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Stainless green: Considerations for making green steel using carbon capture and storage (CCS) and hydrogen (H₂) solutions

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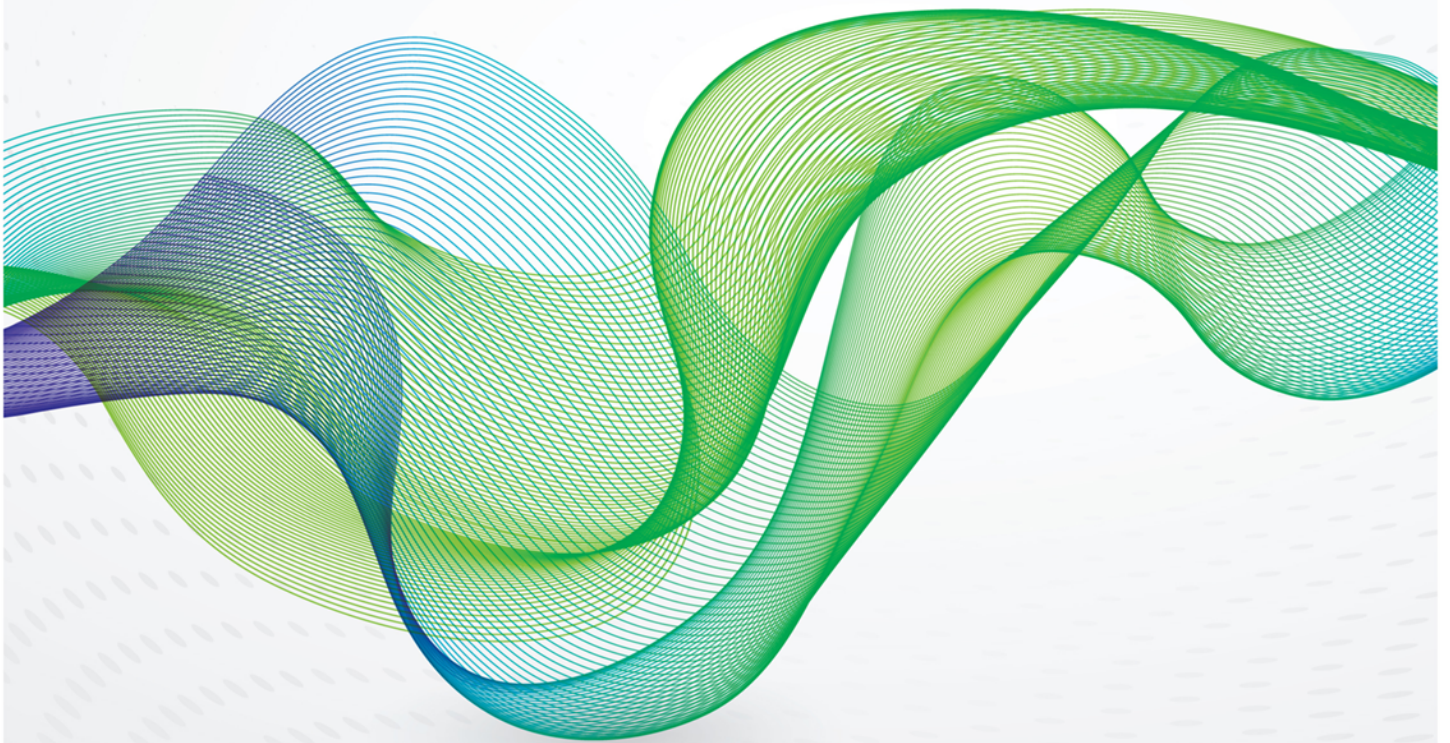
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May 2023

Stainless Green:

Considerations for making green steel using carbon capture and storage (CCS) and hydrogen (H₂) solutions





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Contents

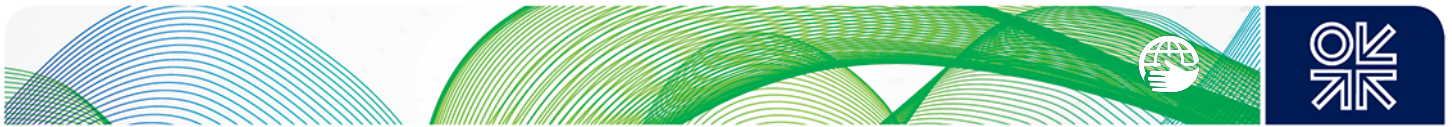
Contents.....	ii
Figures	ii
Tables	ii
1. Introduction	1
2. How is (green) steel made?	2
2.1 Integrating CCS into steelmaking	3
2.2 Hydrogen-based steelmaking	4
3. The green steel premium	6
4. Competition, trade and regulation.....	8
4.1 Supply side ‘push’ mechanisms	9
4.2 Demand-side ‘pull’ mechanisms	10
5. Implications and concluding remarks.....	11
References.....	13

Figures

Figure 1: Top 10 steel-producing countries in 2021.....	1
Figure 2: The iron and steelmaking process.....	2
Figure 3: Biomass and CCS in the steelmaking supply chain.	3
Figure 4: Business ecosystem of an automaker adopting green steel.	11

Tables

Table 1: Green steelmaking initiatives	5
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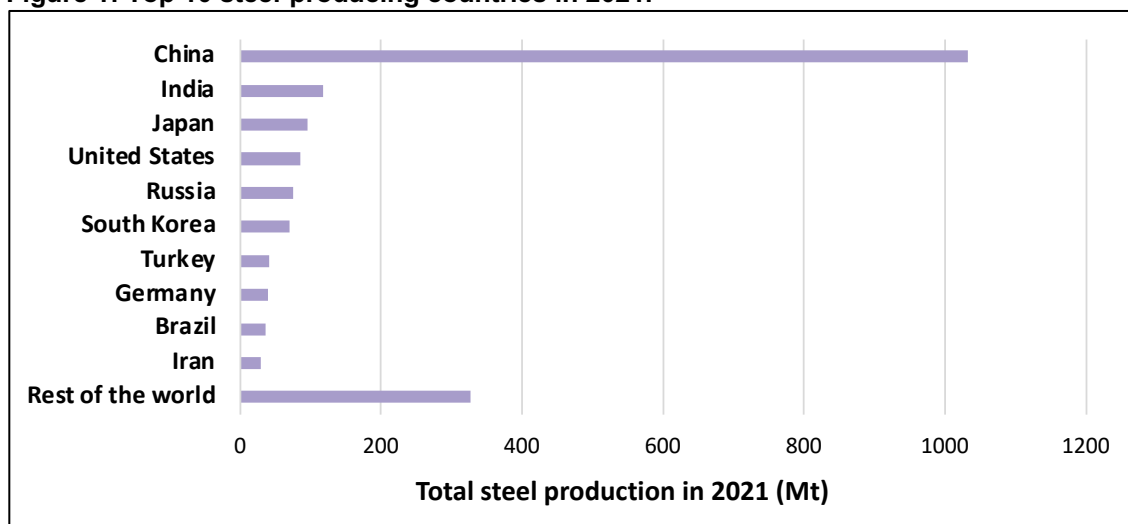
1. Introduction

Climate change has led to the acceleration of decarbonisation in almost all aspects of modern society and economies, most recently in the non-power industrial sector (International Energy Agency, 2022). Steelmaking is one of the main contributors to emissions in the industrial sector – second only to cement production – and accounts for 7% to 9% of global anthropogenic CO₂ emissions (World Steel Association, 2021a). Recently, the steel sector has witnessed several new developments to lower emissions in the sector led by its stakeholders worldwide, namely the move towards producing what is now dubbed ‘green steel’ (Muslemani et al., 2021; Griffin & Hammond, 2021; Vogl et al., 2021). While the exact definition of green steel remains debatable – and is itself a core subject of research, the concept has gained traction within the global community, as investment is being channeled from governments, steelmakers and large steel consumers to produce or procure green steel, however it is defined (Pooler, 2021).

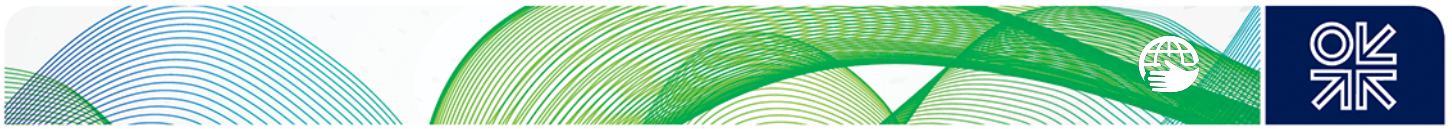
In fact, on a per-tonne basis, steel already has one of the lowest carbon footprints amongst materials used today, with 1.89 tCO₂ emitted per tonne of primary steel produced (World Steel Association, 2021a). In comparison, producing primary aluminum emits between 7-20 tCO₂ per tonne, depending on the production process and energy input used. However, steel’s significant contribution towards global emissions is due to its sheer volume: around 1,950 million tonnes of steel were produced in 2021 (World Steel Association, 2022). Steel, a material that is endlessly recyclable in nature and is indispensable in certain applications, will continue to remain a critical element of society. Yet, from an emissions standpoint and unless urgently addressed, the steelmaking sector alone is on track to consume 50% of the total remaining carbon budget needed for a 1.5°C scenario by 2050 (Rocky Mountain Institute, 2019a).

To appraise the potential for decarbonizing the steel sector is to first understand how steel is made. Broadly, crude steel is either made using a primary route, i.e., producing ‘virgin’ steel from iron ore, or a secondary route where steel scrap is recycled into new steel. More than 75% of global steel is produced via the primary route, a process that can be more than four times as emissions intensive as the secondary route (1.89 vs 0.45 tCO₂/t) (World Steel Association, 2021b). This perhaps makes for the case that recycling steel should be prioritized over primary production when possible. However, while the argument has merit, a limited availability of high-quality scrap globally and the superiority of primary steels over recycled steel in terms of strength and durability means that primary steel production cannot be substituted. For geographical context, more than half of global steel is produced in China, with heavy reliance on coal as an input material into the production process (Figure 1).

Figure 1: Top 10 steel-producing countries in 2021.



Source: Based on data by World Steel Association (2022).



Technically, the literature on routes to decarbonizing steel production is vast, yet one thing is made evident: relying on traditional energy-efficiency measures alone is not enough as, collectively, they can only contribute towards 25-40% of overall reductions in process emissions (An et al., 2018; Liang et al., 2020). More drastic reductions can only be achieved by integrating breakthrough low-carbon technologies into steelmaking, which can be broadly classified into three groups:

- i) Carbon-based, where CO₂ is eliminated from the process using carbon capture and storage (CCS) technology (i.e., process integration pathway);
- ii) Hydrogen-based, where hydrogen substitutes coal or natural gas as input material (i.e., carbon avoidance pathway); and
- iii) Electricity-based, where iron ore is reduced using electricity (i.e., electrolysis).

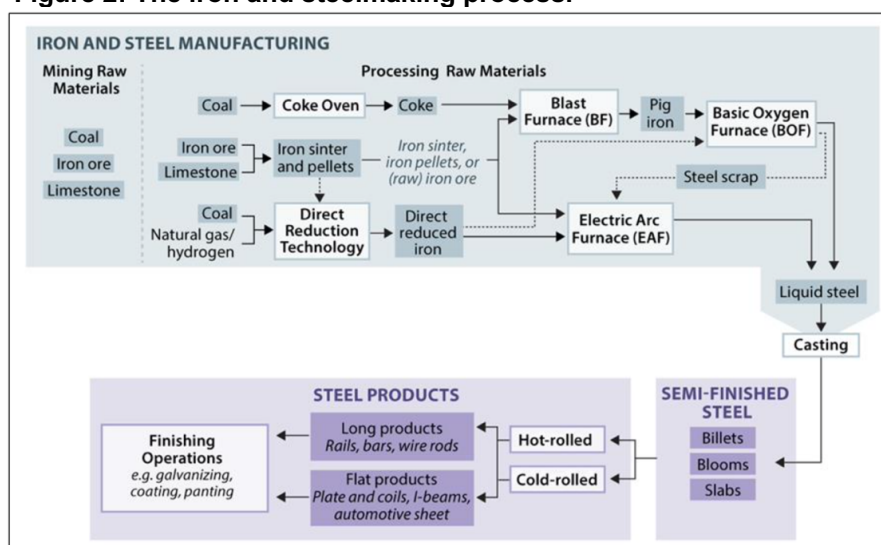
This paper sheds light on barriers and opportunities to decarbonize steel production using CCS and hydrogen-based solutions and the impact on the commercial potential of the (green) steel made using cleaner processes. The paper then reflects on the role that governments and the private sector can play in mobilizing a green steel market.

2. How is (green) steel made?

Primary steel is produced using one of two processes: an integrated route involving a blast furnace combined with a basic oxygen furnace (BF-BOF), or an electric arc furnace (EAF). In the integrated route, coal is first converted to coke in coke ovens through carburization (heating at high temperatures in the absence of oxygen). Coke is then used as a reducing agent for iron ore in the blast furnace, resulting in liquid iron (also called pig iron). Pig iron is subsequently charged with some steel scrap in a basic oxygen furnace where, in excess oxygen, carbon is removed and liquid steel is produced for further processing (i.e., hot and cold rolling).

An alternative to using a blast furnace is reducing iron by removing oxygen directly from iron ore without the need to melt it, a process called direct reduced iron (DRI). The direct reduction (DR) process uses natural gas as input material and, despite being around 20% more energy-intensive than the BF-BOF route, it emits around 20% less CO₂, owing to the lower carbon footprint of natural gas compared to coke (GCCSI, 2017). However, the DR process remains limited to areas where there is abundance of natural gas such as North America or the Middle East (Figure 2). The DR route is often combined with an electric arc furnace which uses electricity to melt steel scrap, and to which alloys are added to adjust the final product to the desired chemical composition. The following sections provide an overview of CCS and hydrogen applicability in the two steelmaking routes.

Figure 2: The iron and steelmaking process.

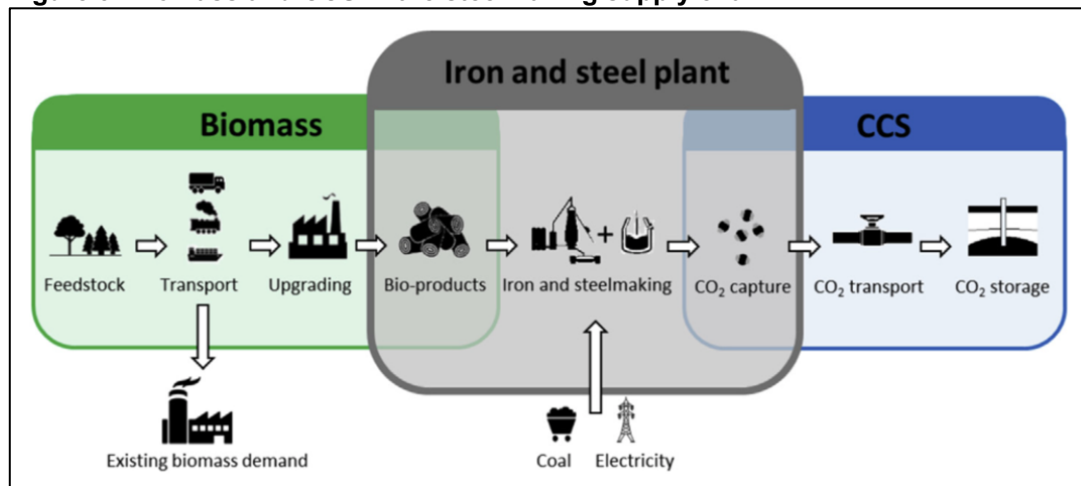


Source: Designed by Muslemani et al. (2021) and later adapted by the US Congressional Research Service (2022).

2.1 Integrating CCS into steelmaking

Most steel is produced using the BF-BOF route, accounting for around 90% of primary production and around 70% of overall global steel production (IEA, 2020; World Steel Association, 2021b). One way to reduce the emissions intensity of primary steelmaking is to use biomass as reductant instead of coal or renewable energy to power the process. Another is to introduce CCS. In theory, producing steel using biomass is promising as the generation of bioenergy itself can be coupled with CCS (i.e., BECCS) which may result in 'carbon-negative' steel. However, biomass itself carries a 'carbon debt', meaning once burned, it will re-emit CO₂ which had been absorbed during its growth. So, unless sustainable biomass resources are used and rigorous interventions and accounting are applied along the biomass's supply chain, producing steel with BECCS may merely shift emissions upstream (Tanzer et al., 2020). More importantly, even if possible, shifting to bio-based steelmaking may be limited to areas with abundant bio-resources, such as Australia and Brazil, and is not a sustainable option for many regions seeking aggressive emission reductions from the sector, such as in Europe. Here, rather than applying CCS to the underlying energy source, it can be directly implemented at emission-intensive stages of the steelmaking process (Figure 3).

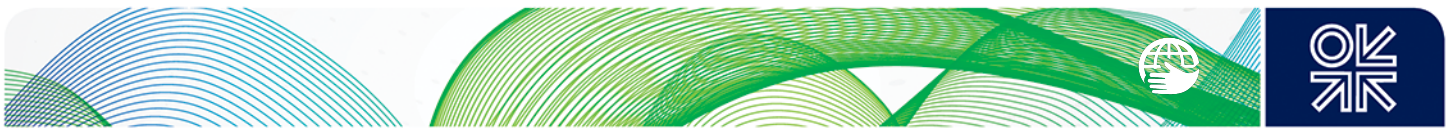
Figure 3: Biomass and CCS in the steelmaking supply chain.



Source: Mandova et al. (2019).

For perspective, an integrated steel mill has multiple emission point sources, including flue gas stacks at the hot blast stove and lime kiln, and the combustion of gases in the coke oven, blast furnace and basic oxygen furnace. These flue gases contain CO₂ in varying concentrations so, from a techno-economic perspective, capturing CO₂ would be most worthwhile where CO₂ volumes and concentration in the flue gas are the highest: that is at the blast furnace. On average, a blast furnace accounts for around 60% of emissions of the entire steelmaking process (GCCSI, 2017). This also entails that even if most emissions from the blast furnace are captured (assuming typical capture rates of around 90%), the emissions intensity of the overall steelmaking process would only be reduced by around half, making CCS only one part of the decarbonisation solution for the industry. Note that, as of the time of writing, no large-scale projects have demonstrated carbon capture at the blast furnace, although small scale trials are now being commissioned including a joint venture by ArcelorMittal, BHP, Mitsubishi Heavy Industries Engineering and Mitsubishi Development at an ArcelorMittal steel plant in Gent, Belgium (ArcelorMittal, 2022).

An alternative to deploying CCS to a BF-BOF route is capturing CO₂ from natural gas when used as input into the DR process (Figure 2). In fact, the only fully commercial steelmaking project applying CCS at scale is a DR-based one: that is the Emirates Steel CCS project in Abu Dhabi, operational since 2016. The case of the Abu Dhabi CCS project is an insightful one as it exemplifies where CCS may be a feasible option for other similar low-carbon steel projects, at least with current economics. The Emirates Steel plant uses cheap natural gas to reduce iron ore which produces a high-concentration CO₂ stream, making carbon capture an even cheaper process. The project is also close to a geological



reservoir (accessible with a 42km pipeline) that allows to use the captured CO₂ for enhanced oil recovery (EOR) (Sheet Piling UK, 2022), which creates an attractive economic incentive in the form of revenue generated from increased oil recovery and sales.

However, obstacles which are inherent to CCS as a technology – regardless of the sector it is deployed in – are important. Geographically and geologically speaking, the capture source (a steel plant in this case) should be close to a storage site, whether for permanent storage or EOR, or at least in proximity to an industrial cluster or a CCS hub from which CO₂ will be collected for eventual transport and storage. Politically, the jurisdiction in which the steelmaking plant operates should allow for the capture, transport and storage of CO₂, or at least for part of this chain. For example, in Germany, steel plants may be able to capture CO₂ at source but, by law, are prohibited from storing CO₂ under national territory. In such instances, the location of the plant and its potential to use a cross-border transport and storage network become key (Dickel et al., 2022).

2.2 Hydrogen-based steelmaking

An alternative to the blast furnace route is an electric arc furnace (EAF) which uses electricity to heat up the metal to a degree where it can be transformed and shaped – around a quarter of global steel is made using an EAF (World Steel Association, 2021b). However, an EAF requires an already-reduced input material: it cannot produce steel directly from iron ore. This material can be direct-reduced iron (DRI) which, as noted earlier, can be produced using natural gas as reagent. This is where hydrogen comes in: hydrogen can substitute natural gas as input material into the DR process, in combination with an EAF (the H₂-DR-EAF method). Note that an EAF can practically produce steel purely from recycled scrap (i.e., scrap-EAF), but due to increasing quality issues with recycled steel, virgin steel (steel sourced from iron ore) will always be needed to ensure high-grade quality of finished steel.

From an emissions standpoint, DR-based steelmaking has two benefits. First, DR eliminates the emissions associated with a traditional blast furnace. Second, if combined with hydrogen, the need for natural gas as a reagent is eliminated, in turn avoiding the emissions associated with its combustion (and hence the need to capture CO₂ at the DR stage as in the Emirates Steel project). However promising, H₂-based steelmaking would still incur emissions elsewhere – and potentially in significant amounts. This is because hydrogen, unlike carbon, is not a resource that is readily available from the geosphere (such as coal or coke) or the biosphere (e.g., biomass and charcoal) and needs to be produced through the electrolysis of water. In this process, large amounts of electricity would be consumed at three stages of the H₂-DR-EAF route: to generate the hydrogen itself, and to power the DR and EAF processes. Therefore, the carbon footprint of an H₂-DR-EAF process will predominately depend on the structure of the power grid supplying that electricity.

For context, producing one tonne of crude steel through H₂-DR-EAF requires around 3.48MWh of power: 2.65 MWh for hydrogen generation and an additional 0.83 MWh to power the direct reduction and EAF processes (Vogl et al., 2018).¹ If a global average CO₂ intensity of 0.48 tCO₂/MWh is assumed, this would correspond to 1.67 tCO₂ per tonne of steel using H₂-DR-EAF, a level not drastically lower than the global average carbon intensity of steelmaking (1.89 tCO₂/t).

It thus becomes clear that the highest potential for emissions reduction for H₂-based steelmaking lies in regions where the energy mix is mainly made up of clean, renewable electricity. It comes as no surprise then that the two leading projects in hydrogen-based steelmaking – HYBRIT and H₂GreenSteel – are both located in Sweden where renewable resources dominate the national grid. In Sweden, process emissions would be reduced by 95% by switching to H₂-DR-EAF, while equivalent emission reductions in European and US steelmaking are estimated at 40% and 20% respectively (Rocky Mountain Institute, 2019a). Counterintuitively, in China, switching to H₂-based steelmaking would *increase* the emission intensity of steel, due to China's heavy reliance on coal for electricity generation.

¹ In comparison, producing crude steel using the BF-BOF method requires around 13.3J/t, equivalent to around 3,68 MWh/t (Otto et al., 2017).



One advantage of switching from a BF-BOF to a DR-EAF route (whether NG- or H₂-based) is that the impact of emissions reduction would be progressively felt over time as more renewables continue to penetrate the electricity grid, meaning there is no need to wait until green hydrogen becomes commercially available. However, the timeliness of the decision as to whether to switch from one production route to another is crucial. Many BF-based steel plants around the world are coming to the end of their operational lifetime and if steelmakers reinvest in existing (carbon-intensive) integrated production assets, they may risk falling into a ‘carbon lock-in’ effect. In this case, operators would continue to rely on fossil fuels that are becoming increasingly more expensive especially following the global energy crisis, and with rising carbon prices on the horizon. Table 1 provides an overview of the underlying low-carbon technologies of existing and forthcoming global green steel projects.

Table 1: Green steelmaking initiatives

Company	Project/Technology	Location	Target
ArcelorMittal	Hydrogen reduction with grey hydrogen	Hamburg,	Fossil free by 2050
	Blast furnace + electrolysis for hydrogen production	Bremen, Germany	
	Hybrid blast furnace with direct reduced iron (DRI) gas injection	Dunkirk, Germany	
	Coke oven gas with grey hydrogen; hydrogen in DRI-EAF	Asturias, Spain	
HYBRIT (SSAB, LKAB and Vattenfall)	Replacing coking coal with hydrogen and fossil-free electricity	Sweden	Fossil free by 2045
Boston Metal, BHP & Vale	Molten oxide electrolysis (MOE) technology	Massachusetts, USA	n/a
China Baowu & BHP	Memorandum of Understanding to share technical expertise in reducing emissions from steel, including using CCUS	Multiple steelmaking bases in China	n/a
Ovako	Hydrogen use to heat steel before rolling	Hofors, Sweden	n/a
Liberty Ostrava	Building hybrid furnaces	Czech Republic	Hybrid furnaces built by 2022
Rogesa	Hydrogen in coke gas as reducing agent	Dillingen, Germany	Started operations in
Tata Steel	CCS under North Sea; water electrolysis to produce hydrogen and oxygen	Ijmuiden, Netherlands	Carbon-neutral in Europe by 2050
Thyssenkrupp	Hydrogen as reducing agent; use of renewable hydrogen from RWE & feasibility study for water electrolysis plant	Duisburg, ^	First phase testing in 2021, second phase in 2022.
Voestalpine Primetals Tech.	Hydrogen as reducing agent to process iron ore concentrates	Linz, Austria	80% carbon emissions reduction by 2050
Tenaris, Edison and Snam	Electrolysis/hydrogen-based steelmaking	Bergamo, Italy	



Salzgitter AG (Salcos project)	Electrolysis/hydrogen-based steelmaking	Wilhelmshaven, Germany	2 million tonnes per year of DRI (by the end of first implementation stage, expected for 2025)
Duferco	Using hydrogen in beam furnace with green PPA.	Brescia, Italy	
Celsa, Statkraft & Mo industrial park AS	Electrolysis/hydrogen-based steelmaking	Norway	50% emissions reduction by 2030, decarbonization by 2050.
H2 Green Steel Initiative	Hydrogen-based steelmaking	Northern Sweden	Planned production to start in 2024. Annual production target of 5 million tons of green steel by 2030.

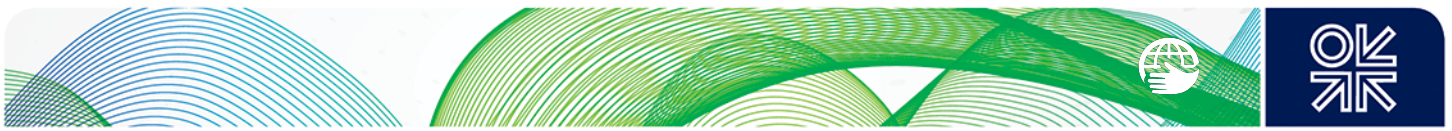
Thus, the choice of integrating CCS or hydrogen into steelmaking relies on several technical, economic and regional factors, while the cost burden for a clean transition in any specific route may not be influenced by the same energy markets and regulations. On the one hand, for a BF-BOF route, costs are highly dependent on prevailing coal prices and whether a carbon tax exists (and the level of said tax): the higher the tax, the more attractive the case for CCS becomes. On the other hand, the likelihood of switching to a H₂-DR-EAF route is highly context- and location-dependent: regions with low-cost, clean electricity, H₂-specific subsidies, and higher availability of steel scrap for recycling are expected to lead this transition (Bhaskar et al., 2022).²

At a corporate level, a number of other broader criteria influence whether a primary manufacturer shifts towards green steelmaking altogether, including i) the potential of that shift to contribute to strategic corporate purposes, such as compliance with climate targets or enhancing a corporate social responsibility image, ii) impacts of the shift on the overall industrial supply chain and its management, not only the steelmaking supply chain itself but also chains of other industries relying on steel as an input material, such as the construction and automotive sectors, and iii) the marketing potential of the final 'green' product.

3. The green steel premium

Perhaps the most notable obstacle to greening steel production is cost. On average, costs of producing greener steel – whether through carbon capture or hydrogen integration – can range from 20-30% (SSAB, 2019; Muslemani et al., 2020) up to 50% higher than conventional production (Rocky Mountain Institute, 2019b). This is largely due to the high capital costs inherent in carbon capture technologies and electrolyzers, despite projections for cost reductions with increased deployment (Patonia and Poudineh, 2022). In effect, the economic viability of green steelmaking will ultimately depend on whether an equivalent premium can be passed down onto final consumers or supported freely by the market. On the latter, a Swedish study shows that H₂-based steelmaking can be cost competitive at a carbon

² The higher the amount of steel scrap in the EAF process, the cheaper the steel produced.



price of €34-68 per tonne of CO₂ and electricity costs of 40 €/MWh (Vogl et al., 2018). It is key to note that future costs will also depend on how quickly energy efficiency can be enhanced and reductions in capital costs realised, while there is an opportunity to commercially exploit the excess oxygen gas which is generated as by-product in the hydrogen-making process.

Steel is an internationally traded commodity which is subject to fierce competition both in domestic and overseas markets, where a premium green steel product would be in direct competition with its traditional, cheaper and more carbon-intensive counterpart. Because they operate on such narrow profit margins, (green) steelmakers would be at risk of losing market shares so early adopters will be at a first-mover disadvantage, unless they compete based on product differentiation rather than on cost. Yet, product differentiation may in itself be a challenge since the final product (green steel) which is fundamentally different from an emission-intensity perspective, is not observably distinct from traditional steels. Indeed, this is one of the issues surrounding – and perhaps hampering – the establishment of a green steel market, where rigorous measurement, reporting and verification (MRV) in addition to clearly defined standards and certification processes should be in place to mitigate against the risk of greenwashing (Muslemani et al., 2021).

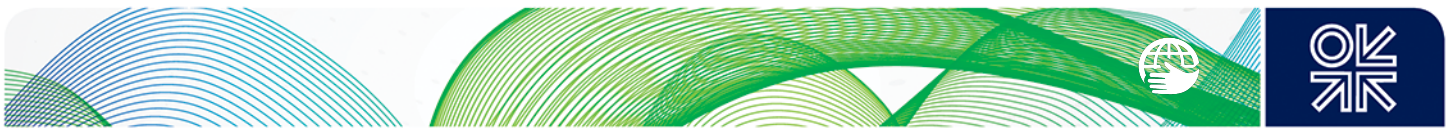
Despite the challenges, unlike renewables which feed into one grid and cannot be distinguished from other fossil sources once in the mix, green steel products can be traced back to specific green manufacturers. Moreover, much like renewables, there may be a willingness amongst end-consumers to pay for greener products: how much of a premium that could be remains to be determined. Studies investigating consumer willingness to pay (WTP) have often been used as a tool by corporates to forecast adoption rates of innovative technologies or new products (e.g. Asgari and Jin, 2019; Olum et al., 2020). For green steel, however, it may be difficult to elicit the end-consumer's WTP due to several factors: for one, it is not straightforward to define *who* the final steel consumer is, as steel only makes up one part of most end-products (e.g., vehicles or bridges). Broadly, the overall value chain of an industrial product like steel consists of three stages: 1) manufacturer of the product (the steelmaker in this case), 2) industrial consumer (the automaker or construction company), and 3) the end user (individuals buying vehicles or houses).

More specifically, eliciting the willingness of a consumer to pay a premium for green steel would be especially challenging since i) a variety of industries with different supply chain structures rely on steel as a major input material, ii) there is a relative disconnect between supply chain players, making it difficult to coordinate amongst and elicit the willingness of each player to pay for a greener final product, iii) proportions of steel in the makeup of final products vary across industries (e.g. roof toppings vs vehicles) and across different products within the same industry (e.g. different automakers producing different car models), and, iv) large-scale consumer WTP studies which have the potential to generate meaningful results would be excessively costly to undertake. For these reasons, the willingness to pay for and adopt green steel is best assessed at intermediate stages along the supply chain, where large points of steel consumption exist (i.e., industrial consumers).

Following this narrative, Muslemani et al. (2022) surveyed a number of automakers and automaker associations to appraise the likelihood of the sector becoming an early adopter of green steel, and several key observations were made. First, it may be possible to pass down the premium cost of green steel onto final products (cars) in a relatively inexpensive way. For perspective, passenger cars contain around 0.9 tonne of steel on average (World Steel Association, 2020): if made with greener steel which costs 20-50% more, the cost of the overall vehicle would increase by around €108-338.³ Given that the retail price of average European passenger cars was around €32,000 in 2020 (International Council on Clean Transportation, 2023), this corresponds to an increase between 0.5-1% in the final cost of the vehicle.

This may still admittedly be too high a premium for middle-income users to pay – especially as end-users are usually more concerned with fuel economy than with how a car is made (Chowdury et al., 2016). The alternative is for vehicle manufacturers to bear increased production costs themselves.

³ Assuming 600-750€ per tonne of steel based on 2019 trends (World Steel Prices, 2020).



Proportionally speaking, this price premium becomes increasingly less significant for higher-end, luxury vehicles, for which buyers may have a higher willingness to pay for ‘greener’ cars. Yet, evidence shows that manufacturers of luxury vehicles are already moving away from steel altogether and towards procuring lightweight aluminum and plastic composites, as they can offer similar performance to steel in terms of durability and resistance, but at a weight reduction (and hence an enhanced fuel economy) (Maw, 2018).

That said, a willingness to adopt premium green steels may exist in the manufacture of heavy-duty vehicles – those which contain significantly more iron and steel by weight (around 5-6 tonnes per vehicle). Moreover, in heavy-duty vehicles, steel cannot always be substituted in the main vehicular body due to safety reasons, especially when demand for trucks with higher load-bearing capacities has been increasing (Santos et al., 2017).

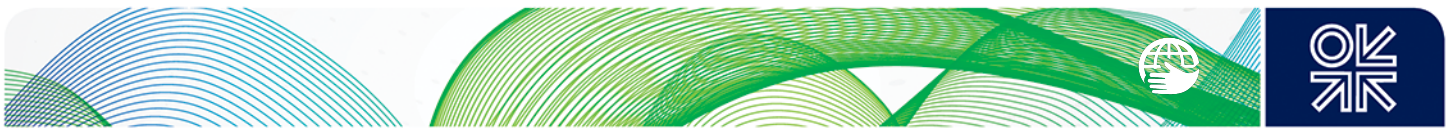
The case for green steel becomes even more appealing in *electric* heavy-duty vehicles, where most lifecycle emissions are concentrated at the production rather than the operational phase of the vehicle (of course, assuming the use of clean electricity). Indeed, from a lifecycle perspective, switching to greener materials as input into these vehicular types is where the highest emission reductions can be achieved (Verma et al., 2022). Economically, integrating green steel into electric heavy-duty vehicles has the potential to become mainstream practice if the manufacture of electric vehicles (EVs) themselves is subsidized: an example of a heavily subsidized EV initiative is that of Volvo Lights in Southern California (Shahan, 2020). Due to the aforementioned reasons, it is not surprising that there has been a recent trend of market collaborations between automakers and green steel suppliers, including between BMW Group and US-based steelmaker Boston Metal, Mercedes-Benz and Sweden’s H₂GreenSteel project, and Volvo Trucks and SSAB’s H₂-based green steelmaking project (HYBRIT), to name a few.

Drawing on a parallel from the construction industry, Subraveti et al. (2023) show that, despite significant increases in steel and cement costs due to CCS integration at steel and cement facilities, the eventual impact on the cost of constructing a bridge as a final product are minimal. The study shows that greener steel and cement made with CCS would only lead to a 1% increase in the overall cost of the bridge, while leading to more than 50% of emissions reduction from the production and use of both materials (Subraveti et al., 2023).

4. Competition, trade and regulation

Green steel products can be subject to market competition on four different levels. First, they will face competition from their locally produced, ‘brownier’ and cheaper counterparts. Second, unless properly regulated, green steels made via different production routes may compete amongst each other. Case in point, steel made through the primary, carbon-intensive route will be under higher emission reduction pressure than its recycled counterpart, while requiring the installation of expensive breakthrough low-carbon technologies (CCS/H₂). In contrast, recycling steel via electrification will not only always be cheaper (as it uses recycled steel as raw material) but will also only require sourcing renewable electricity upstream to meet greener targets (which is technically much easier than switching production processes). Hence, if green steel were to be purely defined in terms of a low carbon footprint, there should be a clear distinction between green steels made via primary and secondary (recycling) routes.

The need for this differentiation is not only an economical and logistical issue but also an accounting one. Recycled steel has an inherent carbon footprint that secondary steelmakers do not bear responsibility for, which puts primary manufacturers at an unfair disadvantage if primary and secondary producers were evaluated against the same emission standards. It may even lead to greenwashing if the true historical carbon footprint of recycled steel is not clearly communicated. Full life-cycle emissions assessment methodologies should be adopted industry-wide to transparently reflect the embedded carbon in steels and allow for a fair comparison between the virtues of different green versions of the same material, as well as comparison with other materials. This could perhaps make a case for establishing different classes – or ‘shades’ – of green steel, based on their environmental integrity.



Third, green steel will face competition from steel imported into the green steelmaker's region of operation, especially if the latter is not held against the same greening standards. National or regional regulatory frameworks can ensure this is not the case, by implementing carbon border adjustments on imports or providing local green producers with exclusive access to certain niche consumer markets. It is also imperative to note that the extent of the risk of imported steel undercutting locally produced green steel can be highly location-specific.

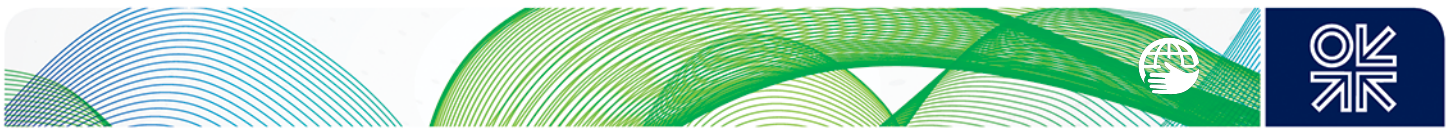
For example, adopting green steel in the North American automotive market may be more feasible than in other overseas markets, as automakers in the USMCA region (US, Mexico and Canada) are under obligation to source significant amounts of steel – and aluminium – from the region (i.e., 70% of total steel and aluminium in vehicles) (The Office of the United States Trade Representative, 2022). Moreover, more than two-thirds of US steel is produced using a recycled (greener) route (Lehman, 2022), leaving little-to-no space for international steel imports to compete whether on a cost or greenness basis, and in turn making for a compelling case for green steel production and consumption in the country. In Europe, product-specific carbon border adjustments will be implemented from October 2023 (European Commission, 2022), where European steelmakers are expected to be able to compete on a cost basis in local markets, assuming all regional and overseas steelmakers are subject to the same emission reduction standards.

Fourth, green steel would be in an indirect competition with other materials that can substitute steel's application in certain sectors altogether. For instance, steel may be substituted with cement (in construction), aluminium (in car manufacturing), plastic (in packaging), or ceramics (in vehicle engine manufacturing). This will naturally have implications on the type of regulation needed in place. In fact, whatever the regulatory framework implemented, it ought to be designed carefully to avoid unintended consequences. Case in point, if emission reduction targets are only placed on the sectors procuring steel – say the construction or automotive sectors – rather than or in combination with the steel industry itself, stakeholders in these sectors may still shift towards consuming cheaper and/or other lesser carbon-intensive materials anyway. Assuming that the purpose of any regulatory mandates is to specifically mobilize investments into green steel initiatives, they should be designed with many aspects in mind, such as the steel industry's capacity to deliver greener steel at desired costs for the end-consumer, which calls for a complementary combination of policies at both the production and consumption levels.

4.1 Supply side 'push' mechanisms

In terms of green steel supply, a combination of reward-based mechanisms (carrots) and legal enforcement disincentives such as carbon taxation (sticks) has the potential to incentivize early-producers. Similar mechanisms have been successful in supporting emerging markets such as renewable energy generation, where energy suppliers needed to purchase a certain percentage of electricity from renewables or face a penalty (such as under the UK Renewables Obligation mechanism). Alternatively, regulatory mandates can be placed on steelmakers to produce a certain proportion of total steel as green, or to meet a pre-defined 'green threshold' for all steel a steelmaker produces on average. This could be implemented in various ways, including via a tradeable certificate scheme for green steel – similar to the UK Renewables Obligation – where steel suppliers or end-users would be required to purchase a certain proportion of green certificates per unit of steel, while producers of green steel would be awarded certificates which they could sell to offset their increased production costs.

As noted earlier, a carbon border adjustment mechanism (CBAM) can also ensure domestic producers are not undercut by steelmakers from countries without equivalent green mandates. However, a CBAM should be implemented with caution. The mechanism may expose local steelmakers – and in turn their related value chains – to carbon costs on their *entire* production, putting them at a disadvantage against importers who would only be liable for carbon costs on steels they import into the region of implementation. It is expected that, in time, a well-designed CBAM would incentivize other jurisdictions with high steel trade with the region of implementation to follow suit in greening their own steelmaking. In fact, even before its implementation, the forthcoming EU carbon border adjustments are already



exerting pressure on international producers (e.g., in India), potentially reshaping and setting new green standards for the global industry (Layek, 2023). Here, the definition of ‘greenness’ of traded steel is key: it is important to ensure that the carbon footprint is measured consistently amongst domestic and international suppliers to enable a robust and meaningful CBAM, otherwise the primary objective of the mechanism could be circumvented.

Even if successful, carbon border adjustments only serve to protect a domestic market from being undercut by *imported* products but does not ensure that exports can compete on a level playing field in overseas markets (for instance, the UK lime sector, as a major supplier to the steel sector, is a significant exporter whose overseas markets cannot be protected by UK Government intervention). Exports could instead be protected by exempting them from domestic green steelmaking mandates, but this would undermine the goal of decarbonizing the steel industry. It is therefore evident that implementing green production mandates in combination with carbon border adjustments will have significant implications on international trade and climate diplomacy, with close cooperation needed between major trading partners.

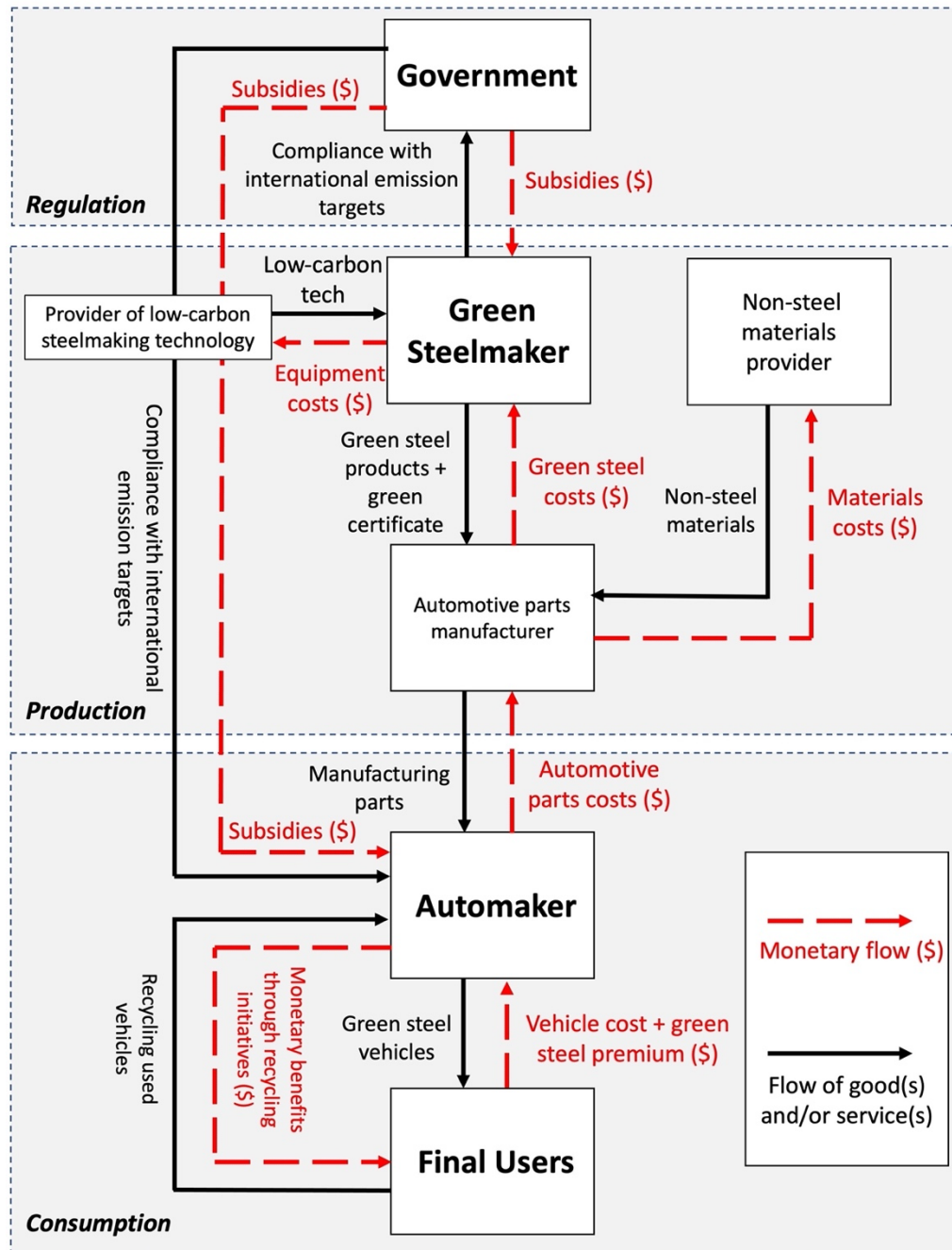
4.2 Demand-side ‘pull’ mechanisms

On the consumer side, a number of interventions can ensure there is demand for green steel. For one, governments, through public procurement, can specify minimum green steel requirements in the awarding of public contracts or – similar to the aforementioned regulatory mandates on producers – can require the use of certain amounts of green steel by industries, either at a sectoral level or by individual companies (e.g., automakers or construction companies). Admittedly, this may limit green steel production – at least in the short term – to certain ‘green suppliers’ and its consumption predominantly to government-backed projects. Yet, in time, green steelmaking may become mainstream practice as steelmakers would seek to avoid production inefficiencies arising from having two distinct production lines for observably similar products. Steelmakers would also be hesitant to lose customers to competitors who are actually greening production.

Absent such public interventions, a green steel market is likely to remain limited to certain niches of existing environmentally-driven consumers who are willing to pay a premium for greener products. This may present an opportunity especially for companies already producing highly-differentiated steel products (such as SSAB in the Swedish market), where consumers are more likely to remain loyal to their supplier (Chang and Fong, 2010). While compelling, developing a niche market for green steel may undermine the overall decarbonization efforts of the industry, unless sufficient policy support is provided to promote the practice from niche to mainstream over time. Another key area of intervention is certification: setting transparent and credible standards for green steel can enhance consumer trust in the product’s labelling and traceability.

Lastly, demand for green steel can be enhanced if a full lifecycle and circular economy thinking is adopted by the major steel-consuming industries (construction, mechanical equipment and automotive). In the automotive sector, an EU-wide fleet carbon intensity target of 95gCO₂/km applies to cars (European Commission, 2021); yet this target only accounts for tailpipe emissions (emissions produced during the car’s operation) and does not include production emissions: better reflection of the true carbon intensity of input materials used in these industries may have potential to drive change. Moreover, end-users (car buyers) could be made aware of the full energy and carbon footprint of their vehicles – through marketing initiatives for instance – whereby they may become more inclined to change purchasing behaviour, and in turn encourage companies to adapt their manufacturing strategies. Figure 4 summarises a number of demand- and supply-side mechanisms which may support green steel adoption in the context of the automotive sector.

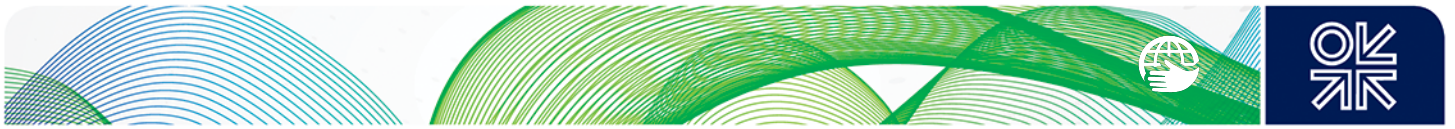
Figure 4: Business ecosystem of an automaker adopting green steel.



Source: The author.

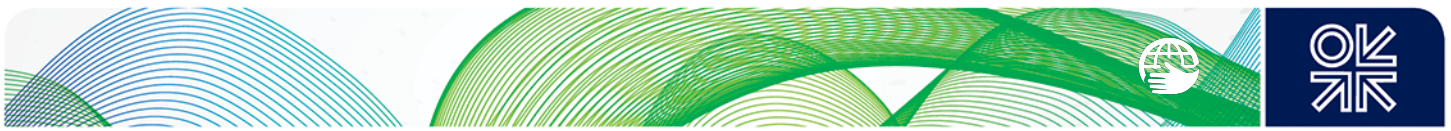
5. Implications and concluding remarks

This paper highlighted key considerations for creating a green steel market, by reflecting on the technical, political and economic underpinnings of existing or forthcoming green steel initiatives either using CCS or hydrogen direct reduction. This work also identified a range of policy mechanisms that can mobilize investments into this market, some of which have been tested and proven in similar emerging markets. However, the choice of specific policies – and combinations of those policies – hinges on the policy landscape in different regions, including government attitudes towards market intervention. Ad-hoc mechanisms may also be needed for major steel-producing countries which



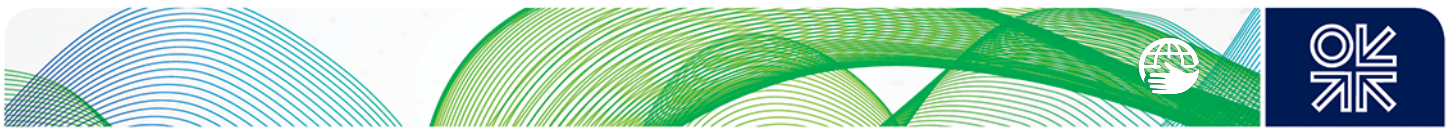
produce greener steel than they import (e.g., United States), which further emphasizes the need for highly context-dependent support policies. Major steelmakers and their largest customers may also voluntarily set emissions targets, for instance as part of the Science Based Targets Initiative (SBTi). Further research is needed to appraise the effectiveness of these different policy combinations.

In the short term, a transitional approach would be needed with governments initially sending strong investment signals to de-risk investments for producers. Subsequently, as producers grow confident that their competitiveness will not be compromised, standards on end-use products can help attract environmentally conscious consumers into the market, as it is likely that producers may not take the first initiative unless there is a certain and existing demand for green steel.

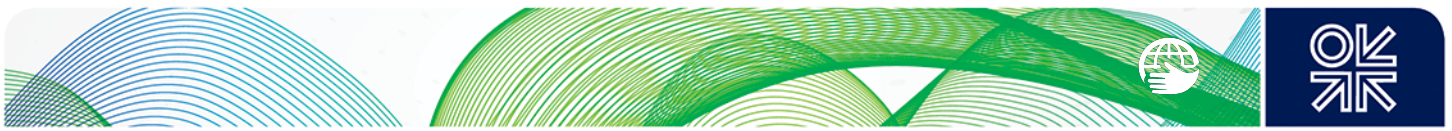


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