Hydrogen steelmaking for a low-carbon economy

A joint LU-SEI working paper for the HYBRIT project

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Contents

Executive summary

Steel production accounts for approximately 7 percent of global carbon dioxide emissions. To meet the targets set by the 2015 Paris Agreement, the steel sector must go through a systemic change that involves the full value chain, from production to recycling. The largest share of emissions in this chain comes from the production of virgin steel from iron ore in blast furnaces (BF). Reducing demand for virgin steel by increasing scrap use could be one part of the solution, but even with increased recycling, the global demand for virgin steel is likely to remain or even increase with growing prosperity. High quality virgin steel is also needed to build the advanced technologies and infrastructures necessary in a future low-carbon society. Technical solutions to eliminate emissions from ore-based steelmaking are necessary. For the EU steel industry, the long-term target compatible with the Paris Agreement is to reduce emissions to practically zero by 2050 at the latest.

In the spring of 2016, three Swedish companies – LKAB (iron ore mining), SSAB (steel manufacturer) and Vattenfall (power utility) – announced their ambition to develop and implement a novel process for fossil-free steel production in Sweden. This process would use hydrogen (instead of coal) for the direct reduction of iron oxide/ore (H-DR), combined with an electric arc furnace (EAF). It would be almost completely fossil-free when the hydrogen is produced from electrolysis of water by use of renewable electricity. The concept is called Hydrogen Breakthrough Ironmaking Technology, or HYBRIT for short.

This report provides an overview and analysis of the H-DR concept and the key aspects that makes it a promising route for decarbonisation of the steel industry. The overall objective is to identify key factors – technical, economic and political – that need to be better understood in order to develop industrial strategies and public policies for decarbonizing the steel industry.

Though focused on the H-DR route, this analysis includes a brief comparison with a carbon capture and storage (a BF/CCS route) alternative, as well as a discussion on the role of biomass in future steelmaking. The transition to fossil-free H-DR steel does not require fundamental breakthrough technologies, even if it represents a major systemic change in terms of replacing the current BF route. The production cost for fossil-free H-DR steel looks promising, although its cost competitiveness with the BF/CCS route depends on the prices of electricity and CO_2 emission credits, as the main cost driver for the H-DR route is the renewable electricity price.

The H-DR route offers opportunities for high production flexibility through storage of hydrogen and hot briquetted iron, as well as varying the shares of scrap used. It may also offer the benefit of technology spill-overs in the fields of electrolysis and hydrogen. However, additional biomethane or other energy carriers will be needed for heating and rolling if the H-DR route is chosen, as the off-gases from the coke oven would no longer be available for process heating.

Although the prospects for H-DR look promising, the risks involved for individual companies to demonstrate and invest in fossil-free steel production mean that public policy measures could be necessary to enable this transition. Our analysis indicates that these risks are political, rather than technical; success depends on how future markets and carbon prices evolve, and how climate and energy policy is implemented. We also identify several barriers to this systemic change, including the de-risking of demonstration projects, uncertain future market demands, carbon leakage risks, infrastructure development needs and a lack of proper regulatory frameworks.

The development of climate-friendly steel in the EU is governed and supported by several policy frameworks pertaining to climate and energy, innovation and industry, and international trade. Within this frame, member states also have their own innovation and industrial policies that complement those at the EU level. How these policies can be aligned to properly address the systemic barriers needs to be understood. Both the policy framework and company strategies need to co-evolve with technical development towards a common realistic vision.

The EU climate and energy policy has a legally binding target in 2030 and an aspirational target for 2050. In order to achieve these targets, EU innovation policy needs to be developed so that risks and benefits are fairly shared between private and public stakeholders and in a way that allows for transparency

and accountability. Fossil-free steel most likely will be more expensive than current steel production. Consequently, market segments that are willing to pay a premium for green steel products – such as fossil-free cars or materials for public infrastructure – may be important complements to carbon pricing and other policies. However, such options are still relatively unexplored by companies, policy-makers and academia. As a climate leader, the EU must deal with the issue of trade and carbon leakage for the globally competitive steel industry. It has a strong climate policy rationale to develop fossil-free steel production technology and spread it globally, which could in the long term give EU steel, electrolysis and hydrogen companies a competitive advantage.

1. HYBRIT in context: a sustainability transition in the steel sector

1.1 HYBRIT

In the spring of 2016, the Swedish companies LKAB, SSAB and Vattenfall announced their ambition to develop and implement a fossil-free steel production process in Sweden. This process would replace coal with hydrogen for the direct reduction of iron, combined with an electric arc furnace. It would be almost completely fossil-free, and if fully deployed, Sweden could see a 10% reduction in its greenhouse gas emissions. The concept is called Hydrogen Breakthrough Ironmaking Technology, or HYBRIT for short.

A pre-feasibility study of the concept was completed in early 2018. It concluded that HYBRIT faced no serious technical obstacles. Most of the technologies in the process have already been implemented in industrial settings. Furthermore, the cost of HYBRIT steel is estimated to be only about 20% to 30% above conventional steel production. Despite these promising results, it will take about two decades to take HYBRIT from concept to commercialization, and the endeavour will demand large resources for research, development and demonstration (HYBRIT, 2018).

In this report, we provide an overview and analysis of the HYBRIT concept and the key aspects that make it a promising route for decarbonisation of the steel industry. The overall objective is to identify key factors – technical, economic and political – that need to be better understood in order to develop successful industrial strategies and policies.

1.2 Global policy context: Paris & the Agenda 2030

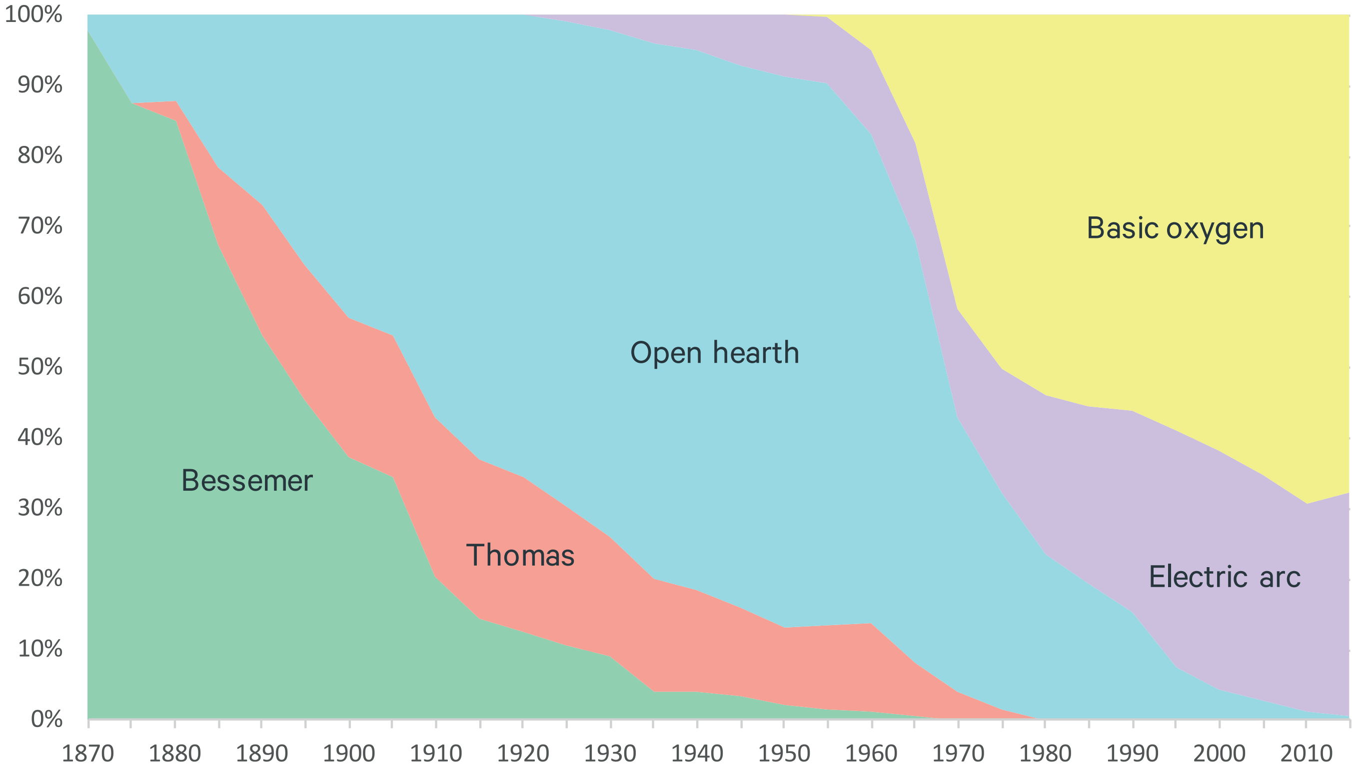
The stated objective of the 2015 Paris Agreement is to limit global warming to “well below 2°C” above pre-industrial levels and to pursue efforts to limit this warming to only 1.5°C (United Nations 2015). In order to achieve this, global emissions of greenhouse gases (GHGs) will essentially have to peak around 2020 and decline to zero in the second half of the current century (Figueres et al. 2017). Although global emissions for 2017 are projected to exceed 2016 (Peters et al. 2017), there are causes for optimism when it comes to the prospects of long-term emission reductions. This is largely thanks to the accelerating deployment and declining cost of renewable energy technologies, especially solar photovoltaics (PV), wind turbines and lithium-ion batteries (Vaughan 2017). These technologies have become increasingly competitive in recent years, as a result of significantly lower capital costs driven by technological improvements and learning effects at all stages of the supply chain (Creutzig et al. 2017).

The positive developments in renewable electricity generation, electric vehicles and energy storage are highly promising. However, scaling renewable electricity generation and electric vehicles to global dominance by 2050 – the Paris Agreement’s target year – represents a great transition. Furthermore, electricity generation and road transport together amount to less than 40% of global GHG emissions (IPCC 2014), and substantial challenges remain in other sectors, not least industry. Global emissions from industry are in the same vicinity as those from electricity generation, but mitigation options in industry have thus far received little attention compared to the corresponding discussion in the power sector (Åhman et al. 2017). The majority of industrial emissions originate in energy-intensive industries like cement, petroleum refining and metal processing, which process raw materials to intermediate products. These processes have large energy demands, use fossil fuel for both energy and feedstock, and also have non-energy emissions related to the manufacturing processes (Wesseling et al. 2017).

Steel production is the single largest sector in terms of industrial emissions, making up about 7% of total global emissions (Pérez-Fortes et al. 2014). At the same time, steel is a central material component for modern industrial societies. Further deployment of steel will be imperative to expand and improve infrastructure and increase global standards of living at a pace sufficient to reach the ambitions in the Agenda 2030 (Jernkontoret and SEI 2017). A central challenge lies in finding pathways that allow for societal use of steel as a material, while at the same time avoiding the negative environmental impacts of its production.

To achieve this, a substantial transformation of current production processes will be necessary. While the long history of the steel industry has seen significant changes, they have not been as profound and

Figure 1. Percentages of global steelmaking processes 1870-2015.



Adapted with persmission from Jernkontoret (2016) based on data from the World Steel Association.

rapid as the one envisioned for fossil-free steel. Historic changes were also motivated by distinct process advantages and profitable in their own right. As a point of comparison, the shift from open hearth furnaces (OHFs) to electric arc furnaces (EAFs) and basic oxygen furnaces (BOFs) in the decades following the 1960s (see Figure 1) were generally considered revolutionary for the global steel industry (Oster 1982; Stubbles 2000; Smil 2016b). But both EAFs and BOFs are still reliant on the centuries-old process wherein coke is used to reduce iron ore to pig iron in a blast furnace (BF) for further processing to steel. EAF mills use steel scrap as raw material; although increased recycling of steel is central to meeting the sector's sustainability challenges, higher utilization of steel scrap will not suffice to meet the expected growth in demand. In other words, production of steel from iron ore (primary steel) will be needed for the foreseeable future and here the blast furnace remains dominant, as it is used for about 95% of global production of primary steel (World Steel Association 2017). Direct reduction iron (DRI), which makes up the remainder, is quite advantageous compared to the blast furnace process from an environmental point of view, but has thus far been dependent on an ample supply of inexpensive natural gas, thereby limiting its economic viability (Smil 2016b).

The dominance of the blast furnace process for iron reduction is central when it comes to addressing the steel industry's climate change mitigation challenges. The process accounts for the majority of steel industry emissions, as CO_2 is an inevitable by-product when iron ore is reduced by use of coke. To transition to zero-emission steel production, the industry must either capture and sequester the CO_2 emissions (CCS) or completely shift to another means of iron reduction (Bataille et al. 2018).

1.3 Steel industry's transition towards deep decarbonisation

The transition of heavy industry in general, and steel production in particular, towards decarbonisation has, up until very recently, not received much attention from the energy and climate research community. This becomes especially apparent when compared to the large body of literature that covers the pace and characteristics of energy system transition and decarbonisation in other sectors (e.g., Sovacool 2016; Smil 2016a; Geels et al. 2017). However, with industrial emissions almost as high as those from power generation, mitigation measures in industry need to be addressed further in the pursuit of deep decarbonisation (Bataille et al. 2018).

1.3.1 Characteristics of a steel industry transition: from OHF to BOF and EAF

Radically reducing the steel industry's emissions will demand a significant transformation of the industry, regardless of whether it is achieved through carbon capture and storage or a technological shift away from the blast furnace[1]. Historically, technological transitions in the highly competitive steel sector have been driven by purely commercial factors; this has come primarily in the form of increased efficiency (and thus decreased cost), as well as improved quality.

As a case in point, the shift from the open hearth furnace (OHF) to the basic oxygen furnace (BOF) in the 1960s and 1970s drastically reduced capital costs and substantially improved labour productivity (Oster 1982; Smil 2016b). The characteristics of this transition have been studied in detail by researchers who aimed to understand why some firms were early adopters of the technology and why others were laggards. US steel manufacturers were slower in adopting BOF than Japanese competitors, partly because producers in Japan were in an expanding phase where they were adding greenfield capacity. US producers, on the other hand, were not expanding. For them, switching to BOF meant converting existing OHF infrastructure, where they had a lot of sunk costs; this made them less eager to adopt BOF (Lynn 1981; Oster 1982). This particular transition also touches upon a discussion about whether small or large firms are more likely to adopt innovations. As is pointed out by Smil (Smil 2016b), the OHF-to-BOF transition contradicts the so-called "Schumpeterian hypothesis" that large firms are more likely to be innovation leaders. The US firms that were the first to adopt the basic oxygen furnaces tended to be rather small in terms of production capacity (Oster 1982).

It is worth noting here that the actual nature of the technology itself may partly determine whether it is more likely to be adopted by large or small firms. Notably, the electric arc furnace (EAF), which dominates global steel production along with BOF, lends itself well to smaller production units. So-called "mini-mills" based on EAF expanded rapidly in the 1980s, especially in large, steel-consuming regions like Europe and the United States where steel scrap was readily available (Smil 2016b).

1.3.2 Drivers of a sustainable transition in the steel industry

There are a host of factors that can drive and enable industrial transitions towards improved sustainability. Many take the form of public policies that incentivize reduced emissions, such as regulations, taxes or subsidies (Sterner 2003). However, firms have also widely employed environmental aspects and sustainability for marketing purposes. So-called "green marketing" can be used to create market niches and thereby appeal to specific groups of consumers, who are willing to pay a premium for a product that is superior to alternatives in terms of sustainability (Polonsky 2014).

Consumer preferences thus can play an important role in driving industrial transformation, but it is rarely seen in heavy industry sectors such as steel, as these almost exclusively work in a business-to-business market (Åhman et al. 2016)[2]. Furthermore, heavy industry largely produces for commodity markets, where cost and availability tend to be the key drivers of competitive advantage. One possibility, however, is to indirectly market commodities as sustainable by adding the "green premium" to consumer products containing the material in question. This premium would not increase prices dramatically, as material is a small share of the cost of a finished product. For example, even if a steel producer paid a high cost for mitigating CO_2 emissions and passed this cost on to its customers, the consumer price of an automobile would only increase by about 0.5 percent (Rootzén and Johnsson 2016).

When it comes to public policy frameworks, a key factor to take into account is that the heavy industry sector – including steel – tends to operate in competitive international markets. This is important for policy design, as national policy measures that penalize emissions run the risk of simply reducing national competitiveness, resulting in production facilities being moved to jurisdictions without such policies. The risk of this so-called "carbon leakage" has meant that policy-makers have been rather unwilling to pursue costly mitigation policies for heavy industry (Åhman and Nilsson 2015).

1 The characteristics of these two strategies are further addressed in section 4.
2 A notable exception here is when Greenpeace and the German publisher Springer focused a joint campaign on the Swedish pulp & paper industry, which played a crucial role in driving Swedish forestry practices towards more concern for biodiversity aspects (Simonsson 2016).

If incentives are introduced, their effect on businesses can vary widely depending on how a firm chooses to respond (Wu et al. 2012). A firm could choose to simply carry on with business as usual and pay penalties or introduce end-of-pipe solutions (Ramanathan et al. 2017). Alternatively, it could approach the new regulatory environment as a structural shift in the market, similar to how a technological innovation (e.g., digital cameras) can create a completely new competitive environment in an industry. Porter and van der Linde (1995) emphasize the role that environmental regulation can play in driving technological development and achieving competitive advantages. These interactions are important to consider amid the recent introduction of several long-term targets for climate change mitigation, both in the Paris Agreement and at the national level (such as Sweden's legally binding commitment to reach net-zero GHG emissions by 2045). Meeting these targets means decarbonizing the global steel industry, with early movers potentially gaining a competitive advantage. Furthermore, in accordance with the responsibilities given to industrialized countries in the United Nations Framework Convention on Climate Change (UNFCCC), it can also be argued that Sweden and the EU should take the lead in developing new technologies and enabling solutions for the global good.

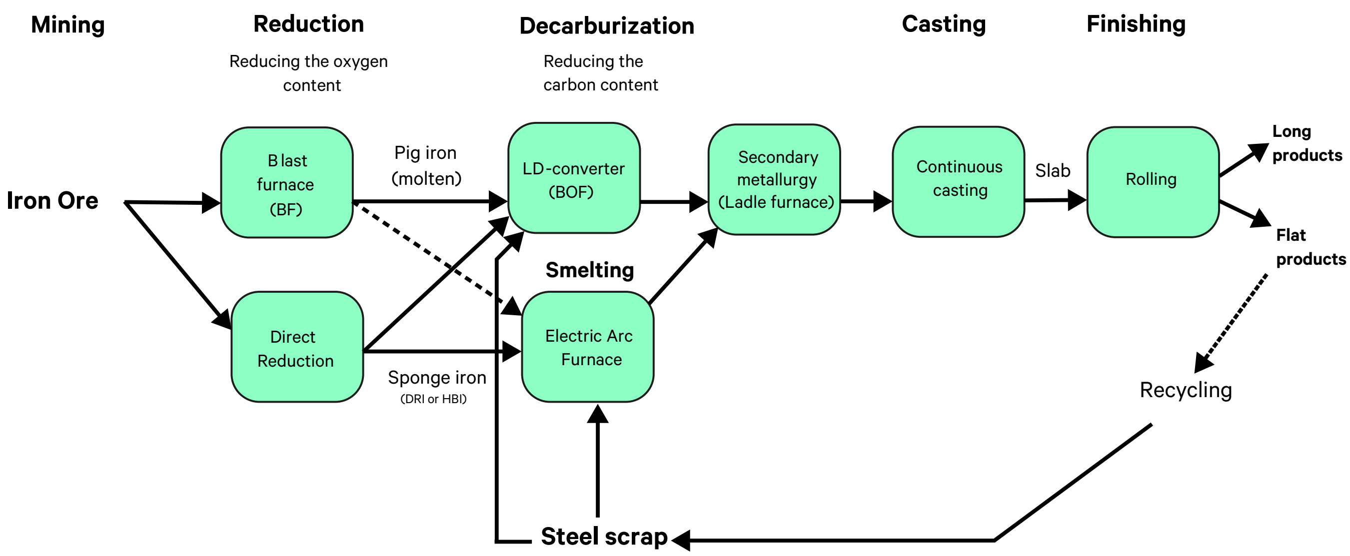
Finally, in practice, the nature of relations among industry actors and between industry and governments can be crucial for environmentally oriented transition processes. Historical cases show how actions and positions by industry associations can either facilitate or hinder a transition, sometimes depending on national culture. An example is the difference between Sweden and the United States. Sweden has been characterized by cooperation within industry as well as between industry and government; the US, on the other hand, has seen both less cooperation within industry and a more confrontational relationship between legislators and businesses in environmental matters (Bergquist and Söderholm 2015).

2. Production of steel

2.1 Current production of primary steel

Steel production begins with the mining of iron ore, followed by the reduction of the iron ore to iron by removing oxygen. Iron is then further converted to steel by lowering the carbon content, adding alloys and removing impurities. In Figure 2, the most common routes for steel production today are schematically illustrated. The main technology used today for reducing iron ore to iron is the blast furnace[3], which uses coke as the reduction agent. The produced liquid iron is called "pig iron", which is further transformed to steel in a basic oxygen converter (LD-converter) and subsequently treated in secondary metallurgy. An alternative production route is direct reduction; in that process, iron ore is reduced directly in solid state by adding methane as a reduction agent in, for example, a shaft furnace or rotating kiln. The product is called "sponge iron" due to its porous structure. Sponge iron is further processed to steel in an electric arc furnace, where it is melted and the carbon content is reduced. Sponge iron can also be used in a basic oxygen converter to make steel. Finally, steel is also made from melting recycled scrap in the electric arc furnace. From the electric arc furnace, the steel is refined in secondary metallurgy before it goes to casting. The recycled scrap steel is sometimes mixed with sponge iron in the electric arc furnace to improve the quality of the steel.

Figure 2. From iron ore to finished steel – the most common routes



Steel that originates from iron ore is also called primary steel, whereas steel that originates from scrap is called secondary steel. Roughly 70% of all steel produced today is primary steel. Speciality steel is made by adding various alloys and removing impurities in the secondary metallurgy processes.

2.2 Resources for steel production

The production of steel is dependent on several intertwined markets, including those for iron ore, scrap steel, coking coal, graphite (for anodes in EAF), natural gas (local/regional), and electricity (regional/national). Other more specific elements (for alloys) are also crucial in the steel value chain, such as manganese, chromium, and molybdenum for making stainless steel and other speciality steel.

Iron ore is a theoretical abundant resource in the world. The major producers are Australia, Brazil, China and India. Sweden is the largest iron ore producer in Europe (USGS 2017). Global iron ore production was growing substantially until 2013, reaching almost 3 billion metric tons annually. Production has since

3 Alternatives to the blast furnace for producing pig iron include smelt reduction.

then declined down to around 2.1 billion tons/year, the same level as 2009. The major change has been a substantial reduction in Chinese production. China used to be the largest producer of iron ore but has since been overtaken by Australia, Brazil and India (USGS 2017). Iron ore is a globally traded commodity, where more than 70% of the ore is shipped overseas. Australia and Brazil are the main exporters.

Steel scrap is also a major input/resource for steel production, and between 500 and 600 million tons of steel scrap is recycled each year. The scrap is produced mostly in mature economies. In the US, for example, 72% of steel is made through the scrap steel production route; that ratio is 54% in the EU, 32% in Japan and 39% in Korea. Growing economies produce, and thus use, less scrap steel; 11% of steel in China and 25% of steel in Russia is made through steel scrap. However, China is growing and expecting to use substantially more domestic scrap in the coming years. Turkey uses scrap imports from the EU to help it stand out as a major steel producer from scrap, with 78% of its steel production coming from this route.

Pauliuk et al (2013) have estimated, based on a stock model, that steel production from the primary route might peak between 2020 and 2030. Thereafter, the amounts of scrap will continue to grow and eventually overtake primary production as the main route for steelmaking between 2050 and 2060 (Pauliuk et al 2013). The World Steel Association also projects that global availability of steel scrap will increase from around 700 million tons per year today to 1,300 million tons by 2050 based on population growth and the associated growth in steel use (WSA 2017). The major trade flows for steel scrap are from the US, EU and Japan to Turkey (by far the largest importer in the world), South Korea and India (BIR 2017).

3. Steel markets

From 2000 to 2016, the global production of crude steel went up from 800 to 1,600 million tons per year, mainly driven by China (which now represents 50% of global steel production). However, the capacity for crude steel production is more than 2.3 billion tons per year, according to the OECD Steel Committee. This means there is a substantial global overcapacity that has been built up over the last 10 years. Roughly 30% of the steel production is traded intercontinentally.

Steel can be sold and bought in over 3,500 different grades, ranging from bulk steel – such as rebar and construction steel – to a host of high quality speciality steels. The major end-user markets are construction (55%), mechanical equipment (15%) and the automotive industry (10%) (Allwood and Cullen 2012). The steel market can be divided into "flat" or "long" products; long products are mostly sold for construction (e.g., beams and rebar), while flat products go to the manufacturing and the automotive industries. Long products are the "bulk steel" with lesser quality demands on purity, whereas flat products generally have higher quality demands and also include "speciality steels". Speciality steel has larger amounts of alloying elements in order to change the properties in a desired way and can further be classified as alloy steel, stainless steel and tool steel. The price difference between bulk steel and speciality steel is quite substantial, with bulk steel costing between USD 400-600 per ton and speciality steel sometimes costing more than USD 2,000 per ton (Åhman et al 2013)

3.1 Future market demands and premium markets

A low-carbon transition will change the requirements and expectations for steel among future customers. High strength steel is seen as vital for the solutions necessary for a low-carbon economy, as it will allow advanced designs and could, for example, replace concrete in the building sector (Jernkontoret 2018, Eurofer 2013; POSCO 2017). On the other hand, a low-carbon transition also poses market risks for steel producers. The automotive industry could, as an example, shift towards using much more aluminium and plastics (already an ongoing trend), driven by the need to reduce weight. An important end-use sector for the steel production is the fossil fuel industry where steel is used in exploration, transport and refineries. In a low-carbon economy, this end-user market for steel will by necessity diminish; however, it could be partly replaced with the needs of a growing renewable energy industry.

Niche and premium markets are generally seen as key to transformation within the academic literature of transitions (Geels et al 2017). The idea is that niche markets will provide a "safe space" for development by offering clients willing to pay more; these niche markets are thus expected to carry the extra cost for new technologies. Premium markets for speciality steel – with substantially higher prices – exist today and are important for Swedish steel manufacturing.

But these premium markets are based on physical quality. So far, no premium or niche market exists for "green steel"; in other words, there is so far no sign of willingness among customers to pay extra for upstream environmental qualities. The potential consumer demand for green steel also suffers from a lack of transparent information and lack of knowledge. The "material component" related to our consumption has not been widely discussed in climate policy so far. However, as we achieve higher energy efficiency and cleaner energy supply, more of the life cycle impacts of buildings, for example, originate in the production of building materials and less in the user-phase.

An example of a successful "market driven" environmental transition in the basic materials sector is the sharp decline of chlorine-bleached paper. The switch to chlorine-free pulp was at least partly driven by consumer awareness and assisted by various policies for a prolonged period of time (Söderholm et al, 2017).

Enabling and articulating the potential consumer demand for greener materials can be a vital component for creating necessary niche markets for development. Public procurement represents a major share of the end-user market; here, government could act directly and proactively by articulating future social demands (Wesseling and Edquist 2018). As an example, Sweden's road administration implemented public procurement rules aimed at only investing in "climate neutral" infrastructure by 2030. A more general policy approach to creating a market for green materials is a material tax (Neuhoff et al. 2015). Labelling of steel is also a path that could enable and create a voluntary demand for green steel. For example, Environmental Product Declarations (EPDs) communicates information about the life-cycle environmental impacts of some steel types in Europe[4]. However, such labelling includes difficult trade-offs between accuracy/accountability and simplicity to enhance communication.

4. Overview of decarbonisation strategies in the steel industry

Bataille et al (2018) propose that deep decarbonisation strategies for heavy industry can follow largely two distinct routes:

1. **Change existing processes** to remove inherent dependencies on fossil fuels. This route tends to rely heavily on electrification, either directly or via hydrogen produced by electrolysis.
2. **Keep existing processes** and address emissions through a combination of CCS/U (carbon capture and storage/utilization) and a shift to renewable sources for process energy.

In the following, we apply this categorisation to the steel sector and explore the two routes to map key characteristics as well as challenges and opportunities pertaining to their implementation. We also discuss the role of biomass in Section 4.3.

4.1 Changing existing processes: electricity and hydrogen

With the growing availability of low-cost renewable electricity, different forms of electrification are increasingly seen as attractive options for decarbonisation of heavy industry (Lechtenböhmer et al. 2016). For the steel industry, a number of different technological solutions have been suggested to this end (Quader et al. 2016). Among the more promising technologies is the electrolysis of iron ore, or "electrowinning". This entails the use of electricity as the reducing agent, akin to how aluminium is produced from aluminium oxide. This process is still at an early stage of development and has thus far only been tried at a lab scale (Fischedick et al. 2014), but it represents a high-efficiency steelmaking option with the promise of large emission reductions in the long term.

The HYBRIT process falls within a category of technological concepts that are substantially closer to commercial deployment. These are based on the use of hydrogen as a reduction agent, with the hydrogen (H_2) being produced through electrolysis based on renewable electricity. From an environmental standpoint, the most important advantage of this is that the exhaust from this process is water (H_2O) instead of CO_2, with a consequent reduction in GHG emissions[5]. HYBRIT is among several initiatives[6] that use an H-DR/EAF setup, combining the direct reduction (DR) of iron ore by use of hydrogen with an electric arc furnace (EAF) for further processing into steel (Ranzani da Costa et al. 2013; Fischedick et al. 2014).

The product from the H-DR process is called direct reduced iron (DRI), or "sponge iron", which is fed into an electric arc furnace (EAF), blended with suitable shares of scrap, and further processed into steel. Although this specific combination of processes has not been implemented at the commercial scale, several of the individual components are already widely used in the global steel industry. EAF-based steel makes up 30% of annual global production. The DR process is also widely employed, being the basis for about 7% of total global iron production and usually integrated with EAF. While pure H_2 has been used commercially as the reducing agent in DR[7], existing DRI production capacity relies on natural gas that is steam-reformed to obtain the reduction agent, a mixture of CO and H_2 (Tacke and Steffen 2004). As the cost of natural gas is a key factor for the economic viability of this setup, most DRI production is located in regions that are rich in low-cost natural gas (CH_4). Recent years have seen an expansion of US DRI production in the wake of the rapid ramp-up of shale gas production (Arens et al. 2017).

4 See http://www.environdec.com/
5 It is worth noting that the use of hydrogen in existing blast furnaces has been explored, and it has been verified that this can contribute to substantial emission reductions (Yilmaz et al. 2017).
6 Other projects that include the H-DR/EAF route are the Austria-based H2FUTURE (http://www.h2future-project.eu) and the German MACOR/SALCOS project (https://salcos.salzgitter-ag.com/en/index.html).
7 This was implemented in the CIRCORED process that was part of a steel mill built in Trinidad in the late 1990s.

Despite the fact that many components of the H-DR/EAF setup have been tested and deployed in industrial settings, key challenges still remain for the process. These are related to process integration, product qualities, scale-up of hydrogen infrastructure (production and storage) and the integration of an H-DR/EAF steel mill into an energy system based on renewable sources of electricity. Sections 5 and 6 in this report discuss these options and challenges in more detail. Another challenge is how to get carbon into the iron in order to make it into steel. From a biomass resource perspective (see Section 4.3), very small amounts of carbon are needed.

4.2 Keeping existing processes: carbon capture and storage/utilization

Carbon capture and storage (CCS) has been an important topic in climate and energy research for a long time. Interest grew in the 1990s with more in-depth analysis of the technology (Riemer 1996). The concept entered more widely into climate policy discussions in the early 2000s as a potential method by which global use of fossil fuels could continue without contributing to greenhouse gas levels in the atmosphere. Carbon capture technology itself is rather mature, following commercialization in the mid-20th century in the food and chemicals industries. Storage has also been successfully tried in natural gas reservoirs, including in Norway (van Alphen et al. 2009). In the early phase of CCS research and development for the purpose of climate change mitigation, the focus was predominantly on applications to the electricity generation sector, especially coal-based power production. However, despite a long list of pilot plants and trial projects, commercial CCS has failed to materialize. This is partly due to cost overruns, partly due to public opposition to underground CO_2 storage and partly due to dropping costs of other less polluting means of power generation such as renewables and natural gas (Bäckstrand et al. 2011; Nykvist 2013; Thorbjörnsson et al. 2015).

Although expectations for the role of CCS in the power sector have waned[8], it is still considered a key option for reducing GHG emissions from heavy industry without major changes to existing processes (Leeson et al. 2017). CCS in industry has certain distinguishing characteristics when it comes to conditions for implementation. An advantage is that CO_2 streams tend to be quite pure in industry compared to power production, which can make the separation and capture stages less complicated. Furthermore, public opposition is expected to be less severe, as there are few renewables-based alternatives for several industries, such as cement. However, heavy industry also has some features that could make CCS applications difficult. First, unlike the power generation industry, heavy industry competes globally, which makes it even more vulnerable to cost increases and more problematic to carry through cost increases to customers (Mikunda et al. 2014). Another disadvantage for the CCS option is that an industrial site hosts a number of CO_2 sources of varying concentration and volumes. Most CCS assessments focus only on the major source of CO_2, whereas capturing all CO_2 from a plant could prove much more difficult and require major rebuilding. Capturing and storing 50% to 60% of the CO_2 emissions at an industrial site could cost EUR 55 to 65 per ton CO_2, according to several assessments (IEA/OECD 2011). However, for capturing higher shares of emissions, the cost structure is more uncertain. Notably, no reliable cost estimates exist for capturing over 90% of emissions (Birat et al. 2010).

The Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) project has identified a number of technologies that can support the implementation of CCS in the steel industry (Quader et al. 2016). One of these, the TGR-BF (Top Gas Recycling – Blast Furnace) process has been tested successfully in pilot plants, resulting in a 24% reduction potential in CO_2 emissions; however, actual sequestration and storage of the CO_2 was not part of this pilot setup (Quader et al. 2015).

In conclusion, CCS currently seems like a more promising solution in industry than in power generation, but there are still inherent problems. First, the potential GHG emission reductions from CCS are limited to about 50%, due to small and diffuse emission sources, lack of space for installations, and other issues (Fischedick et al. 2014). Secondly, storage-related problems -- such as oversight and long-term integrity of storage reservoirs – remain unresolved. Thirdly, CCS comes with very few co-benefits (Nykvist 2013; Åhman and Nilsson 2015), and the presence of co-benefits have been identified as a key facilitator when it comes to accelerating transition processes (Grubler et al. 2016). This is a factor that might hinder widespread uptake. If carbon capture is combined with some form of CO_2 utilization (CCU), there might

8 However, recent developments in carbon capture from natural gas power generation, by use of the so-called Allam cycle (Allam et al. 2017), appear promising (Rathi and Rathi 2017).

be greater opportunities, but there is still much process development to be done. Also, even if the CO_2 is utilized as raw material – for example, in some form of a specialty chemical or fuel – it nevertheless eventually ends up in the atmosphere (Nikoleris and Palm 2018).

4.3 The role of biomass

Throughout most of the history of iron and steel processing, biomass was a key resource. Wood-based charcoal acted both as the reduction agent necessary to rid iron ore of its oxygen components, as well as the source of energy needed to reach the high temperatures necessary. It was not until around 1875 that coke, produced from coal, took over, although it is important to note that charcoal continued to be used up until the mid-1900s, including in Sweden (Smil 2016b). Charcoal produced from fast-growing eucalypts are still used as the main reduction agent in smaller steel mills in Brazil, but this is likely not feasible in larger mills due to limits imposed by the lower compressive strength of charcoal compared to coke (Norgate and Langberg 2009; Smil 2016b). Furthermore, the vast volumes needed and significant challenges in maintaining quality make a full shift from coke to biocoke highly unlikely.

But biomass may still have important roles to play in the decarbonisation of the steel sector, and several different options have been proposed[9]. At the incremental side of the scale is the possibility of blending 5% to 10% charcoal with coking coal in the production of metallurgical coke for use in existing blast furnaces (MacPhee et al. 2009). Another option is to use biomass in the processing of raw iron ore, either as a fuel for the process itself or to produce a composite biocarbon-iron ore pellet that can then be used in a direct reduction (DR) process (Mousa et al. 2016). There have also been trials aimed at using gasified biomass in DR processes (Grip et al. 2015); this approach is feasible but in need of further trials and research[10]. Biomethane will also be an important low-carbon option for heating in the secondary metallurgy process if the off-gases from the coking plant are no longer available[11]. In the long term, various options for electric heating exist, but biomethane could replace the currently used natural gas and coke-oven gases directly, with minimal changes to the process.

However, the systemic challenges for biomass tend to be substantial. In contrast to coal, biomass resources are not concentrated in a specific place (like a mine), which leads to high procurement costs as biomass from geographically dispersed area must be collected, processed and transported to the mill (Norgate and Langberg 2009; Lamers et al. 2012). Secondly, a growing demand for wood could lead to competition with existing users (such as the forest industry), as well as other sectors aiming to utilize biomass to achieve mitigation ambitions. This could in turn lead to higher prices, unless focus is shifted to forest residues that are less in demand. Finally, in order to ensure GHG emission reductions, it is crucial that biomass is sourced from sustainably managed forests (Berndes et al. 2011).

In summary, biomass can come to play a vital role in both the renewable as well as the CCS route. Both require large amounts of heat in the iron ore processing, secondary metallurgy and hot rolling processes. This could very well be provided through the combustion of biomethane. In the CCS route, charcoal could at least partially substitute coke, as long as the mechanical stability of the blast furnace charge is maintained. In the HYBRIT concept, biomass is foreseen also to serve as a carbon source for steel (HYBRIT 2018) and potentially also in the downstream metalworking process (Jernkontoret 2018).

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9 For a more comprehensive review, see Suopajärvi et al. 2017

10 Höganäs AB, a Swedish firm that uses a coal-based DR process to produce iron powders, has initiated real-world trials of a process using wood gasification to produce both biocoke, to be used as reduction agent, as well as syngas, to be used for process energy (and possibly also for reduction). (https://www.hoganas.com/en/news-centre/news/2017/hoganas-and-cortus-energy-break-ground-for-lower-carbon-dioxide-emissions/)

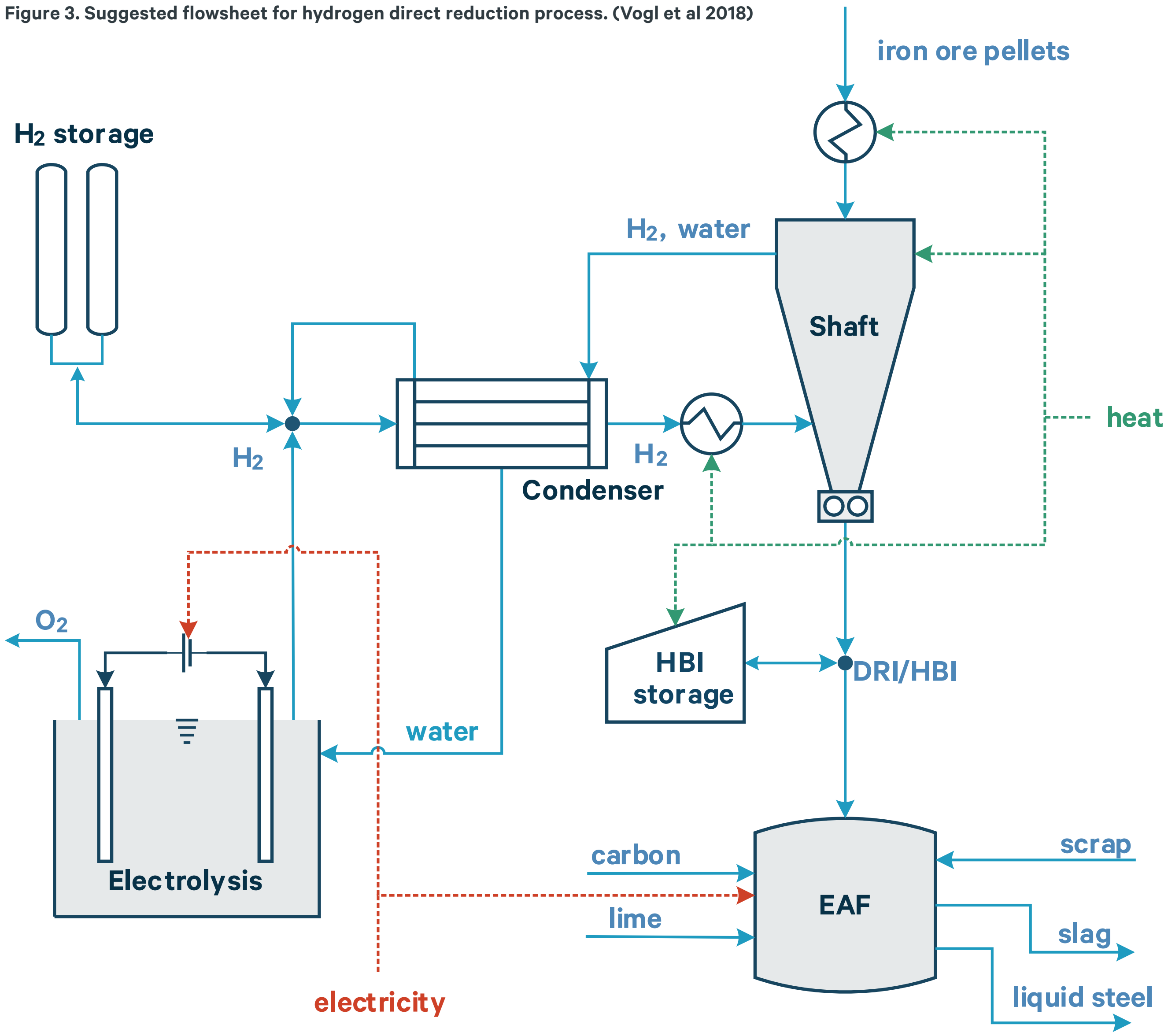
11 In an integrated steel mill, the off-gases from the coking plant are used for heating in the secondary metallurgy processes. With a H-DR concept, this energy has to be replaced.

5. Systemic consequences of hydrogen reduction steel

Apart from the HYBRIT consortium, two other European steelmakers, Voestalpine (AUT) and Salzgitter (GER), are currently exploring hydrogen direct reduction (H-DR) as a future option. This section discusses a general design of a potential hydrogen direct reduction steel plant, based on Vogl et al (2018), with some presented numbers on energy demand.

Renewable electricity is used to split water in an electrolyser, and the hydrogen is then used to convert the iron ore to sponge iron in a direct reduction process similar to processes such as Midrex and HYL/Energiron. Oxygen emerges as a by-product from the electrolysis. The produced sponge iron (DRI) can be compacted to hot briquetted iron (HBI) to facilitate transport and storage. DRI/HBI is further converted to liquid steel in a conventional electric arc furnace. The energy intensity of H-DR is 3.48 megawatt hours (MWh) of electricity per tonne of liquid steel (tLS), and 1.5 tons of ore per ton of liquid steel are consumed (Vogl et al 2018). This can be compared to a blast furnace that requires roughly 4.16 MWh of coke and coal for reducing the same amount of ore (Otto et. al, 2017). In H-DR, if all energy input is electricity, the CO_2 emissions are entirely dependent on the emission intensity of the grid. Downstream heat demand for metal working can be generated from biomass (or electricity), resulting in a process that can be virtually emission-free.

Figure 3. Suggested flowsheet for hydrogen direct reduction process. (Vogl et al 2018)



Switching from BF/BOF (the blast furnace to basic oxygen furnace route) to H-DR requires significant changes in the production process, as the coking plant, the blast furnace and the basic oxygen furnace would be replaced. Instead, H-DR uses a direct reduction shaft, an electric arc furnace and an electrolyser, including a possible heat exchanger and hydrogen storage. The rest of the downstream production process will remain similar and the liquid steel leaving the EAF will be processed in secondary metallurgy, then cast and rolled in similar steps as in current integrated steelmaking. However, new sources of energy will be partly required for these downstream processes, as off-gases from the coke oven, BF and BOF are not available; these off-gases are typically used in integrated steelworks for their energetic value.

A distinct feature of the H-DR process is its operational flexibility. The electrolyser makes it possible to react to fluctuations in electricity supply or variations in electricity prices by producing more or less hydrogen than required for the ore reduction and storing it. Salt cavern and high-pressure hydrogen tank storage can be used to guarantee a continuous supply of hydrogen to the shaft while operating the electrolyser dynamically. HBI stockpiling and the use of scrap metal allows the discontinuous operation of the electric arc furnace, which increases the flexibility of the overall process even more. The scrap-to-HBI ratio in EAFs is variable and is another option for adjusting the process, adding further flexibility.

The process design, with its operational flexibility, bears the potential for new business models and operational strategies. Steel producers could engage outside their typical markets and provide services for the electricity grid. Hydrogen production opens up synergies with various sectors, such as transport, petrochemical, and ammonia production. The current trend of increasing DRI capacities in natural gas DRI plants suggests that economies of scale might also favour large-scale production for H-DR. Recent DRI plants with capacities of around 2.5 million tons per year have been built in Algeria (Tosyali Algeria, Midrex) and Louisiana (Nucor, HYL/Energiron). However, smaller H-DR mini-mills could reduce the pressure on the electricity grid. Another option is a geographically dispersed operation using decentralised energy supply, such as locations with good wind power conditions.

A changeover to hydrogen direct reduction and a fossil-free value chain require a series of changes to current practices in the steel industry. The shift from coke to hydrogen could promote independence from international coking coal markets in Europe, and Sweden could be even self-sufficient in steelmaking due to its iron ore deposits. A fossil-free value chain, however, also requires zero-emission inputs to the process. It is not yet clear how zero emissions can be realised in both lime use – which will be necessary for slag foaming in the EAF – and carbon, an essential component in steel. Process emissions caused in the production of lime might make it necessary to find another material for slag foaming. Carbon could come from biogenic sources and be added in the EAF, but it requires further research to determine its applicability. Furthermore, it is still unclear how the large volumes of oxygen produced in the electrolyser can be used. For every ton of steel, over 400 kg of oxygen are produced and only small amounts would be used in the process, in pelletizing or in the EAF for example.

Production through the HYBRIT process would cost 20% to 30% more than through the current blast furnace process, according to an initial cost assessment (HYBRIT 2018). The new concept could thus be competitive with a typical blast furnace production that comes with a carbon price of between EUR 40 and 60 per tonne of CO_2, assuming the H-DR process is completely CO_2-free[12]. However, a key determinant for production cost is the cost for electricity, and most of it is needed for hydrogen generation in the electrolyser.

12 Assuming 2 tonnes of CO_2 per tonne of steel and a steel price of 400 EUR.

6. The policy landscape for European steel

As noted in the introduction, a tough climate target is pushing European steel producers to drastically reduce GHG emissions in the coming 25 to 35 years. At the same time, EU steel production is exposed to international competition on a global steel market that currently is suffering from substantial over-capacity. Both the EU and Sweden also have policies to maintain a thriving steel industry within their borders.

The objective of climate and environmental policy is often framed as “internalising externalities”, or making sure that actors take on responsibility for the emissions they cause. This can be implemented by policies such as putting a price on carbon or enforcing an environmental code. In light of the significant challenges and long-term time frame, climate policy today also relies heavily on research and innovation, where the aim is to help actors overcome barriers to development. These barriers can be specific (such as a lack of private research funding), as well as systemic, including lack of infrastructure, lack of proper regulations, lack of coordination among private actors and government agencies and lack of foresight for de-risking long-term investments (Edquist 2006). A third and important function of climate policy is to “cushion” and ease the unwanted side effects of major transformations, protect commonly agreed social values (such as employment opportunities and local communities), and, not least, maintain industrial competitiveness (Johansson et al, 2018).

These objectives are part of the wider policy landscape through which the European Commission and its member states aim to maintain a thriving steel industry as well as ensure that industry reforms substantially to reduce its greenhouse gas emissions. The major policy domains important for the steel industry are thus climate and energy policies, research and innovation policies, and trade and competitiveness policies, which together form the basis for a comprehensive industrial policy[13]. Below, we describe and analyse the current framework for governing an industrial low-carbon transition at the EU and member state levels, and also through global agreements such as the World Trade Organization (WTO) and the UNFCCC.

6.1 Climate and energy policy

GHG emissions from steel production are mainly regulated via the EU Emissions Trading Scheme (ETS) that puts a cap on total emissions within the EU. The ETS includes all major industrial facilities, heat production, and power production. Installations included in the EU ETS under the emission cap will, by definition, collectively reach the targeted reductions. The “cap” is set to decrease to 43% below 2005 emissions levels in 2030 (EU COM 2017), with an aspirational cut of 80% to 90% in 2050 (EU COM 2011). The EU ETS has been viewed as the “flagship” of EU climate policies with many other “flanking” policies attached to it. Such possible policies include allocating initial emission rights for free to avoid carbon leakage, financing the demonstration of new technologies via the proceeds from the auction of emission rights (NER 300), and the linking of ETS to the international climate efforts via the Clean Development Mechanism (CDM)[14] or other off-setting/carbon trading mechanisms in the future.

EU climate policy is tightly linked to its energy policy, which includes both specific targets for renewables and energy efficiency as well as regulations governing the coordination of the various energy markets within the EU. The competence for deciding on the energy mix is still primarily with the member states, but the EU has the authority to push the development and integration of the EU energy market via the “single market” mandate. The specific targets for renewables and for energy efficiency were recently amended and prolonged to 2030 (EU COM 2017). The way the renewables polices were implemented has had a major, mostly positive, effect on the energy cost for industry. The energy intensive industry (EII) has been largely exempt from bearing the incremental extra cost for the support schemes for renewable electricity (RES) and has benefitted from direct fiscal support for increasing energy efficiency (Stenqvist 2014).

According to industry representatives, the uncertainty that prevailed regarding long-term climate targets and energy policy were problematic for making long-term strategic decisions. However, the development

13 Other policies are also deemed important for competitiveness such as education policies, tax policies and other environmental regulations (e.g., the Industrial Emissions Directive)

14 A mechanism that allows companies within the EU to “offset” part of their climate target by buying reductions credits achieved outside the EU.

of a mix of both aspirational and legal long-term targets in recent years (see EU COM 2050, Swedish and UK Climate Laws, Paris Agreement, etc.) and the strong development of renewables appear to have reduced this uncertainty substantially.

Another key EU environmental policy is the Industrial Emissions Directive, IED (2010/75/EU), which regulates all emissions to air and water except CO_2 emissions (as that is done within the EU ETS). This regulation serves as the basis for granting and updating industrial permits at the national level, based on the European Commission's Best Available Techniques (BAT) reference documents (Remus et al 2013). It has thus had a direct effect on the same facilities and technologies that are regulated under the EU ETS (such as industrial furnaces). The IED is designed to "cut the tail" and to ensure a necessary upgrade to the best available environmentally friendly technologies. It is thus not designed to drive innovation and the development of new technologies for decarbonisation.

6.2 EU industrial policy

As the emissions from steel production in the EU is covered by the overall cap set by the EU ETS, the real climate issue is thus not if the targets will be met, but how and at what cost[15]. For industry, different outcomes are plausible (including closure) and strongly dependent on complementary policies. Here we will focus on industrial policy (IP), which covers the whole set of policy instruments and polices, and the effect these can have on deciding how industrial decarbonisation would occur.

Industrial policy could be defined as the coordination and implementation of several different policy instruments, with the aim of restructuring (or maintaining) the industrial structure of an economy. Industrial policy has a long history in Europe and elsewhere (Grabas and Nutzenadel, 2013). It is often associated with failed government attempts to rescue outdated or ailing industries, or with failed attempts at "picking winners" in terms of technologies or emerging companies. After the financial crisis in 2008, there was a renewed interest in "green industrial policy" with a stronger focus on innovation and R&D as a way of promoting green growth and maintaining industrial capacity within the EU.

In the EU, industrial policy is a shared competence between the commission and the member states, where the European Commission ensures that sufficient coordination is taking place and that member state policies do not disrupt the internal market. Industrial policy in the EU has been mainly about horizontal policies that safeguard the functions of the internal market and thereby help to create one of the largest single consumer markets for industrial goods. However, since the 2008 financial crisis, the vertical or sectoral strategies have gained influence in several member states and also within the EU. In 2010, the European Commission tabled its "Integrated Industrial Policy for the Globalisation Era, Putting Competitiveness and Sustainability at Centre Stage" (European Commission, 2010) which has its roots in the Lisbon agenda (2000) – a strategy to make the EU the most competitive economy in the world – that specifically addresses both horizontal and vertical (sectoral) industrial polices. Since then, the industrial policies have evolved but mostly with the aim of increasing competitiveness and creating new innovative industries. Less attention has been paid to the "heavy incumbents", such as the energy intensive industry. Wyns (2017) gives an overview of the various IP activities implemented by the EU since 2000.

Innovation and support for technical change along the whole innovation chain (including research and development (R&D), demonstration, pilot test and market formation support/early deployment) is a key policy area linked to decarbonising industry and a key element in the current industrial policy narrative of "green industrial policy" or "IP 2.0" (Warwick 2013; Nilsson et al 2017). A number of EU research programmes are relevant to the energy-intensive industry, such as the ultra-low carbon dioxide project for steel (ULCOS), several efforts in the area of bio-economy, and the Strategic Energy Technology Plans for industry focusing on CCS. Within the EU, the major "supply push" technology development programme targeting the steel industry has been the ULCOS programme that was a joint research programme between the EU steel industries and the European Commission. The ULCOS programme ran between 2004 and 2010 and investigated several pathways for the steel industry to achieve major (50%) reductions. However, the ambition from the beginning was not zero emissions, nor did the initiative include any analysis of strategies for market deployment and upscaling; it focused only on supporting R&D and pilot

15 This logic has recently been somewhat changed with an amendment to the EU ETS that allows for retiring emission allowances to be put in reserve if the price on the EU ETS is too low.

projects. A planned follow up programme (ULCOS II) for financing demonstration projects never materialised. The path that was develop up to piloting level was top gas recycling with potential CCS, which was piloted successfully in Luleå and HIsarna in IJmuiden.

Within the EU framework program (Horizon 2020), mitigating climate change, supply of raw materials and development of smart materials have all been identified as key areas with support for targeted research for key enabling technologies. The research relevant for steel has focused on high quality and new smart materials downstream, and not on reducing up-stream emissions from the process or on zero emissions. In the discussions on the next EU framework program (FP9), a more mission-oriented approach has been suggested (Mazzucato 2018), where the EU steel industry could link steel, climate change and deep decarbonisation in a "mission" worth supporting.

6.2.1 The role of finance in de-risking low carbon investments

Inadequate access to financing is a major barrier for low-carbon technologies, especially in the early stages of market development. The reasons for this include lack of knowledge among financers and inertia within financing institutions. Energy-intensive heavy industries like the steel industry can face particularly difficult financing challenges due to the combination of long investment cycles, high capital intensity, the need to develop new technologies/production systems to achieve deep decarbonisation, and intense global competition (Bataille et al., 2018; Fischedick et al., 2014). In the last five years, several countries around the world have established "green investment banks" with a direct mandate to provide attractive funding to low-carbon investments (New Climate Economy, 2017).

Getting from research to market is an identified bottleneck in the innovation system. The EU has introduced several different financing mechanisms – for instance, via the European Investment Bank (EIB) and the New Entrants Reserve programme (NER 300) – for securing ample finance to scale-up and demonstration projects that are high risk. The NER 300 is an EU scheme to provide financial support to innovative renewable energy technology and CCS, by using the income from 300 million auctioned emission allowances under the ETS. Beginning in 2020, it will be replaced by the EU Innovation Fund.

The NER 300 programmes focused on energy and not on industry, though CCS for industrial application was eligible. One demonstration project – a CCS-equipped steel mill in Florange, France – was awarded but never finalised due to uncertain steel markets and a low price on European Emission Allowances (EUA). However, the EU Innovation Fund, which will fund projects from 2020 to 2030, specifically includes energy-intensive industry. The importance of public financing, as well as its limits, can clearly be seen from the experiences so far with the NER 300. The programme had ample of funds for investment grants (over EUR 2 billion), but several of the planned and granted projects were never implemented due to uncertain market conditions and a lack of demand-oriented policies (Åhman et al. 2018)

The discussion on "greening finance" also involves raising awareness in the financial community about climate change as both a major risk and an opportunity. Financing institutions generally have a lack of knowledge on the options to make a sensible risk assessment (Polzin 2017). In a low-carbon economy, investments in fossil-based companies can be a high risk (Leaton 2012; Battiston et al 2017), as demonstrated by the devaluation of assets by European energy utilities in recent years (Material Economics & SEI 2018). The risks involved in both direct fossil fuel investments and in companies reliant on fossil fuel markets (such as those selling equipment and services to the fossil fuel industry) have recently been highlighted in several initiatives (WRI/UNEP-FI 2015), as these risks are still not properly analysed by the financial community.

6.3 Trade policy and industrial competitiveness

Steel is in general a globally traded commodity. If the EU imposes higher carbon costs on steel production (via EU ETS or a forcing regulation) and at the same time maintains free trade with countries with less climate ambition, this could lead to "carbon leakage" and climate-related trade conflicts. Such conflicts could exacerbate or complicate already ongoing conflicts around steel tariffs.

To maintain the steel industry's competitiveness and decrease the risk of carbon leakage, the EU has sheltered the energy-intensive industry (EII) from the direct and indirect cost increases from climate policies (Åhman and Nilsson 2015). For compensating the direct cost increases via the EU ETS, the EII receives mainly free allocation of emission permits according to predefined benchmarks to industries deemed exposed to carbon leakage (usually up to 90% of actual emissions). Furthermore, the EII receives preferential tax treatment with lower energy taxes and is exempted from the financial burden of renewable energy support schemes. Compensation for electricity price increases (indirect cost increase of the EU ETS) is also allowed under the ETS Directive (2009/29/EC). Nevertheless, European industry is facing considerably higher energy prices than important competitors in countries such as the United States and China (IEA, 2013). The strategy to shield industry from the carbon costs seems to have worked so far, since there is no real evidence of carbon leakage from Europe from the first periods of trading up to 2012 (Bolsher et al., 2013). However, future and more stringent climate policy will exacerbate the disadvantages, and the current compensation measures will be insufficient, as the carbon budget of the ETS gets tighter.

There is a long-term conflict embedded in the UNFCCC between achieving global cost efficiency and global fairness based on national differentiation. This is especially difficult for the steel industry, which produces goods traded on a global market, unlike the electricity or heat industries that mainly serve national markets. Introducing trade measures (such as carbon border adjustments) has been proposed and would probably be possible from a WTO perspective but could be challenged under the UNFCCC. However, the Paris Agreement, which embraces “self-differentiation”, sets a new basis for discussing trade issues and competitiveness driven by varying climate change ambitions (Åhman et al., 2016).

Furthermore, several of Europe’s competitors also subsidise capital and energy for the energy-intensive industry (Haley & Haley, 2013). Under the WTO, the EU can challenge non-EU countries that give unfair support to their industries through tariff and non-tariff barriers, subsidies and export incentives. It is difficult to judge how traded steel would be affected if the EU and other countries with high climate ambitions used some sort of carbon inclusion mechanism. Would it lead to retaliatory measures or open up opportunities for international agreements and strategies to decarbonise steel?

7. Opportunities and barriers for fossil-free hydrogen steel (H-DR)

In this working paper, we have identified several opportunities for fossil-free hydrogen steel, as well as several uncertainties and barriers that need to be overcome in order to make hydrogen steelmaking a reality within the next 20 to 25 years. Below we outline key questions and areas of interest that need to be explored in order to develop industrial and policy strategies for decarbonisation. These are structured into three sections: (7.1) techno-economic realities, (7.2) market changes and (7.3) policy preconditions. However, most of the opportunities and barriers are interdependent and need to co-evolve.

7.1 Analysing the techno-economic consequences of hydrogen steelmaking

What techno-economic pathways are feasible and flexible?
Shifting the current BF/BOF primary steel production to H-DR includes several sequential steps and depends on internal, as well as external, developments of technologies and markets. Several setbacks or unexpected developments may arise along the way. The understanding of how different pathways can evolve needs to be understood. This includes potential fallback strategies (e.g., reverting to natural gas instead of hydrogen), options for system integration and industrial symbiosis, the potential uses of oxygen, and the co-evolution with the use of hydrogen (for example, in the transport sector).

What is the development trajectory for electrolysis?
In the H-DR process, electrolysis (i.e., the development of electrolysis and catalysis as a general purpose technology) stands out as a key technology. The development of electrolysis matters both in terms of its investment and operating cost, as well as its energy efficiency and flexibility – all of which have implications for the production cost of steel. Analysing the development of electrolysis with the aim of understanding the various driving markets and applications (external to steelmaking) is valuable for understanding the risks and opportunities of this technology development block. The success for H-DR would result in a major growth in the electrolysis market. Ranzani da Costa (2013) conditions the success of the H-DR/EAF route on the emergence of a "hydrogen economy". However, the deployment of hydrogen-based steel production could act as a facilitator for the hydrogen economy, by growing the market for electrolysers and contributing to lowering costs.

What will be the future price of electricity for industrial customers?
A key determinant for the future competitiveness of fossil-free hydrogen steel is the cost of electricity. How could various market designs and institutional developments change the availability and cost of electricity for large industrial consumers? Thus, how the electricity market is designed and functions is of major importance and needs to be analysed in this context. This means looking at all the determinants that eventually set the total cost of electricity for a steel plant, including how climate policy and renewable energy policy is implemented, how and if capacity markets are set up, tax-exemptions, grid connections, cost developments for renewable electricity, relations to electricity suppliers, etc.

How flexibly can an H-DR plant be operated?
A feature of H-DR is the possible flexibility in power demand through production strategies and the provision of system services to the electricity grid. This is particularly important in power systems with increasing shares of variable renewable production. How this can technically be implemented while maintaining product quality and process integrity needs to be studied further in order to assess the economic costs and benefits of a flexible operation.

7.2 Identifying risks and opportunities with future markets

Can there be a premium market for green steel?
Fossil-free steel will most likely come at a premium cost compared to current steelmaking, at least with current low carbon prices. However, the markets for steel are not all driven by strict cost competition; several market segments are willing to pay for special features of the steel. Whether there can be a viable

market and willingness to pay for steel with no up-stream emissions is still uncharted territory – how, where and when needs to be explored. This also relates to the question of whether policy can help make the "green" visible to end consumers, such as through labelling and traceability, or stimulate market development in other ways.

How can customer demand for specialty steel develop?
The main focus for the steel industry is to create value for its customers. It is thus important to understand customers and their current and future needs. This could include understanding current customers (several of which are in the fossil fuel industry and thus at risk), as well as potential new customers (such as in fuel cells, light steel construction or even hydrogen infrastructure) who are likely to have new demands on both the quality and "green" credentials of the steel.

How can green steel develop outside the EU and Sweden, and could H-DR development spawn an export market?
The largest climate benefits will come from wider deployment of the H-DR technology and the replacement of blast furnaces or natural-gas-based steelmaking in countries like China, India and the Middle East. In this context, it would be interesting to explore the prospects for building coalitions or alliances for developing key technologies, green steel production and markets. This could be accomplished under the UNFCCC and Paris Agreement framework, or through bilateral and other cooperation agreements. Developing a new H-DR process could also spawn a market beyond steelmaking. The EU could be motivated to take the lead on H-DR development by the potential for future patenting and licensing of key technologies for application in other sectors and to capture the advantage as an early adopter.

7.3 Addressing systemic innovation barriers with policy

How does the current industrial policy in the EU and Sweden address barriers for development?
To overcome specific and systemic barriers to the development and deployment of H-DR is likely to require new EU (and Swedish) industrial policies – ones that include zero emissions as a necessity in addition to traditional industrial policy goals. A better policy framework should include both "push" and "pull" policies that are integrated towards a common goal. Policies at the EU level that need to be discussed with this in mind include the Innovation Fund, the Horizon 2020 R&D, the post-2020 Renewable Energy Directive, state aid rules, public procurement rules, labelling schemes (e.g., for green buildings), and proposed material taxes or green material quotas.

How can policies reduce financial risk for large-scale green investments?
An overarching aim of innovation support is to de-risk investments for technology development, pilots, demonstrations and eventually commercial scale plants. The governance of finance includes financial institutions that condition the availability of finance and financial risks, such as development banks, government loans and subsidies, export credits and ownership structures.

How does the global and highly competitive structure of the steel sector influence prospects for decarbonisation?
The steel industry is exposed to competition from countries with far lower climate ambitions and thus lesser direct or indirect "carbon costs". This raises the question of carbon leakage and future loss of competitiveness. Viability of investments are thus potentially dependent on policies such as direct public support and de-risking, border carbon tax-adjustments or other carbon inclusion mechanisms, trade policy, and embedded carbon requirements in domestic markets. Investments could also be affected indirectly by policy impacts from other sectors, especially unexpected changes in energy policy.

8. Conclusions

When the Paris Agreement was signed in December 2015, climate mitigation policy entered a new phase. A systemic change in how we produce, use, and recycle steel needs to evolve in the coming 20 to 30 years for the steel sector to have its place in a low-carbon society. This report is focused on the production of primary steel via fossil-free hydrogen (H-DR process) and provides an overview and analysis of the key aspects that can make this a reality. We also identify key issues that need to be better understood in order to develop effective industrial strategies and public policies for decarbonizing the steel industry.

The transition into fossil-free H-DR steel does not require fundamental breakthrough technologies, though it represents a major systemic change in terms of replacing the current blast furnace to basic oxygen furnace (BF/BOF) route. The success of the H-DR route is technically dependent on the development of large scale electrolysis and, in some cases, on hydrogen storage. Both these technologies exist today and the potential for cost and efficiency improvements is large. In addition, the development costs may be shared by several sectors, since these technologies have a potential for other applications. An H-DR steel plant could essentially be built based on current available technologies. However, further advances are needed to integrate the various technologies and for testing, developing and demonstrating the quality of the H-DR liquid steel.

The production cost for fossil-free H-DR steel looks promising. For expected carbon prices, it is in the same range as the production cost for the other main alternative route for decarbonising steel, the blast furnace to carbon capture and storage (BF/CCS) route. The main cost driver for the H-DR route is the electricity price. The H-DR route offers high production flexibility through storage of hydrogen and hot briquetted iron, as well as through varying the amount of scrap steel used. It may also offer the benefit of technology spill-overs in the fields of electrolysis and hydrogen.

Although the prospects for H-DR look promising, the risks involved for individual companies to demonstrate and invest in fossil-free steel production mean that public policy measures could be necessary to enable this transition. The risks appear to be less technical in nature and more about the political landscape, in terms of how future markets will evolve and how climate and energy policies are implemented. The risks and benefits of investing in a major shift need to be shared between private and public stakeholders in a way that allows for transparency and accountability. Some challenges must be tackled, such as the effects of this shift on trade and carbon leakage for the globally competitive steel industry. As a climate leader, the EU has a strong climate policy rationale to develop fossil-free steel production technology and spread it globally.

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