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Steel from DRI without CO2 emissions

A brief risk assessment with comparative pathways

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Policy Brief

Steel from DRI without CO_2 emissions – a brief risk assessment with comparative pathways

This Policy Brief was prepared for the Agency for Growth Analysis, Sweden

Lund, 27 February 2024

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1. Introduction

Sweden is at the forefront on technology development for the decarbonisation of the global steel industry. With the launch of HYBRIT, the first ever stated ambition by a steel company to reduce emission along the whole value chain down to zero; much attention has been given to what is happening in the northern part of Sweden. H2 Green Steel has also enter the "race to fossil free steel" and LKAB (the mining company has a vision to reduce all of its mined iron ore at the mining site to 2045. Other steel start-ups are also engaging in northern Scandinavia with BlastrSteel as a recent example.

The common denominator is that all these projects have chosen the same basic technology (but with some variants), namely hydrogen direct reduction for iron making followed by an electric arc furnace for steel making (H-DR- EAF route). This brief report aims to shed light on this choice of technology and the risks from a competitiveness view that might arise in the longer term. The risks investigated are resource risks, e.g. iron ore and electricity, and competitiveness risks, e.g. is there another technical options or regions that might outcompete Swedish hydrogen steel. The report does not give definitive answers as this is not relevant for a development that is still just emerging and where some of the key factors will be influenced by policy actions. The aim is to point to some areas of interest that might pose a risk and areas where Sweden should develop further.

For sake of transparency, I have been involved as a WP leader in HYBRIT RP1 which was the first research project (2017 to 2021) that "lay the research foundations" of the continued HYBRIT development.

2. The global green transition - steel still locked into coal

Pending on which scenarios we look at, the global steel industry needs to reduce their emissions down to zero by somewhen between 2050 to 2070 at latest. Sweden, as a developed country and in accordance with article 3 on "Common But Differentiated Responsibilites" (CBDR) in the UNFCCC (1992), needs to reach climate neutrality before 2050. This is also reflected in the Swedish Climate Law and in EU ambitions to assumes net zero by 2045 to 2050.

Today, steel is repsonsible for around 7% of global CO_2-emissions (IPCC 2022). The main culprit is the traditional steel making process of using a blast furnace that runs on coal, the BF-BOF process. This process is dominating global steelmaking with 70% today but is increasingly being questioned due to climate concerns. A blast furnace is estimated to last at least 40 years (IEA 2020) but has every 18 to 22 years a major renovation (relining of the blast furnace) that represent rouhgly 50% of the original CAPEX (Vogl et al 2021). These time windows is an opportunity to shift technology with limited stranded capital. However, as can be seen in Figue 1 below, new investments in long lived BF-BOF assests are still being planned, especially in Asia where the major growth of new steel capacity is expected to come.

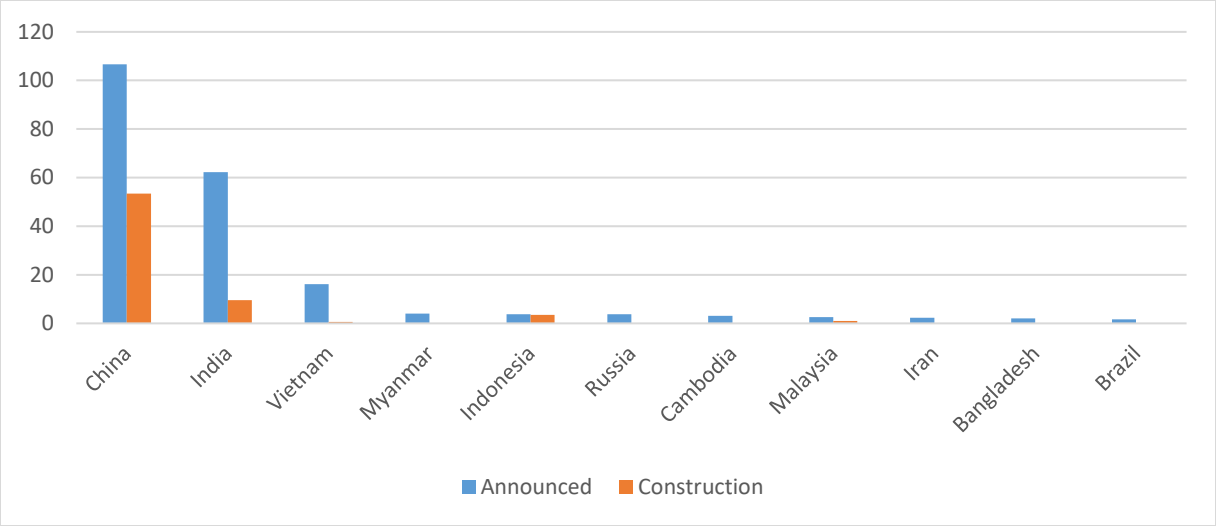

Figure 1: Unmitigated *Blast furnace capacity (MT) announced and under construction in the top ten countries* (Swalec & Grigsby-Schulte, 2023). For comparison: the total production of primary steel is around 1900 mt/y whereof 1350 Mt/y is primary steel.

The BF-BOF route can be decarbonised with CCS but it is difficult to reduce emissions below 80% (roughly) and with substantial cost increases the deeper in emission reductions you go, see e.g. (IEA 2017, Eurofer 2013). It is theoretically possilbe to reach carbon neutrality if you combine BF-BOF w. CCS with biomass that replaces a maximum of the 40% the total coal used that comes as pulverised coal in the Tyueres, the pipes that inject oxygen and pulverised coal for heating purposes in the lower part of the blast furnace (Mandova et al 2019). At the moment, no BF-BOF with CCS projects are planned. The new investments in Figure 1 are all unmitigated BF-BOFs. The global steel industry is still heavily locked into coal with a pipeline of new announced or under construction investments of blast furnaces that are not in line with the Paris Agreement.

However, something is happening and for the past six years there has been an increasing number of steel projects aiming for producing green steel, here defined as steel produced with GHG emission 85% below the traditional BF-BOF route . Several options exists[1] but so far hydorgen direct redcution (H-DR) is dominating, see Figure 2 below. Given the time constraints for meeting the reduction targets of the Paris Agreement and the long investments cycles of the steel industry, options at a lower TRL level are not discussed further. However, these options might well prove competitive beyond 2040 and deserves futher research efforts.

[1] I. Smelt reduction (HIsarna) with CCS: A planned demo was abandoned in Ijmuijden, Netherlands by Tata (will do H2 instead) and the project moved to Jamshedpur in India by Tata. Unclear but seems to have a pilot soon running.
II. Molten Oxide Electrolysis (Boston Metal) Pilot. Uses electricity only. Pilot scale that has surprisingly high energy need in for the pilot. TRL level is estimated to between 4-5
III. Alkaline electrolysis/ Electrowinning (Siderwin) use electricity only and is at pilot-level. TRL 4-5
IV. BF-BOF with CCS: no projects currently and it is difficult to get above 60 to 70% reduction of CO2. BF-BOF was previously the main option in e.g ULCOS project (2006-2010).
V. Biochar in BF-BOF: This is done for smaller scale BFs in Brazil (tecnored) but it is difficult to scale up due to mechanical properties of the biochar and due to cost considerations.
VI. Hydrogen Plasma Smelt Reduction (HPSR) developed by Voestalpine in “Susteel” project. TRL 4-5

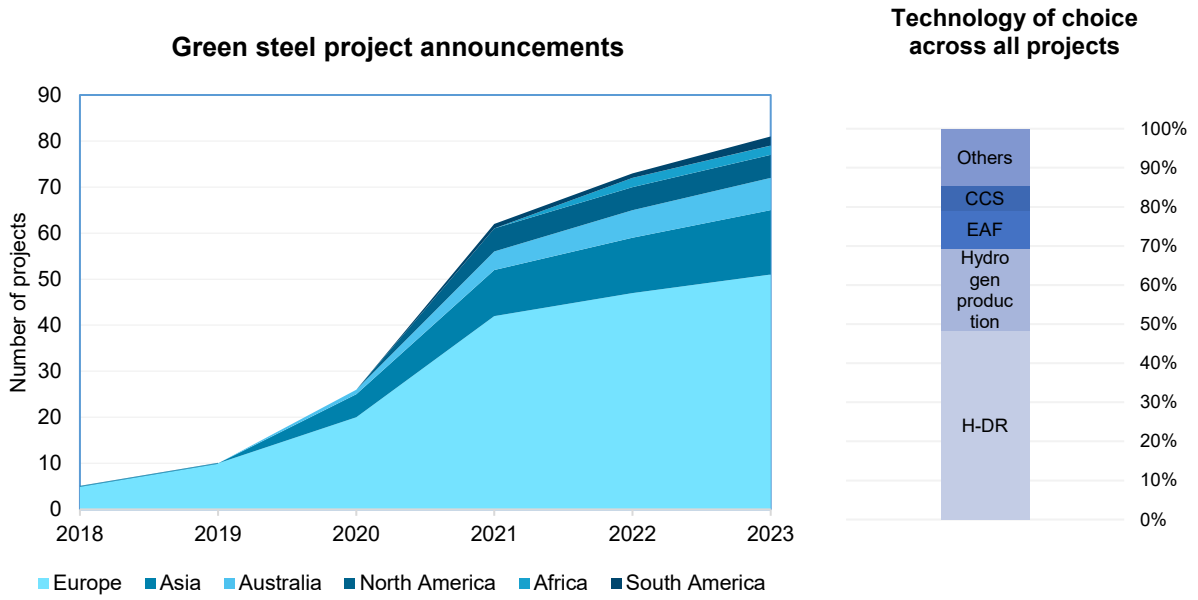

Figure 2. Announced green steel projects according to the Green Steel Tracker (Åhman et al 2023)

The green option currently dominating is the hydrogen direct reduction option. Hydrogen direct reduction with an electric arc furnace (H-DR – EAF) can reduce GHG emission >95% if using renewable electricity and biocoal in the EAF (Vogl et al 2018). The strong development of the H-DR- EAF is based on the technical readiness and the anticipated access to future low cost renewable electricity. Low cost electricity makes this option economically feasible compared to the traditional unmitigated blast furnace option. Another benefit is the potential to mix, to a greater extent, the secondary and primary steel production routes via the EAF. For a fully developed H-DRI – EAF facility, a price on CO2 representing 100 Euro/tonCO2 is estimated to mitigate the cost penalty compared to relining a BF-BOF at a power price of 60 Euro/MWh (Vogl et al 2018). BF-BOF with CCS is currently not being invested in at scale but might come back as both a retrofit option and as a green field option in countries that are heavily reliant on coal such as China and India (IEA 2020). Some of the east Asian countries that is currently planning for and making new investment into BF-BOF steel (see Figure 2 above) will be forced to address these large emissions the coming 20 to 30 years.

In table 1 below, we give the average emission intensities for the major current steel production routes as estimated by the IEA

Table 1 CO2-emission intensities of main production routes (IEA 2020)

	BF-BOF	Scrap EAF	N-gas DRI-EAF
Direct emissions	1.2	0.04	1.0
Direct + indirect	2.2	0.3	1.4

3. The gas-based DRI options available to reduce emission >85%

Reducing iron ore in solid state (direct reduction) is done with syngas (CO+ H2) or pure H2. The syngas can come from either reformed natural gas or from e.g. gasified biomass. Pure hydrogen with low or zero emissions can come from electrolysis of water (green H2) or natural gas with CCS (blue H2). Green hydrogen is emissions free whereas blue hydrogen will have residual emission as the capture unit does not capture 100% of CO_2 in flue gases and also have some minor leakage of methane that has a high global warming potential (GWP). More advanced options for the future for both syngas and H2 production exists but are not discussed further. Below, are the main options for producing steel with hydrogen or syngas.

3.1 Hydrogen options:

3.1.1. H-DR EAF: Hydrogen direct reduction with an electric arc furnace.

HYBRIT develops a pure hydrogen feed DRI furnace with an EAF (Vogl et al 2018). H2 Green steel is developing a similar set-up but with a "off-the-shelf" shaft furnace that will a the start use smaller amount of natutral gas in the reduction process (similar to a normal DRI furnace) to ensure the carbon content in the steel. Blastr Steel is planning for a H-DR steel facotry in Ingå outside Helsingfors around 2029 with imported pellets from their own supplies in an agreement with Cargil Metals[2] . Salzgitter in Germany is planning to phase in H-DR-EAF in their opretaitrons in a step by step timeline (having several blast frunaces)[3]. Salzgitter is also looking into developing more advanced high temperature electrolysis.

3.1.2 H-DR SAF-BOF: Hydrogen direct reduction with a submerged arc furnaces and a basic oxygen furnace.

Several German steel makers are developing H-DRI but with a smelter (SAF) and a BOF instead of an EAF. The main reason is to be more flexible with regards to iron ore quality and to be able to keep the BOF at existing sites. With a smelter step a slagg is formed in the smelting step that makes it possible to clean the iron ore from gaunge and other impurities and thus to use lower grades of iron ore. The costs of this option are estimated to be in the same range as HDR-EAF if you include that you can use cheaper iron ore (Agora Industrie/Wuppertal Institue 2024).

3.1.3 Hydrogen reduction with a fluidised bed.

Korean steel manufacturer POSCO is developing a fludised bed hydrogen process (HyRex) that builds on their earlier fluidised bed steel process, FINEX[4]. Here, again the benefits are that they can use lower grade iron ore and does not need to pelletisise the iron ore to sinter. The first ever, now abandoend, hydrogen steel project in Trinidad was based on fluidized bed technology, i.e Circored (Otto et al 2017).

[2] https://www.blastr.no/
[3] https://salcos.salzgitter-ag.com/en/index.html
[4] The "FI" stands for fines, i.e that they use iron ore fines instead of pellets

3.2 Syngas options

3.2.1 Natural gas DRI-CCS

Natural gas DRI (N-DRI) is produced today but without carbon capture and storage (CCS). Without CCS an N-DRI, facility emits roughly 1 to 1.4 tonCO2/ton of DRI (IEA 2020).

In the N-DRI process, the natural gas is first converted to a syngas (H2 + CO) and CO_2 in a steam reformer before entering the shaft furnace. To reduce emissions, the CO_2 can be separated, cleaned, compressed and stored with CCS technologies. This would *potentially* open up for gas rich countires to continue using natural gas even under the Paris Agreement (if residual emissions are accepted and can be compensated). Gas rich countries are foremost Iran, Russia, Oman, Saudi Arabia, Qatar but also US with shale gas. These countries will also have the possbility to develop blue hydrogen from their gas (see below). Today N-DRI is only competitive with the BF-BOF if gas prices are low which is the case in "gas-stranded" regions with ample of captive reserves with few options for exporting this gas (e.g. Iran)[5].

Only one N-DRI with CCS project exist today and that is in the UEA (Emiratea Steel). The captured CO_2 is used of enhanced oil recovery and the share of emissions capturted is estimated to be only 14% of the totla emissions (ARIA 2023). The project has basically just fitted a compressor and pipline system to the refomer unit where parts of the CO_2 is separated from the natural gas (ARIA 2023). DRI from shale gas has grown in the US since 2010 due to the "shale gas revolution". In the MENA region, natural gas has replaced coal for DRI steel facilites (Deloitte 2013). These investments are usually based on long-term (e.g. 20 years) supply contracts of pipe-lined gas. Nucor in the US has recently signed a MOU with Exxxon Mobile for a 0.8 Mton/y capture unit to their 2,5 Mton/y N-DRI plant in Lousiana[6]. No details on the technical solutions nor capture rates are given but I estimate that this would roughly be a 23% capture rate using same assumptions as ARIA (2023)[7].

3.2.2 Bio-syngas-DRI.

Syngas, a mix of CO and H2, can also be produced by thermal gasification of woody biomass There are a couple of projects in Sweden exploring the use of biomass derived methane or syngas to produce iron or steel.

Syngas is directly applicable in shaft furnaces to reduce iron ore to sponge iron. FerroSilva in Sweden is developing this concept. Ferrosilva is developing a concept of gasifying biomass for use in DRI furnaces together with Ovako[8]. Theoretically , this system could acheve negative emissions if coupled with CCS in the gasification part (Tanzer et al 2020).

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[5] India produces about a third of all DRI but this is mostly produced from gasified domestic coal in a shaft furnace or directly use of coal in a rotary kiln. DRI with coal has a huge carbon footprint (around 2.2 to 3 t CO2/t LS). Development is nascent but emerging on replacing this coal with hydrogen or biosyngas.

[6] https://nucor.com/news-release/19816

[7] It is also easy to compared 2.5 Mton DRI/y with a normal emission of ~2.5 MtonCO2/y (direct emissions) with the captured 0.8 Mton/y. Add to this methane and upstream emissions from increased energy use in the capture unit

[8] https://www.ferrosilva.com/ovako-som-ferrosilva-pionjar/

Höganäs is, in collaboration with Cortus, developing a 6 MW gasifiers to produce rouhgly 50 GWh (not confimmed) methane to replace their current use of natural gas from the grid[9]. In the future, this proicess may also produce a biocoke from the resisdies that could be used in the process. However, Höganäs produces *iron powder* and uses an unique process, a so called tunnel furnace ("tunnelugn"). Together with the projects using biochar in Brazil (tecnored), I´m not aware of any other major steel decarbonisation projects looking into using biomass in a blast furnace.

4. Cost and price considerations – cost projections for renewable electricity and biomass

Is the so far chosen technology route for Scandinavian steel projects the right one? We need to look at both competitiveness from Scandinavia and from abroad as steel is a globally traded commodity.

The competitiveness of the many hydrogen steel projects in Scandinavia could face competition within Sweden from biomass-syngas DRI. From outside of Sweden competition might come from natural gas DRI with CCS or also from H-DR from countries with better access to renewable electricity (so called "renewable pull" (Samadi et al 2023). Using natural gas for DRI as a large-scale option in Sweden is unrealistic as this would require building new gas-infrastructure. Natural gas pipelines normally are financed and built with 20 to 30 year off-take agreements between states and this thus risk to lock-in in several decades of gas use. With the latest development in neighbouring countries, this option has become even more unthinkable. Importing LNG would be too expensive for steel use.

Cost estimates of the various way of producing steel are uncertain and differ pending on who is presenting the estimate and how and which assumptions that are made. The IEA (2020) published reasonable and globally acceptable estimates on the production cost of various steel options and these are given in Table 2 below. Agora Industry has also produced comparative studies and "Transition Zero" has presented a global cost database for the current production of steel (Transition Zero n.d. , Agora Industry/Wuppertal, n.d.)

[9] Höganäs uses roughly 150 GWh natural gas/y to produce 500 000 tons of iron powder

Table 2. Cost estimates for steel production (IEA 2020)

Steel routes	***Cost ranges***	***My comments***
Unmitigated steel		
BF-BOF	350 to 475 USD/tLs	
DRI-EAF	400 to 590 USD/tS	The major ranges attributed to varying gas prices
Mitigated steel		
DRI-EAF with CCS	450 to 650 USD/tS	The major ranges attributed to varying gas prices. Also unclear and undefined capture rates
H-DRI-EAF	500 to 850 USD/tS	The major ranges attributed to assumption on power prices

There are substantial uncertainties for the cost estimates given in Table 2. The costs of adding CCS to an existing or to a new built DRI facility will add costs but the true costs are still largely unknown. The same goes for H-DR but here the market of key components is bigger and the prices of these components such as electrolysers and shaft furnaces are better known. Note also that the cost of producing steel varies already today substantially across the world with India as the cheapest production countries due to low cost iron ore (also with lesser quality) and low working costs (see Transition Zero (n.d)). Some crucial inputs to steel are globally trade such as iron ore and scrap whereas other cost such as workers cost and access to gas, coal or renewable energy could differ (coal with certain qualities are also trade globally). To simplify, the cost comparison between these alternatives boils down to a cost comparison between energy carriers. CAPEX has also a differing influence between options but energy supply is dominating the cost structure with around 30%.

Below I discuss the current and future costs of green hydrogen, green syngas within Sweden and blue hydrogen and natural gas in the world**.**

4.1 Hydrogen and syngas costs

4.1.1. Green hydrogen:

Current assumptions of green hydrogen ranges between at most 3 to 6 USD/kgH2 for current production down to future promises of 1 to 1.5 USD/kgH2 (IEA 2022). The highest estimates above 5 USD/kgH2 assumes actual grid electricity cost as of today for "medium sized industries[10]" with prices of between 60 to 90 USD/MWh in central europe and the US, see e.g Fan and Friedmann 2021. The long-term optimistic and low estimates assume that hydrogen production will use renewables at "cost based" prices of 20 to 25 USD/MWh. In Figure 3 below, the cost relation between green hydrogen and the electricty price is given.

[10] Power prices for the really electricity intensive industries are seldom disclosed in statistics as they are too few users and this risk confidentiality. However, case studies have shown that, before Ukraine and inflation crises, the prices were tightly linked to the production cost of new renewable electricity at prices between 30 to 50 euros/MWh (Åhman et al 2020)

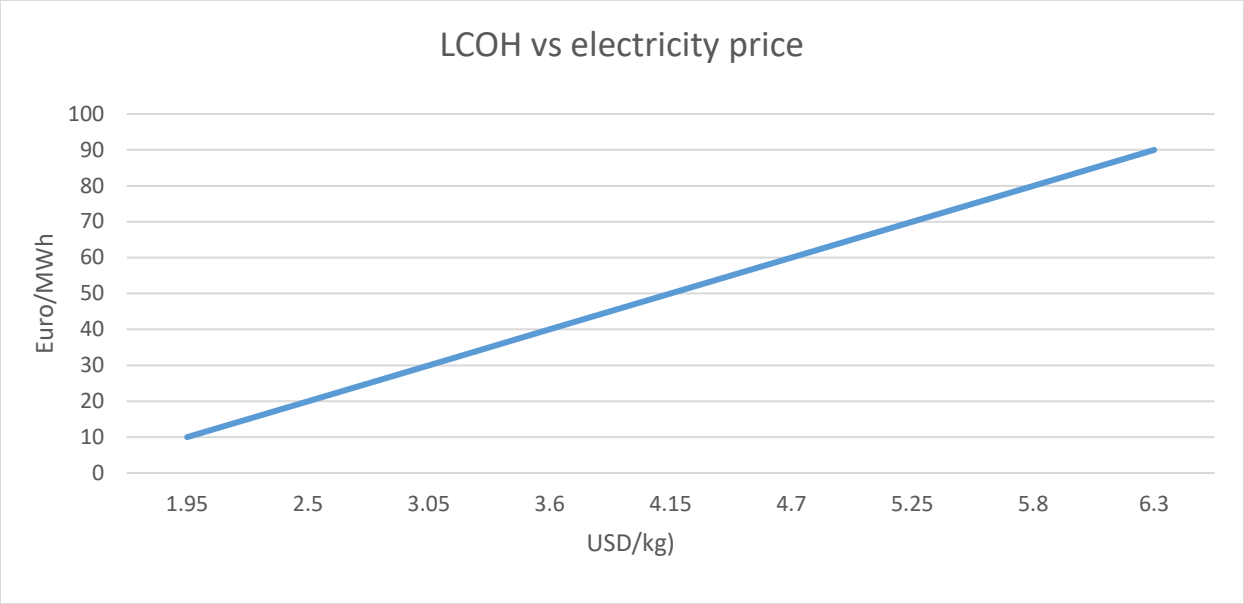

Figure 3 LCOH (H2 USD/kg) as function of power prices (euros/MWh) . Source: Calculated using https://observatory.clean-hydrogen.europa.eu/tools-reports/levelised-cost-hydrogen-calculator

The cost of green hydrogen depends on many varibles, power prices and it´s time profile which also relates to the number of hours the electrolyser is running, CAPEX of course with assumption on interest rates, degredation of electrolysers, possilbe sale of oxygen (could be quite large but the market will moslt likely soon be oversaturated)[11].

4.1.2 Biosyngas/biomethane

Biosyngas costs are less studied globally as this is partly a Scandinavian niche given our huge biomass resources. However, according to a recent estmiate the current cost estimate is around 80 to 100 Euro/MWh (assuming a biomass price of 10 to 20 euros/MWh as input (Hansson et al 2023). This biomassprice reflect the average prices of woody residues biomass in Sweden. Lower quality biomass can today be sold at 10 euro/MWH to large consumers (Svebio 2020, page 31) and pellets at 300 euro/MWh

In a study assuming learning curves Detz et al (unpublished) estimate future bio-syngas cost in 2050 to be 42,3 euro/MWh (42 öre/kWh) with a biomass price of 150 Euro/ton (equals 22,8 euro/MWh) thus around 50% of the cost for the feedstock. Ferrosilva claims that they can produce green steel with bio-syngas at a cost of 300 to 320 Euro/t DRI with biomass cost of 20 euros/MWh (note: it is DRI – not steel). However, the can+t provide any cost details or details on assumptions due to confidentiality.

[11] CAPEX requirements for an installed electrolyser system are currently in the range of USD 5001 400/kWe for alkaline technology and USD 1 100-1 800/kWe for PEM, while estimates for SOEC range from USD 2 800-5 600/kWe Source: IEA (2023). https://www.iea.org/energy-system/low-emission-fuels/electrolysers

4.1.3 Blue Hydrogen

The estimates of producing blue hydrogen varies but the IEA in their CCUS report estimates the costs to 1.2 to 2.1 USD/kg by the IEA (2020b). A more recent academic study esmimates blue hydrogen costs to be somewhere between 2.36 to 2.55 USD/kg H2 for blue hydrogne with decent capture rates (Oni et al 2022). However, the capture rates ot these blue hydrogen projects are poor. Even with a 85% capture rate assumption of the capture unit, the life cycle capture rates is below 65% for the best technology (Auto Thermal Reactor with CCS) (Oni et al 2022, table 6). This low LCA caputre rates comes from increased energy use and upstream emisisons of e.g methnae and CO2. More critical anlayses (Vogl 2023) also argumems that methane leakage is underreported and if adopting a 20 year GWP calculation to the methane emisisons (due to the limited time to avoid negative climate feedback loops) would decrease the total capture rate even further.

The cost of natural gas is a key component in the total cost of blue hydorgen and typically amounts to ~0.5 USD/kg H2 of the totla cost assuming a gas cost of 1.96 USD/GJ gas price. If the global gas market is weak then domestic gas could potentially be priced strategically or, if completely stranded, as low as the actual production cost. However, the captial and running cost of capturing and separating CO_2 from natural gas still represent roughly 1.5 to 1.8 USD/kg Blue H2 and with a relatively low capture rates of the total LCA emissions.

5. Energy supply considerations

The energy supply constraints are tigjhtly linked to the future cost or price of energy carriers. The supply of biomass, electricty or natural gas will affect the market and the makret clearing price substantially. In a equlibrium situation where demand can be met with no restraints, the price will converge to the long term marginal cost of supply. However, if the market is “tight” and suply somehow restricted, then the marginal willingness or ability to pay will determine the price. Normally, a makret will always develop with both tight makret situation and oversupplied situation (where the price could reflet the short term amrignla cost). For understanding the long term market outlook (which is key for understanding investments into “slow” assets) we need to look at fundamentals on what might detemrin or influece the long term market equlibirum for electricty, natural gas or biomass.

Renewable electricity potential is physically large - only in Sweden there is currently plans of off shore wind equalling more than 150 TWh[12] . However, may of these will not get permission due to land /sea use conflicts. However the short term projection of the Energy Agency is that to 2026 we will have 20 TWh more on shore wind power in Sweden[13] .

In general, there are several potential ways as to in which sector s and by whom the available Swedish bioenergy might be used in the future. Ther allocation to users and the amount of bioenergy available is uncertain and depends on several factors such as the relative price between renewable electricty and

[12] Looking at vindlov.se I can estimate up to >400 TWh/y of onshore and off-shore wind project in planning. However, several of these covers the same area and are thus double counted. www.vindlov.se

[13] https://www.energimyndigheten.se/statistik/prognoser-och-scenarier/kortsiktiga-prognoser/

biomass, technical development within several sectors (moslty the industrial and the transport sectors) and not the least the timing of developments to “lock-in” future development paths for bioenergy use, see e.g (Börjesson and Björnsson 2024). A typical example can be the timing between future bioenergy and windpower supply. IF, as suggested by Sandberg (2023), the paper- and pulpindustry is electrified then a large amount of bioenergy (the black liquor) could bemade avialable for use in e.g. the steel sector as gasified biomethane. However, the steel sector needs to make a decision today on which technology route to follow and cannot wait until after 2030 to evalutate if bioenergy will be available at the required scale.

The furter potential for biomass for energy purposes is large but often contested (especially outside Scandinavia). Svebio assumes, based partly on Börjesson a huge potential of increasing Swedish biomass with 82 TWh in the short term and up to 147 TWh in the longer term (2050) whereof 42 TWh respectively 74 TWh will come from woody biomass, mostly forrest residues (see page 16-17 in Svebio 2020). However, this cost is dependent on that it is allowed to use forrest residues for bioenergy purposes within the EU. In the revision for the renewables directive in 2023, the first proposal excluded all “primary forrest” including the woody residues. However, this propsoal was eventually overtunred in the negotiatins that led to the final decision. A ban on forrest residues would have had huge effects on both current Swedish bioenergy uses but moslty on the furute potential supply. The price (vaue) of biomass could change in the future as more and more sectors are seeking to use it. Especially the “hardest to abate” sectors such as for feedstock in chemicals and for SAF (sustainable aviation fuels) will become a market for wood biomass in the EU as the blending requirement for aviation is sett to increase substantially after 2030.

Natural gas is used in DRI now in countries where the supply is large and the cost of natural gas is low (e.g. not set by internationla oil or gas markets). Natural gas prices US: 10 USD/MWh, n-gas prices in EU: 34 USD/MWh. The low prices comes from either strategic considerations e.g. industrila policy wish to maintain a steel industry within the country or from the fact that some gas fields are “stranded” meaning that the export opportunites are low. Examples are Iran and Oman. However, the market for exporting gas has developed considerably since the mid-2010s with the building of LNG tankers. This has for exampel made Qatuar the world largest LNG exporter and this is slowly changing the gas-market and the “lock-in” effect of certain gas fields.

Natural gas has only recently begun to develop a global market with international trade. For a long time, natural gas was traded in three separate regional markets with differentiated prices (the North American, the European and the East Asian market) due to the high cost and the lack of flexibility of transporting natural gas via pipelines. The natural gas market via pipelines market is mostly based on long-term fixing the price of natural gas to the price of oil as these resources is seen as complementary to oil. However, since the introduction of vessel-ships for transporting liquefied natural gas (LNG) in early 2000s, the global trade of LNG has grown substantially. This trade was further strengthened after the shale gas revolution in the US in 2005 to 2010 that made US an exporter of LNG instead of an importer. Today, the value of LNG and it´s strategic role has grown tremendously and LNG is developing into a global commodity (Sakmar and Kelmar 2009). Qatar has taken a big role in the LNG trade with early investments in LNG infrastructure, which has made Qatar very rich the past 10 years (Krane 2020).

6. CO_2 target considerations

Pending on the reduction targets implemented in the long term, some options might find it difficutl to meet these. The "green market" currnelty driving a lot of these investments with off-take agreemnts (Åhman et al 2023) does so far not seem interested in neither CCS nor offsets.

CCS does not capture 100% of emissions and is also difficult to retrofit CCS on all sources at an integrated BF-BOF site.[14] The same goes for natural gas feed DRI with CCS or even blue hydrogen. However, with technology development and adding biomass as partial input some of these options (especially blue hydrogen) could become >95% reduction options but the cost would then substantially increase for the last tonnes of CO_2. Compensation of the residual CO_2 will not be available in the long term and will most likely not be allowed (or preferred by customers) according to the currently negotiated EU "Green washing directive"[15].

7. Iron ore considerations

Iron ore quality is of significance when the world is moving towards direct reduction of iron ore. The iron ore needs preferably to have a high iron content (>67%) and manageable impurities of gaunge, and other impurities. Iron ore with "DR-grade" currently makes up only about 4% of the global iron ore supply that is in balance with the current market demand

There is a risk that iron ore of good enough quality might not be available for an expansion of DRI production. However, the market is dynamic and can respond in several ways to enable an increasing demand.

(i) With increasing demand, the most natural response is to increase mining capacity of high-grade iron ore. This is happening and several mining companies are currently looking into expanding DR-grade iron ore capacity, see e.g. report from IEEAF (Nicolas 2024).

(ii) Another response is that lesser iron ore can be used with various technologies including a smelting step, e.g. SAF, Induction or via fluidised bed, see section2.1 above.

(iii) You can also beneficiate the iron ore quality, i.e. raise the quality by remaining impurities and increasing the iron content. This will of course cost some energy and some money but is expected to grow. See Barrington (2021) for an overview.

In conclusion, there are several responses on how to solve the iron ore quality issues, see also IEEFA for some overviews [16] and Insight 13 in Agora Industry and Wuppertal report[17]

[14] An integrated BF-BOF has several point sources of CO2 emissions and with varying CO2 concentrations that makes capture more costly. Furthermore, coal used for the BF-BOF has unreported upstream methane leakages that so far has not been acknowledged but is increasingly coming to focus (Vogl 2023)
[15] Goes for environmental branding which is a key market or green steel https://environment.ec.europa.eu/topics/circular-economy/green-claims_en
[16] Basirat (2022) and Nicolas and Basirat (2022)
[17] Agora and Wuppertal (2022)

8. Concluding risk assessment

Swedish steel makers are developing and planning to invest heavily into hydrogen direct reduction the coming 10 to 35 years. We need to understand and anticipate if there are any major risks from a resource or competitiveness perspective to this technical system. The choice of technology was a strategic choice by the state but independently made by the companies. However, the state and later the EU, supported the start with both financial R&D support and support for constructing the first pilot and the upcoming demonstration plants (for both HYBRIT and H2 Green Steel) in their general function to support R&D and risk sharing for major demonstrations for climate mitigation.

The market: The market for "green steel" in general is growing and needs to grow rapidly far beyond what Swedish steel makers can produce the coming 20 years if we are to meet Paris targets (or even come close to these). The inertia within the global steel industry is still strong and new unmitigated blast furnaces are still being planned, especially in South East Asia. However, when it comes to technology choice for green steel (here defined as reducing emission >85% compared to the traditional BF-BOF route), the global steel industry seems to be in consensus that hydrogen from renewable electricity will play a key part with at the moment +80 projects involving hydrogen and maximum 1 to 2 projects involving natural gas and CCS. No projects involving BF-BOF with CCS is currently to my knowledge being pushed by the industry.

Scrap based steel: The secondary route from scrap via an EAF can also be labelled as "green steel" for good reasons (very low emission if renewable electricity supply and circularity). However, the availability of scrap is a function of previous primary (ore based) steel production and thus limited as the totals global demand for steel is still growing with global development. Most projections estimate that the share of scrap will grow from around 25% today up to at least 50% by 2050 (more if we take circularity and sufficiency seriously). The scrap option does not really pose "a risk" to the H-DR- EAF route as scrap-supply is already a part of the H-DR- EAF route where most steel manufactures will use a share of scrap in the mix and this share will be flexible pending on cost and availability fo e.g scrap and renewable electricity/fossil free sponge iron.

Bottlenecks: Hydrogen based steel is set to grow substantially the coming years. Potential bottlenecks in the supply chain exist that could create price hikes to this option. The bottlenecks identified are both engineering capacity for building shaft furnaces et.c. , access to high quality iron ore and renewable energy supply/green hydrogen supply. For engineering capacity, HYBRIT, and H2 Green steel are among the first companies doing this which both poses a technical and immature supply chain risks (hence the support from the state and from the EU) but at the same time ensures less competition if the H-DR investments market takes of as foreseen/hope for due to climate reasons. For the bottleneck of iron ore quality there are several options described above that, the market could (and is beginning to…) respond to increasing demand of high quality iron ore. The response from the market is several fold (i) expanding mining capacity and (ii) alternative the steel companies develop technical solutions (smelting step) that can accept lower quality iron ore. With all the responses, there is no apparent physical long-term limitations to sufficient iron ore supply. However, globally supply chain risks are always present when mining capacity is expanding quickly as the mining industry has historically caused several land use and environmental conflicts. For the Swedish steel makers, it is an advantage that LKAB have access to potentially high-grade iron ore. The reduction of iron ore to iron requires huge amounts of energy. The

green electricity demand for HYBRIT and H2 Green Steel is estimated to increase by >25 in the medium term (2030) and potentially with 70TWH in the longer term (2045) if LKAB follows the stated vision to reduce all iron ore at the mine. As described in section 5; the physical potential for increasing wind power is huge in northern Sweden. However, land use conflicts (the lowest cost alternative being onshore wind). The electricity needs not only to be supplied at enough quantity and quality but also at a reasonable price. The power system is sensitive to short-term bottlenecks in supply or distribution and the prices (set today as marginal prices) can increase several times with a supply crises. However, the investment decision for expanding reduction capacity is done usually in steps of 2 to 2.5 Mton iron ore capacity currently and thus the big LKAB expansion would mean up to 10 separate investments decisions over a prolonged period. A phase-in approach will enable that each investment decision is being taken with some kind of a long-term supply contract (e.g. PPA) of electricity. The risk is thus mostly that the expansion could, if access to low cost power is lacking, be delayed or even partly cancelled.

Competing green steel technologies. Even if green steel market is expected to be dominating in the future (completely after 2050/2006 if we are to meet the Paris Agreement) there might always be other technologies that could outcompete H-DR- EAF. These comes both from within Sweden and from other parts of the world, as steel is a globally traded commodity. Competing technologies from Swedish would be using biomethane as reduction agent instead of hydrogen. The choice of green hydrogen over biomethane is a question of both scale and timing. There are more uncertainty with the future access to low cost bioenergy at the scale required for Swedish primary steel making (e.g. would need 15 to 20 TWh biomethane representing roughly 25 to 35 TWh woody biomass at least) to replace the existing coal use in the blast furnaces. However, biomethane is being develop in Sweden for “smaller scale” steel production to serve and complement the “scrap based steel production routes” with alternative fossil free sponge iron. This is a consequence to the anticipated increasing competition for high quality scrap in Sweden as both SSAB and H2 Green Steel are expected to use shares of scrap in their steel production in the future.

Renewables/blue hydrogen pull: There could also be competition from regions in the world that has either lower cost supply of renewable electricity (so called “renewables pull”) and iron ore or possibility to use blue hydrogen from stranded gas reservoirs. However, the market for blue hydrogen from stranded gas is limited and the cost might not be substantially lower compared to future anticipated cost for green hydrogen. There is also a question concerning the long term market acceptability of blue hydrogen due to residual emissions. The most likely scenario in the future is that “renewables tight regions” such as e.g. central Europe, will import the energy intensive part of the green steel value chain in form of green DRI/HBI. Northern Sweden has, comparatively speaking, a relatively good physical opportunities for production low cost DR/ from low cost renewables. There might be other parts of the world with even better access to key resources but the cost of producing steel already todays differ substantially between world regions with up to 25 to 30 % between e.g. India and Germany (Transition zero 2022) with major relocations. Factors such as industrial policy, sunk cost, transport cost, labour efficiency and closeness to market also determines location.

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