or an electric arc furnace (EAF). While integrated players produce steel from iron ore and need coal as a reductant, EAF producers use steel scrap or direct reduced iron (DRI) as their main raw material. As the predominant production method in Europe is the conventional, coal-dependent BF/BOF process, the need to assess alternative breakthrough technologies to reduce carbon dioxide emissions is high. Indeed, almost all European steel producers are currently developing decarbonization strategies and running pilot plants to assess different production technologies (Exhibit 1). These include:

BF/BOF efficiency programs. Such programs improve efficiency and/or decrease production losses in different ways, for example: 1) optimizing the BF burden mix by maximizing the iron content in raw materials to decrease the usage of coal as a reductant, 2) increasing the use of fuel injection through, for example, pulverized coal injection (PCI), natural gas, plastics, biomass, or hydrogen (as an additional reagent on top), or 3) using coke oven gas in the BF as an energy source, just to name some of the options. These processes may have the potential to decrease carbon dioxide emissions without eliminating them, but do not offer fully carbon-neutral steel production.

Biomass reductants. This process uses biomass, such as heated and dried sugar, energy cane, or pyrolyzed eucalyptus, as an alternative reductant or fuel. As such it is regionally dependent and mainly important in areas where the biomass supply is guaranteed, like in South America or Russia. In Europe, the availability of biomass is likely not enough to reduce carbon emissions on a large scale.

Carbon capture and usage.[5] This uses emissions to create new products for the chemical industry, such as ammoniac or bioethanol. At present, carbon capture and usage remains technologically premature and yet to be proven economically.

Increase share of scrap-based EAFs. This process maximizes secondary flows and recycling by melting more scrap in EAFs. EAF producers are more environmentally friendly and flexible to the ups and downs of demand. However, shifting to EAF-based steel production requires the future supply of renewable electricity to be commercially available, as well as a sufficient supply of high-quality steel scrap. High quality scrap is necessary for the production of high-quality products, which are nowadays mainly produced through the integrated route. If high-quality scrap is not available, lower-quality scrap can be mixed with DRI to ensure a high quality EAF input.[6] Increasing the share of EAF-based steel production will play a key role in decarbonizing the steel industry. However, this role will be dependent on the regional availability of high-quality scrap and could therefore be limited in regions with an inadequate supply of high-quality scrap, making other technologies a must. Increasing demand for high-quality scrap will also lead to extra cost for the EAF-based steel production.

5 Carbon capture and storage not further detailed as political/regulatory approval is uncertain across different regions due to potential insecurities during storage.
6 The exact scrap/DRI ratio depends on the scrap quality and end product.

Optimize DRI and EAF. This requires boosting usage of DRI in combination with EAF. DRI-based reduction emits less carbon dioxide than the integrated method and enables the production of high-quality products in the EAF. High-quality products require the highest quality of steel scrap; if scrap is limited, the use of DRI is necessary to guarantee specific qualities. DRI production requires cheap and readily available natural gas. Thus, regions with low natural gas prices – the Middle East or North America – are big DRI producers whereas the process is less common in Europe. Selected European steel players import Hot Briquetted Iron (HBI, a less reactive and therefore transportable form of DRI) to use either in the BF to optimize the burden mix or in the EAF where they mix it with scrap in order to increase quality.

DRI and EAF using hydrogen. This uses green hydrogen-based DRI and scrap in combination with EAFs. The process replaces fossil fuels in the DRI production stage with hydrogen produced with renewable energy. It represents a technically proven production method that enables nearly emission-free steel production. All major European steel players are currently building or already testing hydrogen-based steel production processes, either using hydrogen as a PCI replacement or using hydrogen-based direct reduction. At this point it is important to note that EAF-based steel production will not require a completely green hydrogen-based DRI supply to be able to fulfill current customer requirements and achieve carbon neutrality.

As BF/BOF efficiency programs only result in a reduction in carbon dioxide emissions, without eliminating them entirely, they cannot be a long-term solution. Biomass reductants and carbon capture and usage are either only feasible in certain regions or still in the early stages of development. The share of EAFs producing high-quality steel will increase but requires the availability of scrap and DRI. Hence, adopting an approach combining scrap, DRI, and EAF using hydrogen is currently considered the most viable option and the long-term solution to achieving carbon-neutral steel production, especially in Europe.

Exhibit 1: Steel producers are evaluating decarbonization strategies

Focus of this document

	CO_2 reduction			Full decarbonization possible		
	Blast furnace efficiency (BOF)	**Biomass reductants**	**Carbon capture and usage**	**Electric arc furnace (EAF)**	**DRI plus EAF using natural gas**	**DRI plus EAF using H_2**
Strategy	Make efficiency improvements to optimize BF/BOF operations	Use biomass as an alternative reductant or fuel	Capture fossil fuels and emissions and create new products	Maximize secondary flows and recycling by melting more scrap in EAF	Increase usage of DRI in the EAF	Replace fossil fuels in DRI process with renewable energy or H_2
Examples	Optimized BOF inputs (DRI, scrap), increased fuel injection in BF (e.g., hydrogen, PCI)	Tecnored process	Bioethanol production from CO_2 emissions	EAF – usage to melt scrap	Current DRI plus EAF plants using natural gas (NG)	MIDREX DRI process running on H_2 HYL DRI process running on H_2
Current outlook	Technology readily available at competitive cost	Process possible in South America and Russia, due to biomass availability	Not available on an industrial scale	Technology readily available at competitive cost	Technology readily available	Technology available at high cost

SOURCE: McKinsey analysis

Green hydrogen-based steel production as a silver bullet?

Although hydrogen is one of the most abundant elements on earth, in its pure form it is rare. Extracting hydrogen from its compounds requires a lot of energy. Although these energy sources can be diverse, the most popular hydrogen production method is carbon dioxide intensive. Most of the world's hydrogen production consists of "grey hydrogen," produced via steam methane reforming (SMR), which forms both hydrogen and carbon dioxide. In contrast, the term "blue hydrogen" is reserved for hydrogen production that involves carbon capture and usage or the storage of emitted carbon dioxide. Additionally, the electricity-intensive electrolysis of water is yet another process for producing hydrogen and is the only carbon-neutral technique (provided that renewable energy sources can be used); this is known as "green hydrogen."[7]

There are generally two ways to use (green) hydrogen in steel production. First, it can be used as an alternative injection material to PCI, to improve the performance of conventional blast furnaces. Although the use of PCI is common, the first pilot plants using hydrogen injection have recently been set up to assess decarbonization potential. However, while the injection of (green) hydrogen into blast furnaces can reduce carbon emissions by up to 20 percent, this does not offer carbon-neutral steel production because regular coking coal is still a necessary reductant agent in the blast furnace.

Second, hydrogen can be used as an alternative reductant to produce DRI that can be further processed into steel using an EAF. This DRI/EAF route is a proven production process that is currently applied using natural gas as a reductant, for example by players in the Middle East with access to a cheap natural gas supply. However, the direct reduction process can also be performed with hydrogen. Based on the use of green hydrogen as well as renewable electricity from wind, solar, or water, a DRI/EAF setup enables nearly carbon-neutral steel production.

In more detail, a large-scale, green hydrogen-based DRI/EAF steel production process involves the following core process steps:

1. **Green hydrogen production.** Green hydrogen is produced by electrolyzing water in a process that requires significant amounts of electricity. Obtaining sufficient electricity from renewable energy sources will be the key challenge for green hydrogen production in Europe.

2. **DRI production.** In the DRI plant, iron ore in the form of DR pellets[8] is reduced with hydrogen in order to form DRI.[9] Using hydrogen as the reductant releases only water (i.e., it does not produce carbon emissions).

3. **Raw steel production using an EAF.** In the EAF, the DRI is heated and liquified together with steel scrap to produce raw steel. The use of electricity in this process (assuming it is from renewable sources) does not lead to any carbon emissions.

7 Hydrogen Europe, US Office of Energy Efficiency and Renewable Energy.
8 Production of DR pellets is not entirely carbon neutral due to natural gas or oil residues used in baking.
9 Hydrogen 5.0 with a purity of >99.999 percent needed as a reduction agent in the DRI.

The key cost drivers for the pure hydrogen-based production process, i.e., maximum use of green hydrogen-based DRI, are similar to those of the EAF process, and include raw materials and electricity as well as processing and labor costs. The biggest cost differences and uncertainties are the generation of hydrogen (mainly determined by the electricity costs for water electrolysis) and running the EAF and caster on renewable energy.

Green hydrogen prices today are high, but these are expected to decrease rapidly over time (Exhibit 2).

Historically, gas used for grey hydrogen production was cheaper than renewable electricity for green hydrogen production, such that electrolysis has been rarely used in the past. Today, grey hydrogen is less than half the price of green hydrogen; however, prices are expected to turn around by 2030. This decline in price for green hydrogen is driven by:
a) lower renewable electricity costs driven by lower prices for solar and wind energy, and
b) falling costs for electrolyzers. The falling costs for electrolyzers are based on scaled up production, learning rate, and an increase in system size from 2 to 90 MW as well as efficiency improvements. As a result, green hydrogen is predicted to become significantly cheaper. Grey hydrogen prices will suffer as a result of increasing penalties for carbon dioxide emissions. The price outlook for blue hydrogen is relatively stable.

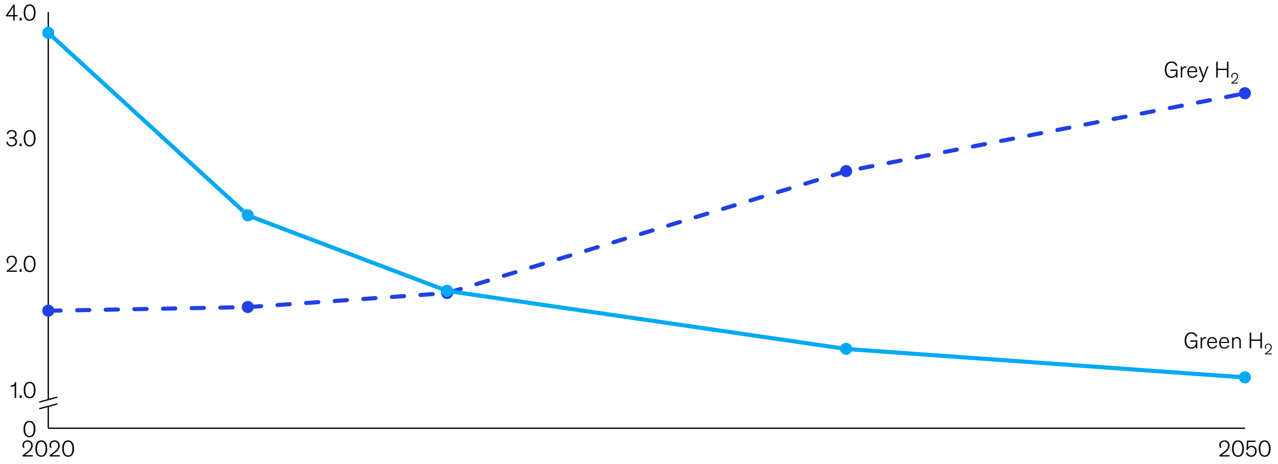
To assess the holistic economic competitiveness of pure green hydrogen-based steel production compared to conventional blast furnace production, one also needs to consider the cost of carbon dioxide.

In Europe, the EU emissions trading system (EU ETS) pursues a cap-and-trade strategy. The total amount of greenhouse gases that companies within the EU ETS can emit is limited by an industry-specific "cap" on the number of emission allowances. Over time, the cap is reduced, and total emission allowances fall. Within the cap, companies can receive or buy allowances. Every year, companies must relinquish all their allowances to cover their emissions, otherwise heavy penalties are imposed. Carbon dioxide prices are expected to significantly increase until 2050 and will be highly dependent on political regulations in every EU country. At the end of 2019, the average price of carbon dioxide in Europe was EUR 25/ton. Germany has already announced prices in the range of EUR 55 to 65/ton after 2026[10] and, by 2050, carbon dioxide prices in the range of EUR 100 to 150/ton could be a reality in Europe.

10 For the transport and buildings sector

Exhibit 2: Green hydrogen prices are expected to halve over the next ten years

H_2 price development, Germany, EUR/kg H_2



SOURCE: Hydrogen Council

Further, the cost competitiveness assessment of hydrogen-based steel is only viable if the capex implications (depreciation) are excluded, as conventional steel production assets are largely written off. However, capex requirements for the setup of pure hydrogen-based steel production (DRI plus EAF) in combination with the required hydrogen transport and storage will be significant. Surging carbon dioxide prices and decreasing hydrogen prices are crucial to ensuring the economic viability (according to cash cost) of pure hydrogen-based steel production. For this, renewable electricity prices need to fall below a threshold of approximately EUR 0.027/kWh to ensure cost-effective production of green hydrogen (Exhibit 3).

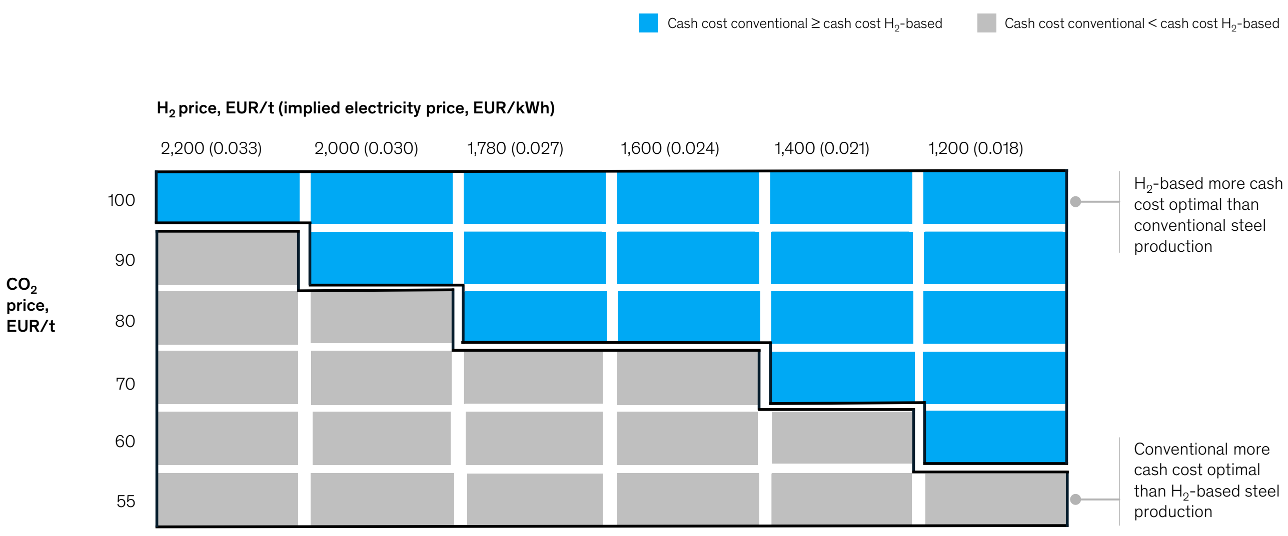
With expected carbon dioxide prices of around EUR 55/ton and hydrogen prices of some EUR 1,780/ton (implied electricity price at EUR 0.027/kwh) in 2030, conventional steel production still retains a cash cost advantage. However, this scenario changes as soon as hydrogen prices drop (driven by the cost of electricity) or carbon dioxide prices increase. Following this logic, pure hydrogen-based steel production is expected to be cash cost competitive between 2030 and 2040 in Europe.[11] As a consequence – and leaving aside environmental issues and any potential public concerns and investor fallout from not meeting carbon dioxide emission targets – the industry is likely to see the first large-scale replacements of integrated production facilities with DRI and EAF setups in Europe.

In this context it is important to note that a complete transition to a pure hydrogen-based steel production will not be needed to achieve the goal of a carbon-neutral steel industry. Instead, hydrogen-based steelmaking will represent one key production technology to replace the current integrated BOF route (likely with a focus on the share of high-quality products produced using the integrated BOF route) together with other production technologies such as the extended use of scrap-based EAFs. This mix will result in lower operating costs (as highlighted above for the pure hydrogen-based steel production), reduced investment needs, and will enable carbon-neutral steel production.

11 Cost competitiveness assessment of hydrogen-based steel is only viable if capex implications, i.e., depreciation, are excluded, as conventional steel production assets are largely written off.

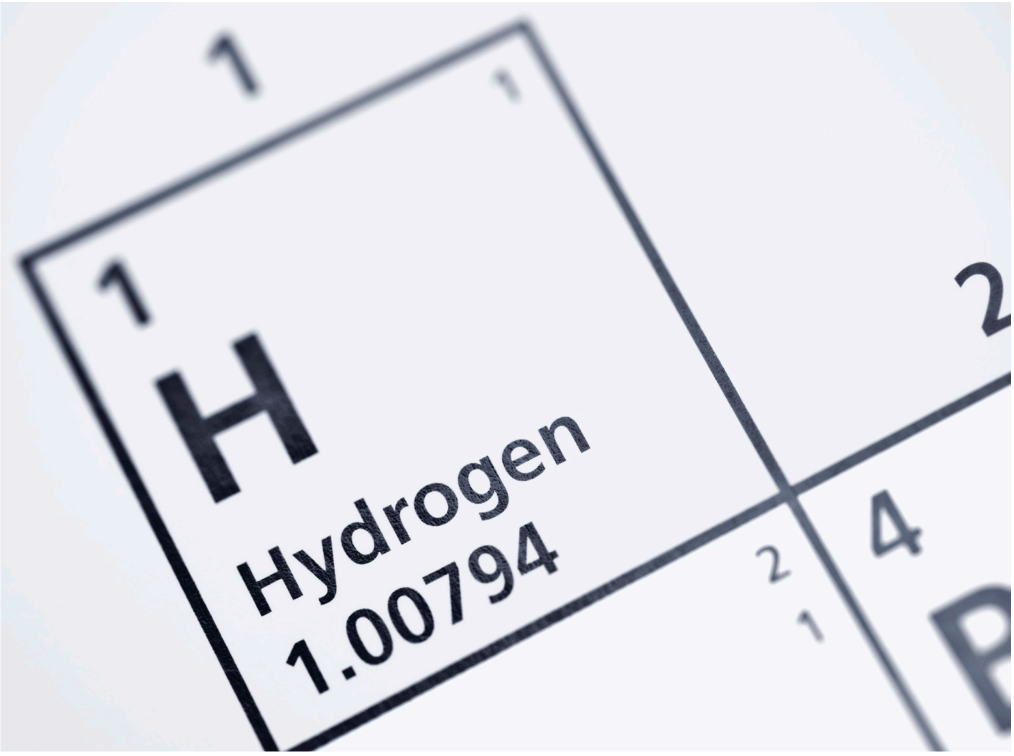
Exhibit 3: Cost competitiveness of pure hydrogen-based steel production based on hydrogen cost decline and carbon dioxide price rise

Sensitivity analysis of cash cost, excluding depreciation (for H_2 and CO_2 only)



SOURCE: McKinsey hydrogen-based steel model

“Hydrogen-based steelmaking will represent one key production technology”



Potential path forward for steel players in Europe

Today, hydrogen-based steel production using an EAF is technically feasible and already considered to be part of a potential long-term solution for decarbonizing the steel industry on a large scale. The question is not whether but when and to what extent this transformation will happen. However, there are a variety of interdependent factors that will determine when the decarbonization tipping points will occur in the steel industry. We have identified six external factors that will shape the future development and time to adoption of green hydrogen-based steel:

1. **Power supply.** Green hydrogen-based steel creates a need for a significant capacity increase in electricity derived from renewables. To put this into perspective, the total energy required to produce two million tons of hydrogen-based steel is about 8.8 TWh, which equates to the output from 300 to 1,100 wind turbines (depending on the output capacity of current and future turbines).[12] Hence, availability, steady supply, and competitive renewable energy costs are key decisive factors for the technology shift.
2. **Hydrogen-supply security.** The future shift to hydrogen-based steel relies heavily on the broad availability of green hydrogen on an industrial scale. Producing two million tons of hydrogen-based steel requires a green hydrogen amount of 144,000 tons. A capacity of 900 MW, or nine of the world's largest planned electrolysis plants producing 100 MW (for example those in Hamburg), are needed to produce this amount of green hydrogen. Hence, providing the required production capacity and infrastructure for hydrogen-based steel production on a large scale has a significant impact on the timeline for the commercial availability of hydrogen-based steel. Furthermore, green hydrogen prices, largely driven by renewable electricity, must decrease simultaneously to make the economics work, linking hydrogen supply security to the importance of renewable power supply. Finally, other industries and applications will compete for green hydrogen as it is likely going to be a scarce resource. To produce steel in Europe it will, however, be important to clarify that hydrogen needs to be leveraged to stay a player in the arena.
3. **Raw material.** To switch production from BF/BOF to DRI/EAF using hydrogen, raw material changes are necessary and will especially increase demand for DR pellets. The security of DR supply in the case of a massive switch to hydrogen-based steel production is uncertain and could result in rising price premiums, negatively affecting the economics of the new production method. Moreover, to guarantee carbon neutrality throughout the whole value chain, tight cooperation with steel suppliers, such as the iron ore industry, is essential.
4. **Production technology.** The basic production method for DRI/EAF powered with natural gas is already established and working on a large scale in certain markets that benefit from an abundant supply of cheap natural gas. Moving forward, switching the process to an entirely hydrogen-powered process is technically feasible, although the overall cost is still high, and the technology has yet to be proven on a large scale. On the upside, however, it is considered relatively easy to switch a DRI/EAF production method powered by natural gas over to hydrogen. Also, flat steel producers in North America have shown that even high-quality products can be produced via the DRI/EAF method.

12 Assuming approximately 3.5 and 13.0 MW installed capacity per wind turbine, respectively. Assumed utilization 25 percent.

5. **Willingness to pay.** Considering steel's vital role in the global economy, customer support, acceptance, and eventually demand are required for the success of green hydrogen-based steel. Only if customers value carbon-reduced/neutral products, and are willing to pay for decarbonization, can this shift in production technologies happen. End user industries show a growing interest in carbon-reduced/neutral steel products to decarbonize their own value chain, in combination with a willingness to pay a price premium, also driven by recent discussions on Ecolabel approaches by the European Commission. Alternative to this would be a legislative intervention that takes the balance of benefits and extra cost into account. Given the nature of emissions it is clear that this regulatory initiative requires focus on regional production as well as on imports.

6. **Regulation.** The economics of increasing the share of hydrogen-based steel are dependent on continuing political momentum for decarbonization via measures such as carbon dioxide pricing and carbon border tax to avoid carbon leakage. Equally important is the provision of start-up capital and subsidies for initial investments to compensate for the capex requirements of the technological shift. Depending on scale, a plant based around DRI and EAF using hydrogen would have significant capex requirements. Therefore, this technological shift is dependent on a collaborative effort between regulators, governments, and industry stakeholders to facilitate access to required capital and to eliminate potential red tape.

Taking stock, the shift toward hydrogen-based steel cannot happen overnight and is only one key production technology that can be leveraged to achieve a carbon-neutral steel industry. Future availability of cheap energy from renewables and regulation will be the two key drivers for the adoption of hydrogen-based steel. Despite the goal of becoming carbon neutral (in Europe) still being 30 years in the future, it is crucial to act now: industrial sites have lifetimes exceeding 50 years and investment planning horizons of 10 to 15 years. Asset and footprint decisions need to be made today and must follow a clear decarbonization road map. The road map itself must combine long-term goals with actionable quick wins to allow for a gradual shift toward decarbonization that keeps all stakeholders on board. In Europe, green hydrogen-based steel production is likely to become one key technology that shapes the route to decreasing emissions – this could entail first optimizing BF/BOF processes, then switching to EAF using scrap and DRI powered with natural gas or imported HBI – and ultimately adopting carbon-neutral EAF production using a mix of scrap and hydrogen-based DRI. The mix of scrap versus DRI-based production using EAFs will depend on future product portfolios. The DRI method using hydrogen will be key to enabling the production of high purity steel grades in the future without the emission of carbon dioxide. As such, hydrogen-based steel is an opportunity to secure the future production of steel in Europe.

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