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Why both Hydrogen and Carbon are Key for Carbon Neutral Steelmaking

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Introduction

In 2019, 4 years after the Paris Agreement, the united nations announced that already over 60 countries had committed to become carbon neutral by 2050. This was including the European Union, but not yet the 3 largest CO2 emitters China, the United States and India. In spite of the Paris Agreement, the global CO2 emissions continued to grow to a record high 36,44 billion tons of CO2, 24% higher versus 2005 and 60% increase vs 1990 (figure 1).

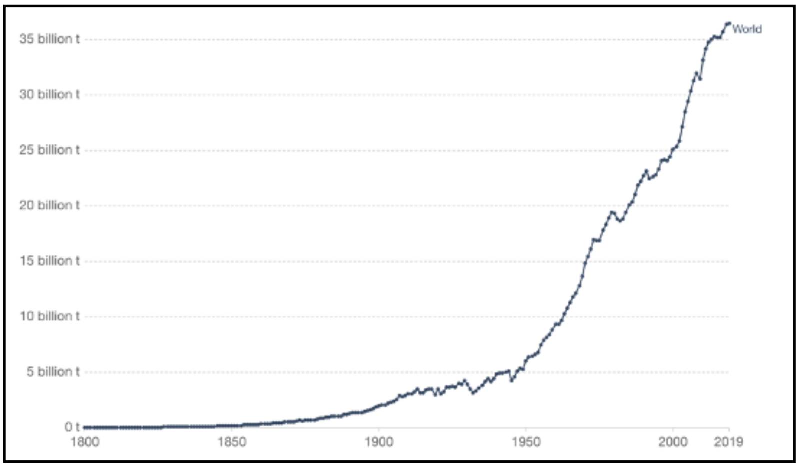


Fig.1 Evolution of Total CO2 emissons related to use of fossil fuels and cement production. Land use not included[1]

Since end of 2019, the world has dramatically changed. The coronavirus pandemic quickly spreads over the world with an unprecedented impact on our daily lives and economies. Global CO2 emissions dropped in 2020 with 7% to 34 Gtons and the commitments to tackle Climate Change picked up:

- China, the largest CO2 emitter today, announced in September 2020 it's new objectives to peak CO2 emissions before 2030 and to be carbon neutral in 2060.
- US announced In March 2021 to become carbon neutral in 2050 and to reduce it's GHG in 2030 with 50 to 52% versus 2005.
- The European Union, traditionally a front-runner, increased it's commitment in April 2021 to reach 55% GHG reduction in 2050 versus 1990.

Also, within the steel sector, the commitment to tackle its CO2 footprint gained momentum. Within 6 months, the top 5 companies in the sector all announced to become carbon neutral in 2050 (table 1).

Steel is one of the corner stones of our economy. It is one of the most important construction materials which

	Production in 2019 (mton)	Announcement
ArcelorMittal	97,31	September 2020
Baowu	95,47	January 2021
Nippon	51,68	December 2020
HBIS	46,56	March 2021
POSCO	43,12	December 2020

Table 1. Announcement of Top5 Steelproducers to become Carbon Neutral in 2050

is present in nearly all aspects of our lives. Steel will be crucial to transform to a carbon neutral economy: renewable power generation will require more steel (figure 2), steel for CO2 and hydrogen pipelines will be required, electrification of transport will boost the demand for electrical steels, …

It is expected that between now and 2070 steel demand will further grow to 2,8 billion tons per year (figure 3).This growth is conflicting with the need to reduce the CO2 emissions. Indeed steelmaking is energy intensive and carbon is playing a key role. In 2019, 1.875 billion tons of steel was produced, emitting on average 1.85 tons of carbon dioxide(3). With a total of 3,45 billion tons of CO2, steel is responsible for 8,5% of all GHG emissions and 9,5% of the CO2 emissions related to the use of fossil fuels.

Going forward, the steel industry needs to asses and decide already today on which pathways are technologically and economically viable and scalable in order to reach the carbon neutrality.

Discussion

GHG generation related to the current iron and steelmaking processes

Steelmaking is a mature industry, optimized over the last 150 years. Steel is also the only material which is intrinsically circular. Recovered steel scrap is representing nearly one third of the iron resources to make up new steel products. However in spite of the growing scrap availability, it will take until 2050 before the primary steelmaking will start to (slowly) come down (figure 3).

Primary steelmaking starts from iron ore which is reduced to iron in a high temperature gas reaction with carbon monoxide (CO) and hydrogen (H2).

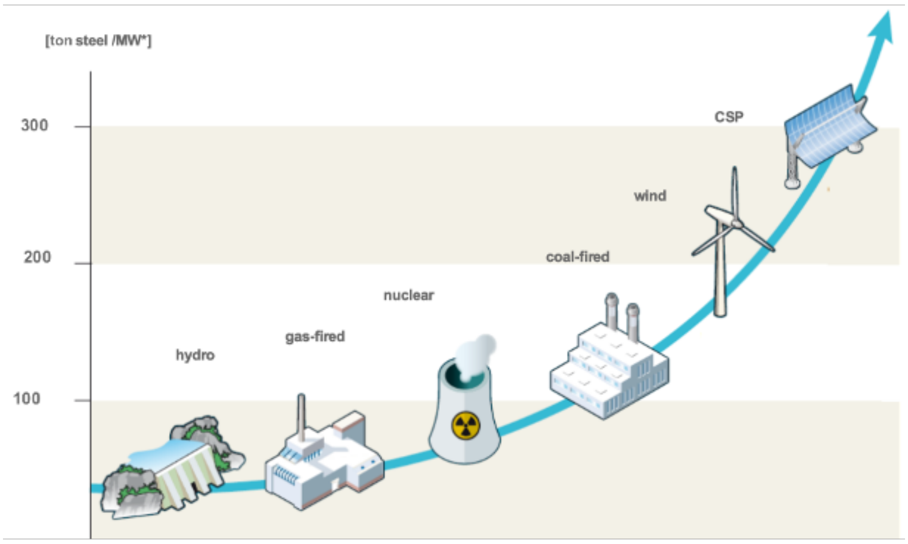


Fig. 2 Ton steel used per MW power generation capacity (2)

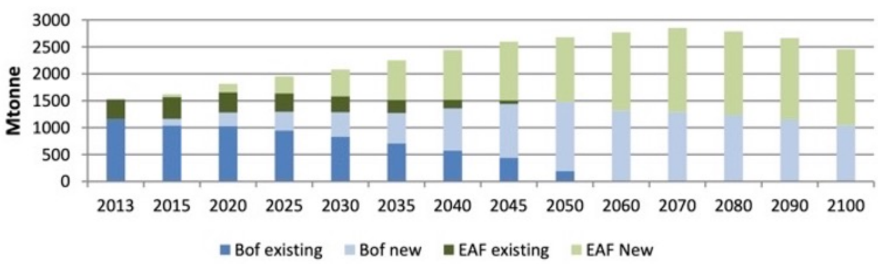


Fig. 3 Expected evolution of primary (BOF) and secondary (EAF) steelmaking in the 21th century 36

The Blast Furnace based route (BF/BOF) is dominant with a market share of 90% where mainly carbon (coke and coal) is used both for the heating and the chemical reduction but also for the melting of the iron into liquid hot metal. The other commercial production is done by so-called direct reduction in a shaft, where solid iron (DRI or sponge iron) is produced by using a mixture of reactant gases CO and H2. The sponge iron is melted in an Electric Arc Furnace by using electricity. The CO:H2 reduction gas is produced in that case from natural gas.

In the BF process, typically 70 to 80% of the reduction is done by CO and 20 to 30% by H2. In the natural gas DRI shaft, 60 to 70% of the reduction is done by H2, the rest by CO reduction, leading to a lower CO2 footprint in this process step (figure 4)

Comparing the GHG emissions between BF/BOF and DRI/EAF plants need to be done at the system

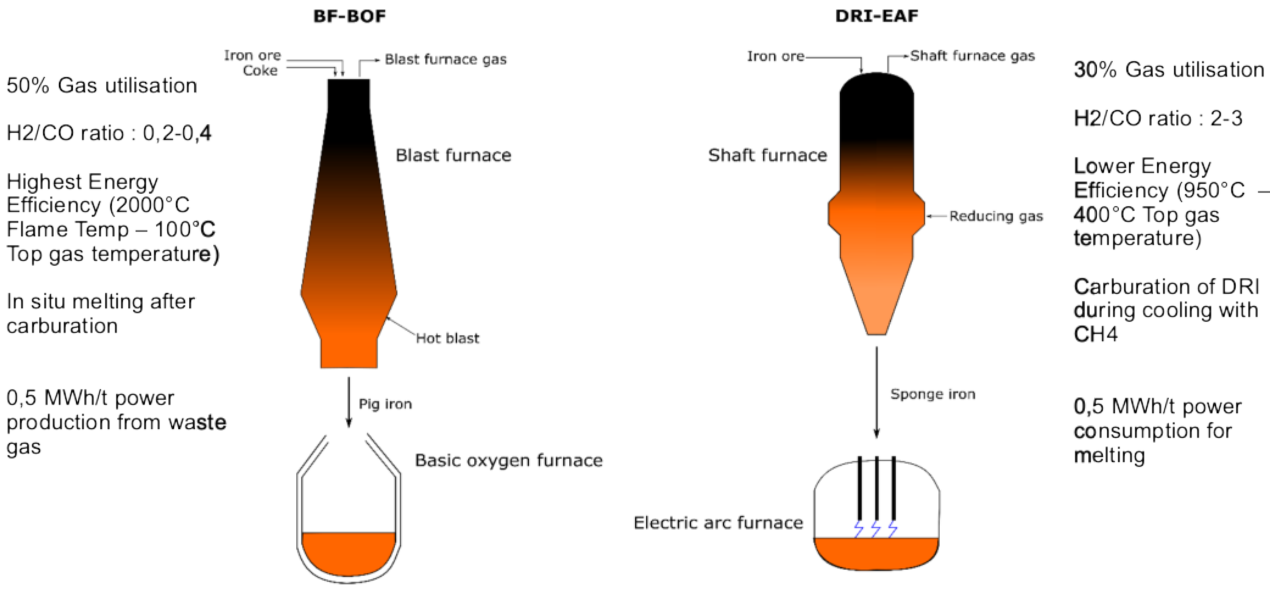


Fig. 4 Major KPI's for the 2 main production pathways to produce iron and steel.

level including the co-production in the BF/BOF plants of 0,5MWh per ton crude steel of power from the syngas generated during iron reduction and the 200 kg per ton cement clinker substitute. In a DRI/EAF plant, those by-products require additional energy in a stand-alone power plant and cement kiln. The analysis of CO2 emission per ton therefor need to be done referring to the marginal power production technology in the system.

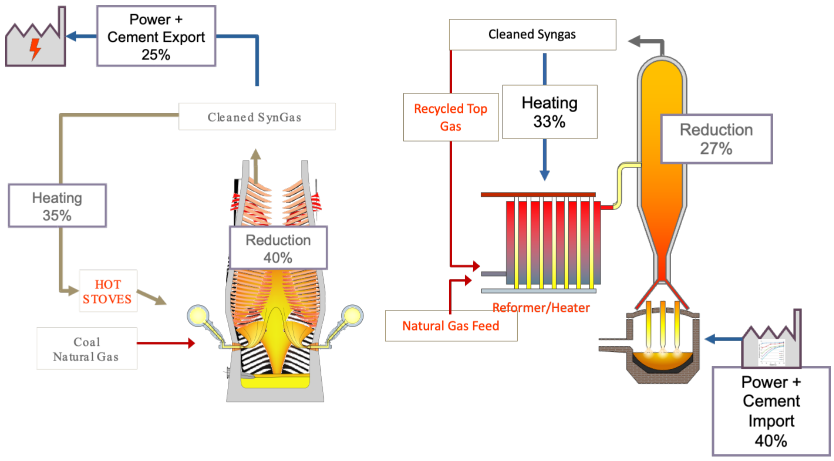


Fig. 5 CO2 emissions in BF/BOF integrated plant and DRI /EAF plant to co-produce 1ton steel + 0,5MWh power +200kg cement clinker in case of natural gas based power system

In the BF/BOF plant, 40% of the emissions are due to the chemical reduction, 35% due to the need for high temperature heat and 25% is generated in the power plant with the exported syngas from the reduction process. In case of a system with natural gas based power, the figures in the DRI/EAF process are not that different : 33% due to heating, 27% due to reduction and 40% is related to the power and cement production in the total system(figure 5).

The total emissions of the BF/BOF and the DRI/EAF produced with Best Available Technology are very close to 1600 kg per ton crude steel in economies where natural gas is used for the marginal power production (is the case in the next decades for most of the countries) (figure 6). When the marginal power is produced with coal (was until now the case in a lot of developed economies), the emissions of the DRI/EAF plant are 25% higher compared to BF/BOF. When we move to a full zero CO2 power system in the future, the DRI/EAF plant will have 30% lower emissions versus the BF/BOF process.

The Hydro:gen opportunity for Carbon Neutral Steelmaking

Industrial experience with Hydrogen utilization for iron reduction until now:

The chemical reaction between iron oxide and the CO and H2 containing reductant gas is responsible for 40% of the CO2 emissions in the BF/BOF process and 27% in the DRI shaft process. The basic concept of hydrogen ironmaking is logic and simple: substituting the carbon (or the carbon

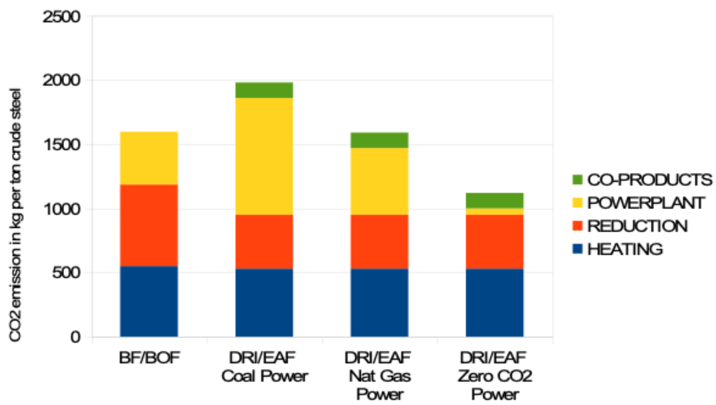


Fig. 6 CO2 emission in kg per ton steel comparison between BF/BOF and DRI/EAF as function of the marginal power generation technology

monoxide) in equation (1) by hydrogen in equation (2) to reduce the ore and releasing water vapor instead of CO_2 as by-product of the reaction.

$$Fe_2O_3 + 6\,CO = 2\,Fe + 3\,CO + 3\,CO_2 + 26{,}6\text{ kJ} \quad \text{(Eq. 1)}$$

$$Fe_2O_3 + 6\,H_2 = 2\,Fe + 3\,H_2 + 2\,H_2O - 99{,}5\text{kJ} \quad \text{(Eq. 2)}$$

High temperature need is responsible for 35% of the CO_2 emissions in the BF, resp. 33% in the DRI. Burning hydrogen instead of coal or natural gas for heat is a second opportunity to use hydrogen (equation 3).

$$H_2 + O_2 = H_2O + 240\text{ kJ} \qquad \text{(Eq. 3)}$$

Although this looks logic and simple to do, there is no or very little practical experience. The only commercial application so far was in Trinidad (Circored) where DRI was produced in fluidised bed reactors with hydrogen from steam methane reforming(4). The DRI production was not emitting CO_2, but the production of hydrogen was CO_2 intensive. The total need of 84 kg hydrogen per ton steel resulted in 29% higher emissions versus the natural gas based DRI process (table 2). The higher emissions and costs combined with technical issues stopped the project and the hydrogen based DRI production was never further industrialized.

Recent years hydrogen for steelmaking has regained attention as a way to reduce the GHG emissions in steelmaking. The SMR can be combined with CCS (carbon capture and storage) to produce the so-called Blue Hydrogen, or even better the hydrogen can be produced with water electrolysis based on carbon free power sources, the Green Hydrogen. Green Hydrogen produced with 100% renewable power can theoretically reduce the emissions of the DRI Shaft process itself to zero (table2). Electrolysers are also of interest for Blast Furnaces : the hydrogen can be injected in the tuyères to replace coal and the oxygen can be used for oxygen enrichment of the hot blast (figure 7).

The thermodynamics of iron ore reduction with hydrogen:

Even when the industrial experience with hydrogen to reduce iron ore is limited, the potential impact on the reduction process of the ore is well understood.

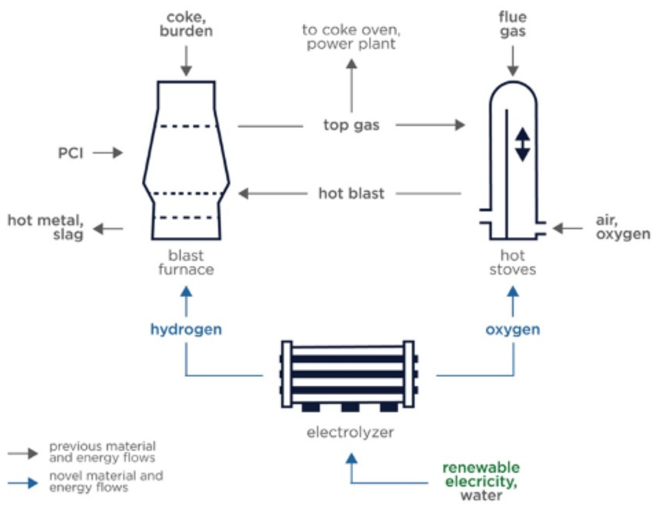


Fig. 7 Integration electrolysers in steelplants allows to use both hydrogen and oxygen(5).

DRI fuel	Natural gas	Hydrogen from SMR based DRI	Hydrogen from SMR + CCS (89%)	Green Hydrogen with Renewable power
Fuel per ton DRI	10,5 GJ / ton DRI	84 kg / ton DRI	84 kg / ton DRI	84 kg / ton DRI
CO2 per unit	59 kg / GJ natural gas	9,5 kg / kg Hydrogen	1,05 kg / kg H2	0 kg / kg H2
CO2 per ton DRI	620 kg / t DRI	798 kg / t DRI	88 kg / t DRI	0 kg / t DRI
% vs Natural Gas		129,00%	15,00%	0,00%

Table 2 Theoretical consumption of hydrogen and related CO2 emissions in the DRI Shaft process

Search Terms	Number of Papers
iron (oxide or ore) reduction	20230
iron (oxide or ore) reduction CO	3692
iron (oxide or ore) reduction H2	109
iron (oxide or ore) mechanisms	792
iron (oxide or ore) reduction kinetics	741

Table 3 : Publications on the reduction of iron oxides from 1900 to 2020 (6)

Over the last century, more the 20.000 paper have been published on iron ore reduction from which 20% focussed on CO and 5% specifically studied the reduction of iron ore with H2 (table 3)

Thermodynamically the differences between CO and Hydrogen reduction are explained in the Baur-Glassner diagram (figure 8). From the point of view of gas utilisation, Hydrogen is the best reduction gas at high temperatures (>850°C) as the reduction is still ongoing even with >30% H2O in the reduction gas. However for lower temperatures (650°C), CO gas is consumed upto 50% CO2 in the mixture, where the hydrogen reduction stops at 25% H2O. From the enthalpie point of view, equations (1) and (2) show that hydrogen reduction is endothermic (thus is cooling the burden) while carbon monoxide is exothermic and helps to keep the burden at temperature.

Hydrogen injection in existing BF and DRI plants:

The above explains why injection H2 in the existing BF or DRI process is possible without major adaptations up to a certain threshold. Modern Blast Furnace are equipped with gas and coal injection systems at the tuyeres and have experience with injecting hydrogen rich cokesgas. Injection of pre-heated natural gas to 320°C is possible upto 140kg/t hot metal(8). Modeling the injection of pre-heated Hydrogen shows that until 27,5kg hydrogen injection per ton hot metal through the tuyeres is possible without major changes in the thermal balance of the Blast Furnace(5). With an average scrap ratio in the BOF, this results in ca 25kg of hydrogen consumption per ton of steel. Based on green hydrogen, CO2 is reduced with 300kg per ton steel (ca 20%).

In the existing DRI shafts (both MIDREX and HYL based) up to 30% of the natural gas can be replaced by hydrogen without major adaptations. This results in 25kg hydrogen consumption per ton steel (22,5 kg per ton DRI) and enables a CO2 reduction of 200kg / ton steel.

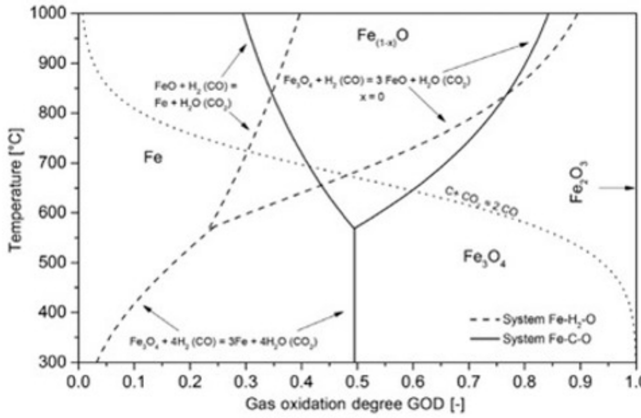


Fig. 8 The Baur-Glässner diagram for H2 reduction (Fe-O-H2 system – dotted lines) and the CO reduction (Fe-O-C system – full lines) as function of the % H2O and CO2 in the reduction gas GOD = 0 means 100% H2 or 100 % CO (7)

With the current technology, both for the existing BF/BOF plants as well as for the DRI gas shaft plants, upto 25kg hydrogen per ton of steel can displace coal and natural gas. For the 1,38 bton of steel produced in 2018 with coal-based BF and gas based DRI, this would lead to a hydrogen consumption of 34,5 million ton per year (table 4).

The constraints to move to full hydrogen steelmaking:

A logic next step could be to move to full Hydrogen by replacing all the natural gas in the DRI shaft process. In Europe, the HYBRIT consortium aims to demonstrate the full supply chain from power to hydrogen, including energy storage, iron ore pelletizing, reduction and steelmaking[37]. Recently also in Sweden, a competing 2nd project was announced “GreenH2Steel” to move quickly to a commercial phase[38]. ArcelorMittal announced a

25kg/t H2 injection	Blue Hydrogen	Green Hydrogen
Steel production (billion tons)	1,38	1,38
H2 demand (million tons)	34,5	34,5
GHG reduction (million tons)	358	402
Power Consumption (TWh)		1725
Power Consumption (EJ)		6,2
Full hydrogen steelmaking	**Blue Hydrogen**	**Green Hydrogen**
Steel production (billion tons)	1,38	1,38
H2 demand (million tons)	115,9	115,9
GHG reduction (million tons)	1529	1782
Power Consumption (TWh)		5796
Power Consumption (EJ)		20,9

Table 4 : Demand for hydrogen, CCS, renewable power in case of 25kg H2 injection and in case of full hydrogen steelmaking simulated for the steel production of 2018

collaboration together with MIDREX to build a 100.000 tons DRI pilot plant which can run on 100% Hydrogen[9].

However, a number of constraints need to be considered before moving to full hydrogen steelmaking :

1. Green Hydrogen Supply Challenge for the Full Hydrogen Pathway

The potential consumption of 34,5 million ton of hydrogen in the existing BF and DRI plants (based on the 25kg/t steel) is comparable to current consumption of the global refining industry (38,2 million tons) or the global ammonia production (31,5 million tons)[(10)]. It is 45% of the current annual hydrogen consumption and all this hydrogen production must be blue or green. In case of green hydrogen, 402 million tons of CO2 would be avoided, but it creates an annual demand of 1725 TWh or 6,2 EJ per year of renewable power (table 4)

Moving to full hydrogen increases the demand to 115,9 million tons or 3x the current demand for the global refining industry. 20,9 Exajoule of renewable power would be required which need to be put into perspective of long term zero carbon scenario's. The Net Zero 2050 scenario of IEA[(11)] is showing a potential power production from wind and solar of 110 EJ (figure 9). Full Green Hydrogen steelmaking would thus consume 20% of all Solar and Wind energy world wide. In that case it would not be available for other sectors and applications.

The IEA Net Zero 2050 scenario itself is projecting ca 35million tons of Hydrogen consumption in the Iron and Steel sector (figure 10). This figure is matching with the 25kg per ton hydrogen injection possible without adapting the BF and DRI plants. Green hydrogen supply in 2050 will thus still be limited and insufficient to justify a complete rebuild of the steelmaking assets for the Full Hydrogen pathway.

2. Technological Challenges for Full Hydrogen pathway related to the ironmaking assets

Moving to full hydrogen steelmaking is for sure not possible with the Blast Furnace process. Metallurgical coal is playing a key role to create the permeability for the reduction gas and to create a high temperature melting zone. The current assets would need to be rebuild by gas based DRI assets which need to be redesigned as in the current processes CO is playing a key role.

In depth research on the impact of H2/CO ratio in a DRI shaft was done in the ULCOS project. Experimental results show an important impact on the metallization of the DRI with increasing H2/CO ration(figure 11). The lower metallization is due to the thermal gradient caused by the endothermic Hydrogen reduction (lower temperature at the center) combined with a slower reduction kinetics at lower temperature. To keep the current metallization degree the productivity of the shaft need to come down. New designs will be required to overcome these problems for a full H2 reduction.

In the cooling zone natural gas is injected which results in minimum 1,5% upto 4% carbon in the DRI. Cooling by nitrogen will require a new concept for evacuation zone. The tightness between cooling zone and reactor will be crucial in order to avoid nitrogen build up in the reactor.

To avoid sticking and powdering in the shaft, the selection of raw material will be more strict putting pressure on the supply of pellets (figure 12). Interesting

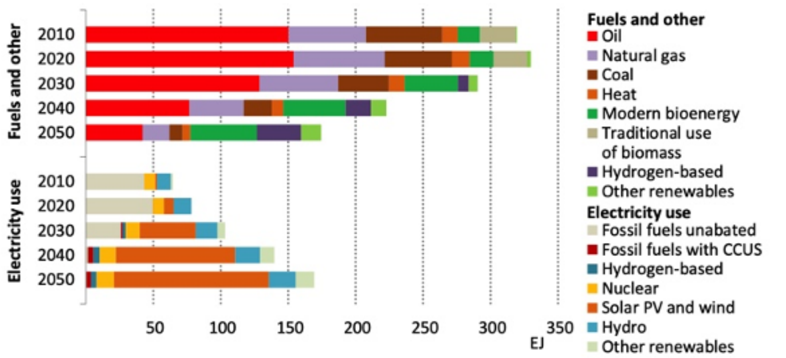


Fig. 9. The global total final energy consumption by fuel in the Net-Zero scenario of IEA. (hydrogen-based includes hydrogen, ammonia and synthetic fuels)[(11)]

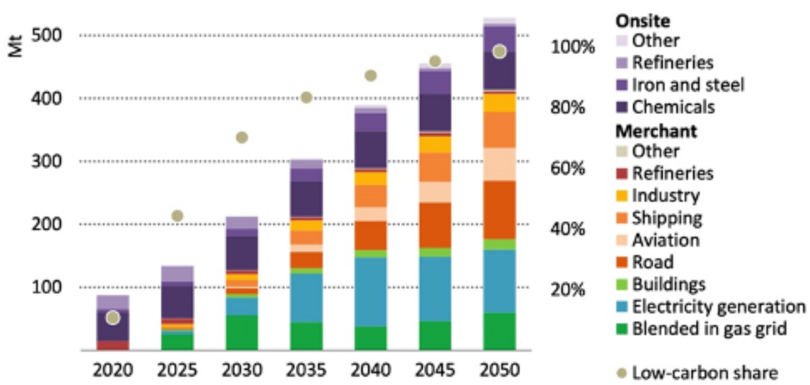


Fig. 10:. Hydrogen and hydrogen derived fuels in the "Net Zero by 2050" Scenario of IEA[(11)]

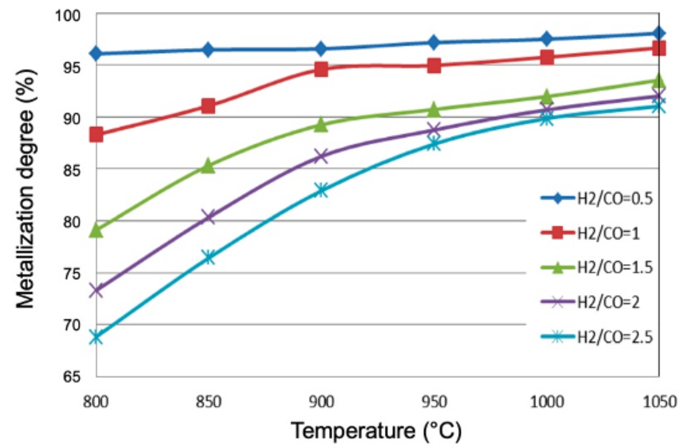


Fig. 11: Metallization degree of the DRI as function of the temperature and H / CO ratio as tested in the ULCOS research program[12]

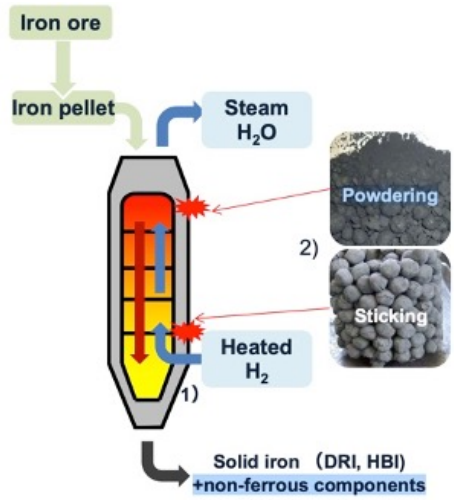


Fig. 12. Challenges with sticking and powdering in Full Hydrogen DRI shaft will put pressure on raw material supply. [13]

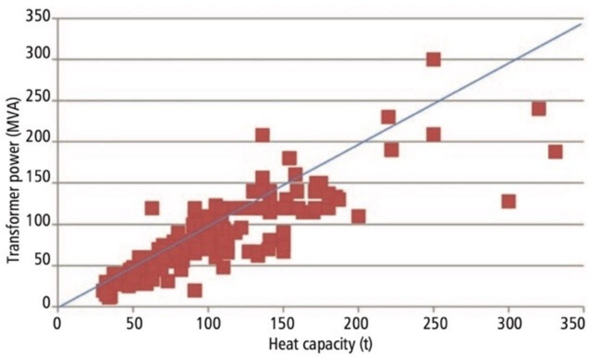
therefor is the announcement of Primetals which is restarting the R&D for a hydrogen based reduction plant with fines and with fluidized bed reactors to overcome those problems[14].

3. Technological Challenges for Full Hydrogen Pathway related to the steelmaking assets

Moving to hydrogen based ironmaking will have a major impact on the steelmaking assets. The average heat size of EAF today is relative small as the EAF is feeding or casters for long products or casting-strip rolling plants (figure 13). When steelmakers want to keep the high productivity secondary metallurgy and continuous slab casting, heat size above 300 ton with tap-to-tap times below 40 minutes is required. This is a challenge for both the electrical transformer as well as for the EAF equipment itself as a specific power consumption above 600 kWh per ton steel is expected.

For the high quality grade steel, the problem of nitrogen pick up from the air during the process will need to be solved.

With the increasing demand for DRI pellets, it is likely that Fe-content of the pellets will come down and the steel slag formation in the EAF will increase. The lower expected metallization in case of full hydrogen reduction and the zero carbon content of the DRI will lead to a high FeO content in the steel slag and thus important yield losses. Today steelmakers are moving from that reason to 4% carbon in the DRI. When starting from zero carbon DRI, the existing EAF design will require significant amount of carbon and oxygen injection to create a protective atmosphere, a foaming slag and keep the Fe-losses under control. In the HYBRIT project, bio-carbon would be injected in the bath for that purpose. However the yield of the carbon injection in EAF can be problematic.



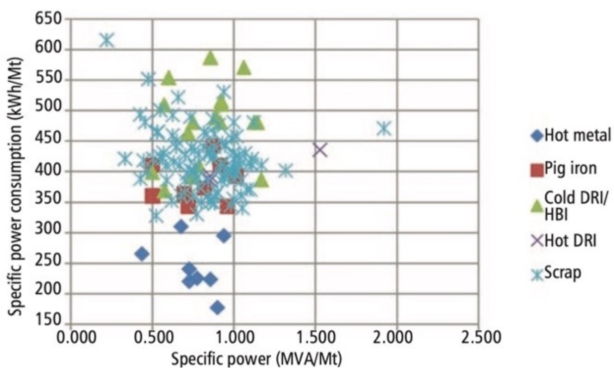


Fig. 13. Average heat size for current EAF plants (left) and specific power consumption as function of the charge (right)[15]

Voest is announcing the development of Hydrogen Plasma melting reduction to overcome the above mentioned problems[39]. A hydrogen plasma would be used to directly move to steel in a type of electric arc reduction/melting furnace. However this development is still at low TRL.

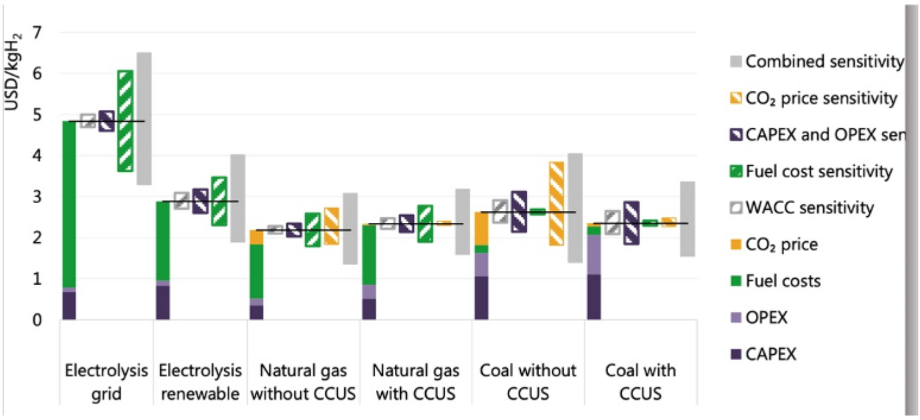


Fig. 14. Sensitivity of Hydrogen cost in 2030 in the IEA Net Zero Carbon by 2050 scenario[11]
Renewable power cost 40 USD/MWh, full load hours at best locations

Interesting is the announcement of TKSE to develop an electrical hot metal production unit[16]. The idea is to melt the DRI from a shaft furnace in an adapted Submerged-Arc-Furnace where Carbon is added to reach a 4% carbon alloyed hot metal. This hot metal can go to the existing BOF plants and slab casters. As 4% carbon is required in the "liquid DRI", this innovation is fitting well with the approach to inject 25 kg hydrogen in DRI shaft, but is less suited for a full Hydrogen pathway.

4. Economical Challenges for the Full Hydrogen Pathway

Probably the largest challenge is economic which can be expressed in the CO2 abatement cost. "CO2 abatement cost" is the break even price you need to make the Green Hydrogen based steel process break even with the current processes.

The production of hydrogen from water electrolysis requires 50 to 55 kWh per kg of hydrogen. The power consumption is responsible for ca 80% of the hydrogen cost. IEA is predicting a 2030 hydrogen cost of 3 USD/kg in case of off-side hydrogen generation with low cost renewable power from wind and solar PV, while 5 USD/kg is expected for on-site grid-connected hydrogen generation (figure 14)

In case of off-side hydrogen generation, additional costs for transport of hydrogen to the steelplant and temporary storage to deal with fluctuations in the variable renewable power production need to be added to the 3 USD/kg. Hydrogen is known for its low energy density per liter which explains why more energy is required for the compression or the liquefaction for transport and storage compared to other energy carriers (figure 15).

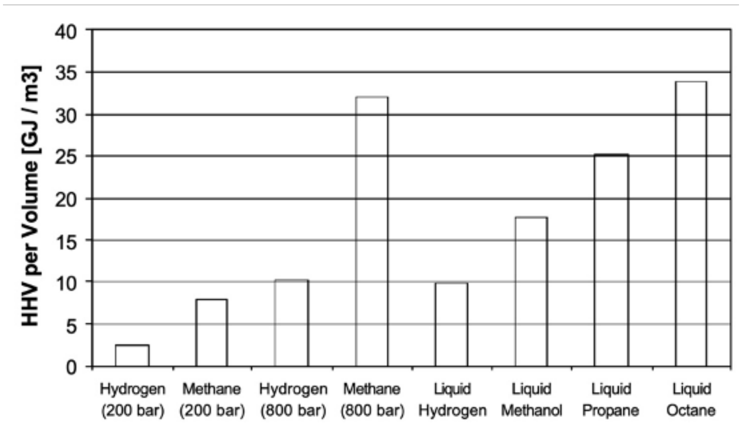


Fig. 15: Energy density of gasous and liquid fuels [17]

According to Bossel, ca 10% of the hydrogen is consumed per 1000km pipeline and 40% of the hydrogen energy is consumed to liquify and store the hydrogen. When we assume 2000km transport in average and temporary storage of 60% of the hydrogen, 44% of the hydrogen would be consumed. In that case, the total hydrogen cost for the steelmaker increases to 4,32$ per kilogram, still below the by IEA projected on-site hydrogen cost of 5 $/kg. The CO2 abatement cost in case of 25kg hydrogen injection per ton steel in the existing Blast Furnace is 342$ per ton CO2 where 474$ is found for the DRI case (table 5).

Those levels are significantly above the projected CO2 prices for 2050 (table 6). Moving to full hydrogen steelmaking will only further increase this number as additional capital costs will be required to rebuild the existing assets. As 3 times more hydrogen would be required, it is likely that hydrogen will need to be transported over longer distances and become more expensive.

Electrification of high temperature heat with zero carbon power:

Hydrogen will play an important role in Carbon Neutral steelmaking as injected gas in existing BF and DRI plants. However banning carbon and

Per ton steel	25kg injection in BF	25 kg injection in DRI
Off-side H_2 generation from renewables (USD/kg)	$3,00	$3,00
H_2 consumption for transport, temporary storage	44,00%	44,00%
Total cost of Hydrogen`(USD/kg)	$4,32	$4,32
Green H_2 cost` (USD/t steel)	$113	$113
Savings in coal and gas cost (USD/t steel)	$10	$20
CO_2 abatement (kg/t steel)	300	195
CO_2 abatement cost (USD/t CO_2)	$342	$474

Table 5: CO_2 abatement cost of 25kg/t steel hydrogen injection in existing BF and DRI plant

USD (2019) per tonne of CO_2	2025	2030	2040	2050
Advanced economies	75	130	205	250
Selected emerging market and developing economies	45	90	160	200
Other emerging market and developing economies	3	15	35	55

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Table 6: CO_2 price evolution in the Net Zero Carbon scenario according to IEA (selected emerging markets includes China, Russia, Brazil and South Africa) [11]

moving to full hydrogen is extremely challenging related to supply, economics and process technology. To reach carbon neutrality steelmakers need to combine in a smart way the use of hydrogen, zero carbon power and carbon.

The need for high temperature heat is responsible for 35%, resp. 33% of the CO_2 emissions in the current BF, resp. DRI plants (figure 4). Technology exists to directly electrify the generation of high temperature heat instead of indirectly work with Green Hydrogen. As the conversion of power to hydrogen and hydrogen to heat has a yield of below 50%, it is smarter and cheaper to directly use power for heating.

Plasma torch applications to generate high temperature heat

An attractive technology for steelmakers is the plasma torche to heat up gas or air. Plasma is an ionize state of gas containing free charge carriers and therefore is electrical conductive. In the thermal plasma temperatures of 1000K and above reached, which results in very fast and efficient thermal conversion without any catalyst. Plasma torches upto 2,4MW are commercially available to replace fossil fuel burners and have electrical efficiencies above 85%[19].

In the course of the ULCOS project, the integration of 2MW torches into the tuyeres of a large Blast Furnace was studied (figure 16). Power consumption is ca 250kWh per ton hot metal (or 0,9 GJ), which is significantly below the current consumption in the hot blast stoves and 220kg/t hot metal CO_2 emission is avoided by not burning Blast Furnace gas.

Once the plasma torches are integrated in the tuyeres, the refractory of the hot blast main is no longer limiting the air injection temperature to 1250°C and superheating of the hot blast can be considered. Figure 17 shows the impact on the operation of the Blast Furnace when the hot air is superheated up to 1800°C. The coke rate is reduced to the minimum theoretical amount needed for iron

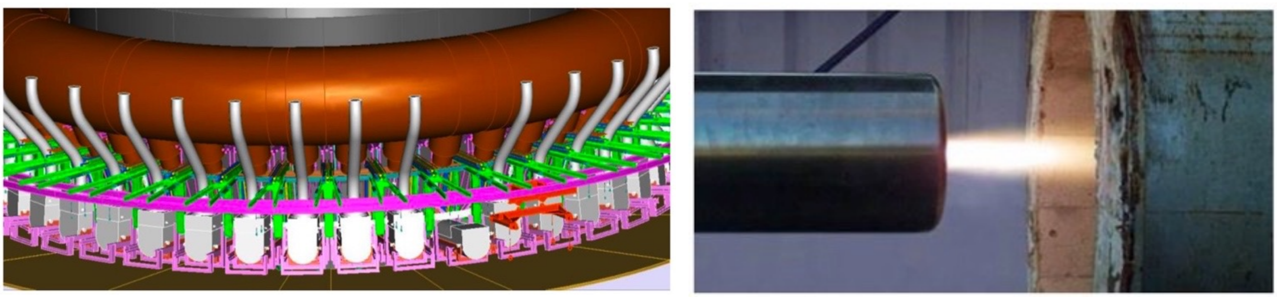


Fig. 16: Plasma torches integrated in the tuyeres of a Blast Furnace to heat up the hot blast [20]

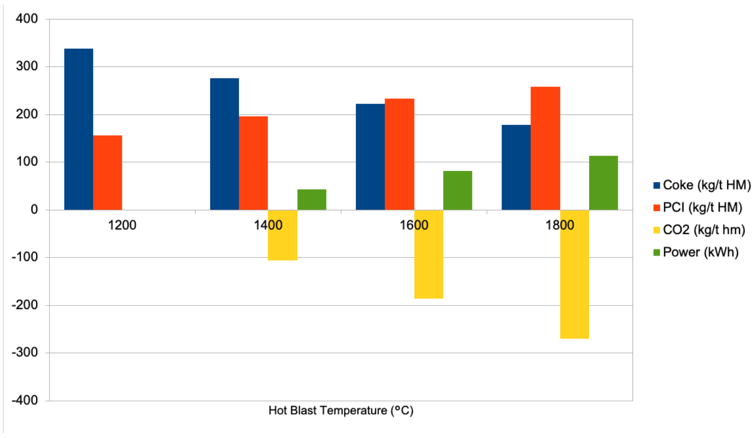


Fig. 17: Reduction of fuel rate and CO2 in the Blast Furnace when superheating the hot blast with plasma torches[21]

carburization and burden support. The flame temperature and top gas temperature is kept constant. Significant higher PCI injection and productivity of the BF are possible without further oxygen enrichment. For a typical medium sized 6000 ton per day BF, 28 MW of power is consumed which is less than 1MW per tuyere. This reduces the CO2 generation with 270kg/t

Plasma torches for Methane Cracking and Dry Reforming of CO2

Another way to electrify is to use plasma torches to reform/heat the reduction gas in the DRI shaft. Today plasma torches are already commercially used for methane cracking.

$$CH4 = C + 2\ H2 – 74{,}5\ \text{kJ} \qquad \text{(Eq. 4)}$$

Methane cracking or pyrolysis is the chemical splitting of hydrocarbons into hydrogen and solid carbon (equation 4). The gaseous hydrogen and solid carbon is produced (no CO/CO2 is formed as no oxygen is entering the system). The most prominent example is Monolith Materials which is operating a 16 MWe plasma torch to produce carbon black with hydrogen as a by-product. Steelmakers can use the hydrogen for injection in BF or DRI and the solid carbon to displace coal for cokemaking and PCI.

Using plasma torch for dry methane reforming has been developed in the course of ULCOS (equation 5). Dry reforming is comparable to the traditional and well-known steam methane reforming (equation 6).

$$CH4 + CO2 = 2\ CO + 2\ H2 – 247\ \text{kJ} \qquad \text{(Eq. 5)}$$

$$CH4 + H2O = CO + 3\ H2 – 208\ \text{kJ} \qquad \text{(Eq. 6)}$$

In dry CO2 reforming, CO2 is used instead of steam to produce a syngas from methane. The reaction is also endothermic and the energy penalty compared to the steam methane reforming is limited (< 20%). Thanks to the high temperature generated in a plasma (>1000 K), the dry reforming reaction is fast and complete without any catalyst. The plasma system is flexible to follow a fluctuating supply of renewable power. The high temperature of the syngas in the plasma makes it compatible with direct injection in the DRI shaft.

For a DRI plant, ca 1MWh per ton DRI will be required for the reforming and heating of the reductant gas without changing the DRI shaft process itself. It avoids the generation of 220kg CO2 due to the current combustion of DRI top gas (figure 18).

By a moderate adaptation of the existing BF, shaft injection of reformed gas is possible at 950°C (figure 19). ArcelorMittal is developing this hybrid

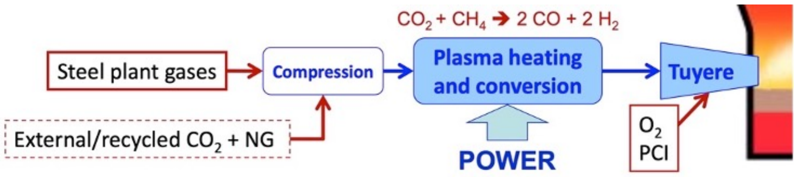


Fig. 18: Plasma heating and reforming of hot syngas for injection in the BF or in the DRI shaft[20]

B F -

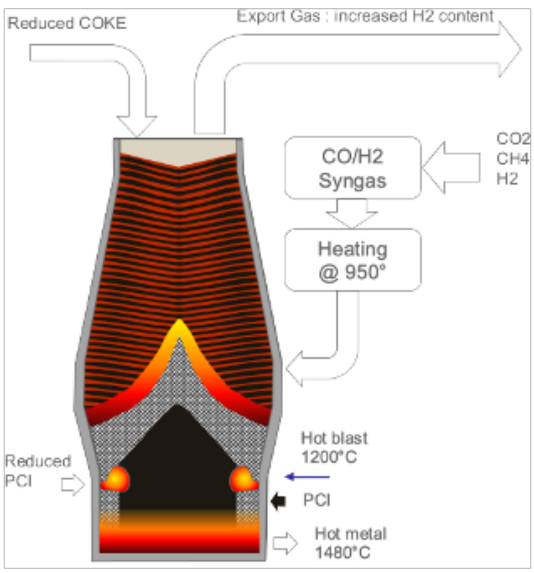


Fig. 19: IGAR Blast Furnace concept with shaft injection at 950 °C (9)

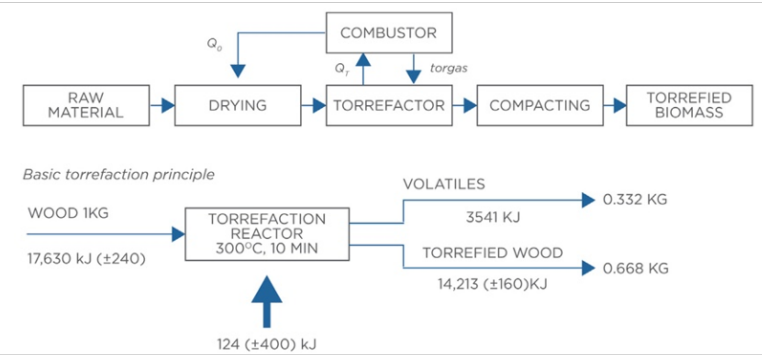


Fig. 20: Process scheme and yield for torrefaction process of wood.

DRI process in the IGAR project in Dunkerque[9]. Approximately 100 kg of cokes and coal input can be replaced by hot syngas shaft injection without major changes in the operating point of the Blast Furnace.

Alternative Carbon Reductants as third step

Gasification of waste to replace natural gas

The use of plasma reforming for DRI and BF is compatible with using waste hydro-carbons instead of natural gas. Plasma reforming is done at very high temperature without catalyst. Advantage is that no purification of the methane or CO2 is required. For this reason, plasma technology is today mainly used in the waste sector to clean gases from waste gasifiers. Municipal waste is gasified in fluidized bed reactors of 160MW of more. After cleaning the gas for chlorines it can be used to reform CO2 in the plasma torch and produce a stable CO:H2 syngas for injection.

Using waste streams for BioCoal injection in BF and EAF

Direct plastic injection in the tuyeres of a Blast Furnace or the use of charcoal in the EAF are other examples of waste sources used as alternative reductants. In Brazil several smaller BF are even running on 100% charcoal produced from Eucalyptus. The low mechanical resistance and the limited supply of fresh wood, does not allow to replace the coke in the large Blast Furnaces, but this is less the case for the coal injection. .Indeed the carbon sourced into the state-of-the-art Blast Furnaces comes for nearly 50% of the injected grinded coal. Waste wood can be an excellent substitute for coal injection after a torrefaction treatment of the wood. Torrefaction is happening when biomass is heated at 250 to 300 °C in absence of oxygen, where charcoal is produced by slow pyrolysis process at temperatures of 400°C or more. Thanks to the lower temperature the yield is significantly better compared to charcoal (Figure 20). More bio-carbon is contained during the torrefaction and is entering the ironmaking process.

Research has shown that torrefied wood, with different ash content and different temperature treatments, is always combusting faster compared to fossil coal (figure 21). The reason is the greater specific surface of biocoal thanks to the cellular structure of the wood.

A demonstrated technology for large scale torrefaction of waste wood is the external heated rotating drum as is commercialised by Torrcoal (figure 22). In the TORERO project, ArcelorMittal is building a first torrefaction plant for 100.000 tons of biocoal injection in the BF which will start in 2022[9].

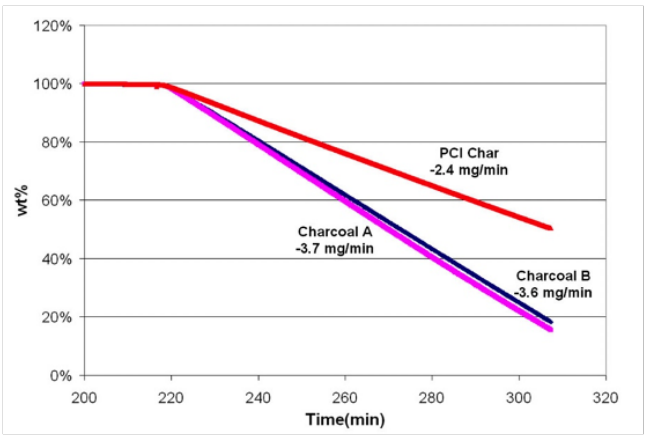


Fig. 21: Combustion rate of different types of biocoal and PCI coal during injection in the BF[27]

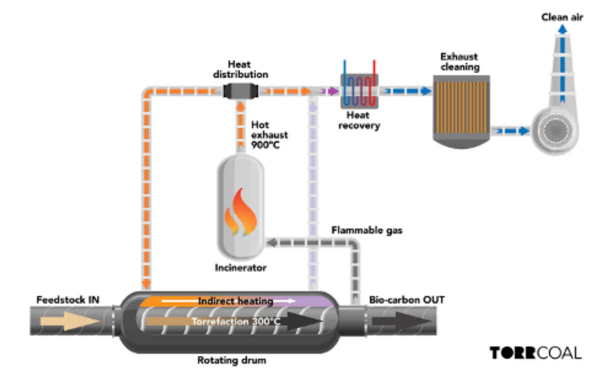


Fig. 22. Torrefaction of waste wood in a rotating drum as developed by TorrCoal[40]

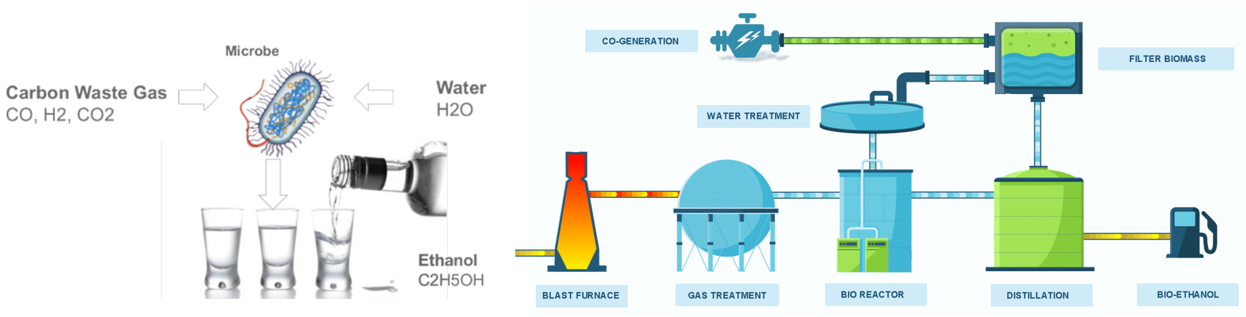


Fig. 24: Gasfermentation of carbon containing waste gas into microbers

Supply constraint for waste wood and waste plastic.

As is the case for Green hydrogen, the injection of biooal and use of plastic waste will rather be constraint by the supply and not due to technical limitations to adapt the existing DRI and BF plants.

In Europe, ca 100kg wood waste per capita or 52,9million tons is generated by end of life products. The demolition and construction market is responsible for 25 to 30% of this supply. Only 15% of this waste is recycled[28]. By closing the coal fired power plants, waste wood becomes more and more available for other purposes.

In 2018, 367million tons of plastics were produced. End of life only 9% of the plastics are recycled and 12% incinerated. The remaining 80% (ca 280 million tons per year) is polluting the environment. One third of plastics is produced in China, 15% in Europe (55 million tons)

Substitution of 50kg of PCI by waste wood and 3GJ of gas by plastic waste gasification at the European steel plants results in a demand of ca 10million tons waste wood and 11 million tons of plastics (ca 20% of supply for both waste streams). Such a scale of waste recycling is feasible both from technology as from supply point of view. It will create significant value for society and reduce CO_2 emissions with 350kg per ton crude steel.

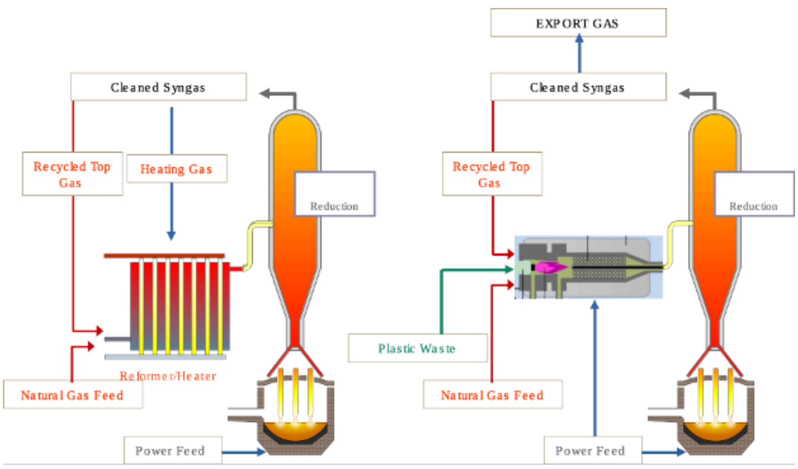


Fig. 23: Traditional process scheme (left) and scheme after electrification (right) of DRI /EAF plant.

CCU technology to close the carbon circle and create value

The consequence of the earlier described electrification is an increase of the amount of available steel waste gas, which will be more and more produced from waste carbon, but which eventually still is converted into CO_2 as long as the exported waste gas is burned in a power plant. It does not make sense to first electrify the heat supply (in order to save CO_2) and as a consequence export the extra waste gas to generate power (which will generate CO_2).

Figure 23 illustrates the impact of electrification of the external heater/reformer as is used in the Midrex DRI Shaft. There are no changes for the inputs and outputs of the DRI process itself. However where today with the thermal heater/reformer ca 4 GJ of syngas is incinerated to supply the heat, this is replaced by 1MWh power supply to the plasma reactor. The end result is the need to export 4GJ of syngas to another process which should not emit CO_2. Another example is the electrification of the hot blast of the BF: ca 1,5 GJ per ton hot metal of steel waste gas will be replaced by 0,25MWh of power.

The steel sector is probably the largest producer of syngas. Globally the steel sector is generating ca 7000 thousands TeraJoule of syngas. This is comparable to the total natural gas consumption of Germany and Italy, the 2 largest economies in Europe.

Syngas is produced on purpose in the chemical sector as first step to produce CO and H2 for the synthesis of hydrocarbons. As the steel waste gas is already available as CO and H2, no or only little cracking and reforming need to be done in order to use it as stockfeed for chemicals. CCU (Carbon capture and use) technologies are bringing new options to convert exported waste gas into products and avoid the incineration of gas in a power plant.

In 2015 TKSE launched a large program “Carbon2Chem” to convert the syngas into chemicals[23]. Tata and AM are studying the same approach in the “Steel2Chemicals” project[24]. The major challenge however is to clean the steel waste gas upto levels that catalysts are not poisoned. On top the ratio CO:H2 need to be shifted to the right amount with the water gas shift reaction which is consuming energy.

A promising innovative approach is the gas fermentation technology as developed by Lanzatech. In contrast to the traditional catalytic chemistry, a fermentation by microbes is used to convert CO/CO2/H2 into products. The bio-process can be compared with the fermentation of sugar from corn or sugarcane into ethanol by yeast. In the gasfermentation, the gas is pressurized and injected into watertanks with microbes. The microbes are directly consuming CO/CO2 and H2 to produce ethanol (C2H5OH) which is continuously distillated out of the broth (figure 24).

The main advantage is the compatibility and flexibility of the gas fermentation with DRI and BF gas:

- the microbe is driven by CO and H2. In case there is lack of H2, the microbe will itself perform the water shift reaction by picking up hydrogen from the water
- the microbe is adapted to the typical DRI and BF atmosphere. Very little or no cleaning is necessary.
- the gases not need to be pure. Presence of CO2 and Nitrogen will not impact the fermentation process as such and does not need to be removed
- the energy conservation of the biobased system is very high : ca 70% of the energy is converted into alcohol, while the other 30% is converted into biomass. This biomass can be fermented into biogas or can also be used as protein rich animal feed.
- by changing the microbes different chemicals can be made and other markets can be reached such as aceton, isopropanol and other.

The Lanzatech technology was first used at commercial scale at Shougang steel where the plant started in 2018. Currently a large investment with ArcelorMittal is close to commissions and will start up in 2022 (figure 25).

When applied at full scale and using all the steel waste gas, a yield of 200kg of alcohol per ton of steel is possible, avoiding 400kg/ton CO2 per ton of crude steel. Further processing of the ethanol into 120kg ethylene per ton steel is straightforward with existing technology. Applying this to the European market as business case, the steel sector can supply 12 million tons of ethylene to the chemical sector, avoiding an additional 24 million tons of CO2 which is emitted when ethylene is produced from nafta. This is ca 50% of the current ethylene market of Europe. Figure 26 illustrates a number of potential markets for Ethanol in 2030 which is 25x larger compared the current application to blend ethanol in the gasoline.

By combining the recycling of waste wood and plastics into the DRI and BF process with the conversion of the steel waste gas into ethanol and chemicals, the steel sector is an enabler of the circular economy by converting waste into products at large scale.

Waste Heat enables low cost Carbon Capture and Export (CCE) of CO2

The remaining CO2 emissions (ca 200kg/t) are mainly from biological origin or from carbon in the plastic waste. Capture this CO2 for transport and storage (CCS) is straightforward and can result even in negative CO2 emissions: the so-called BECCS (bio-energy with CCS).

Fig. 25: Construction of the Steelanol plant at ArcelorMittal Gent[26]

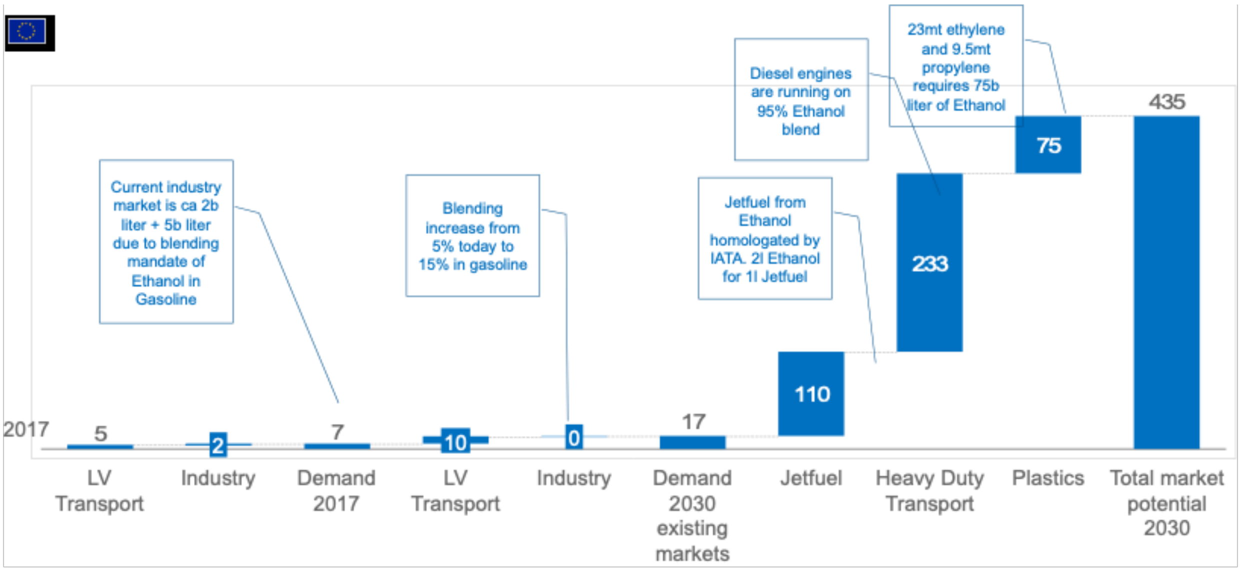


Fig. 26: Potential demand for ethanol (in billion liters) in the EU market is 25x larger compared to the blending into gasoline[25] .

In situ capture of the CO2 in the BF and DRI plant can be done at low cost by using waste heat from the steelmaking processes. Novel approaches with amines washing allows to capture 99% of the CO2 with ca 2,3 GJ per ton CO2 of low pressure steam. Existing steelmaking plants can capture enough waste heat with (easy access) add-on investments to capture at minimum 200kg CO2 per ton steell[32]. A first pilot plant is under construction at ArcelorMittal in the course of the 3D-CCUS project (figure 27).

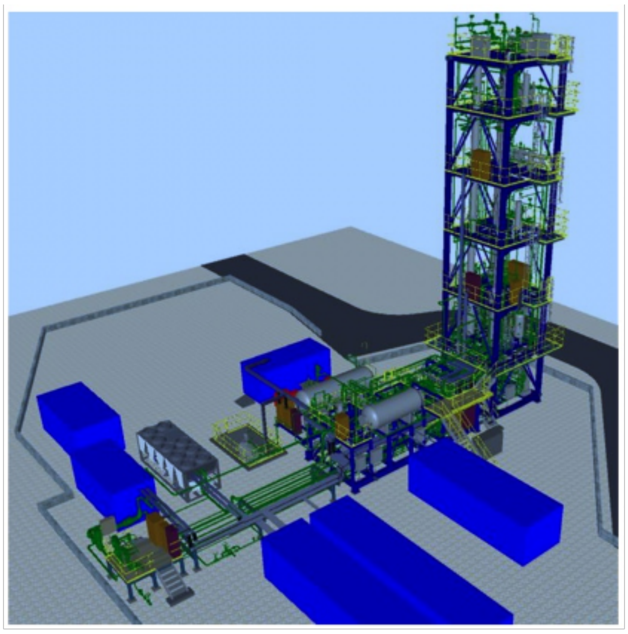


Fig. 27: CO2 capture unit under construction at the Blast Furnace of AM Dunkerque[32]

Opex cost for capture and liquifaction of CO2 with waste heat will be in the range of 15 to 25 USD per ton CO2. Liquid CO2 can be shipped over long distances with the same technology as is used for LNG. Shipping costs on the base of 1 million ton CO2 per year over 1000km distance are in the range of 10 to 15 USD/ton[33] depending on the size of the ships, resulting in overall cost for carbon capture and export (CCE) below 50 USD per ton of CO2.

In a Net Zero world, the industrial regions with high concentrations of chemical and steel plants will need to import renewable energy (RE) over long distances. Figure 28 shows the long term gap between potential of RE generation versus RE needs for West-Europe. North-France, Belgium, Netherlands and West Germany upto North Italy are lacking up to 1000 TWh in total.

New specializations will be created in the global Net Zero Economy. Renewable power generated in regions with a lot of sun, will need to be converted into a liquid energy carrier to transport the cheap energy to the industrial regions. Figure 29 shows the result of a study where import of RE from 4 regions to Zeebrugge (Belgium) as liquid hydrogen, liquid methane (LNG) and methanol was studied. Methanol offers the most attractive case. With a CO2 captured and exported at a cost below 40 EUR per ton, the cost of green methanol is even below the current fossil methanol cost. The result on figure 29 illustrates again the issue with hydrogen: it requires more energy to liquify and transport the

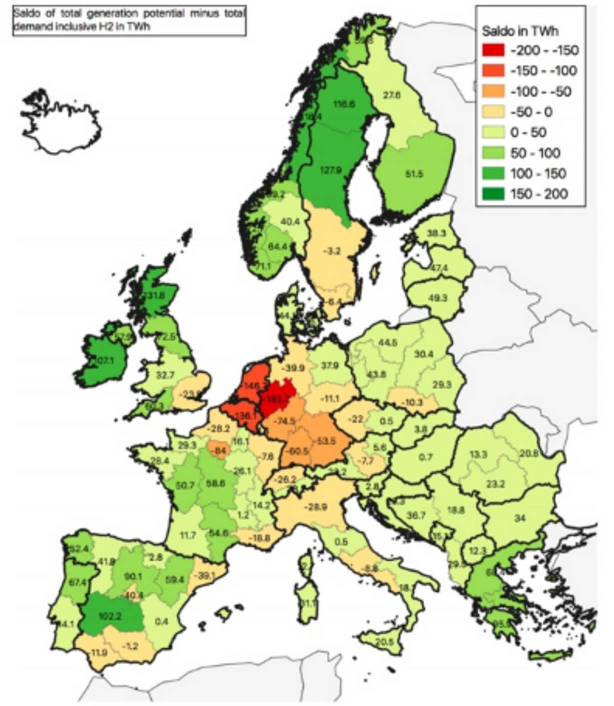


Fig. 28: Balance of renewable power potential versus demand (including Hydrogen) per region in EU [34]

hydrogen itself compared to convert CO2 and H2 into methanol + transport the methanol.

This opens new opportunities for net-zero steelmakers to export the remaining 200kg/t low cost CO2 as stockfeed to produce methanol with low cost renewables. The methanol can be imported back to supply the chemical sector or can be reformed to syngas for the DRI or BF shaft injection[35]

Conclusions

The Smart Carbon Pathway

In this paper, five key enabling technologies to move to carbon neutrality have been reviewed in detail with a focus on the constraints to scale up each solution. All five technologies can be integrated with the BF/BOF plants as with the DRI/EAF plants with only minor adaptations to the existing processes. The fossil inputs (coal and natural gas) are replaced by renewable power, cellulosic waste and recycled polymers. CCU and CCE allows to convert the carbon containing steel waste gas into ethanol and methanol. Biogenic CO2 can be combined with CCS to realize even negative emissions (BECCS as 6th key enabling technology).

As a result, the initial CO2 emissions of 1600kg for BF plants and 1100 kg for DRI plants in the future net zero power world, is stepwise reduced to zero (figure 30):

- The renewable power allows to electrify the high temperature heat generation
- Renewable power is converted into 25kg Green hydrogen for injection in BF and DRI plants
- The cellulosic biowaste is converted into biocoal for the BF and the EAF
- The recycled polymers are gasified in order to reform with CO2 into a syngas for injection in DRI and BF shaft
- The waste gas of the DRI and BF plant is converted into high value molecules with biological gasfermentation
- The remaining fossil CO2 is captured, liquified and exported at low cost and imported again as green methanol produced with low cost renewable power

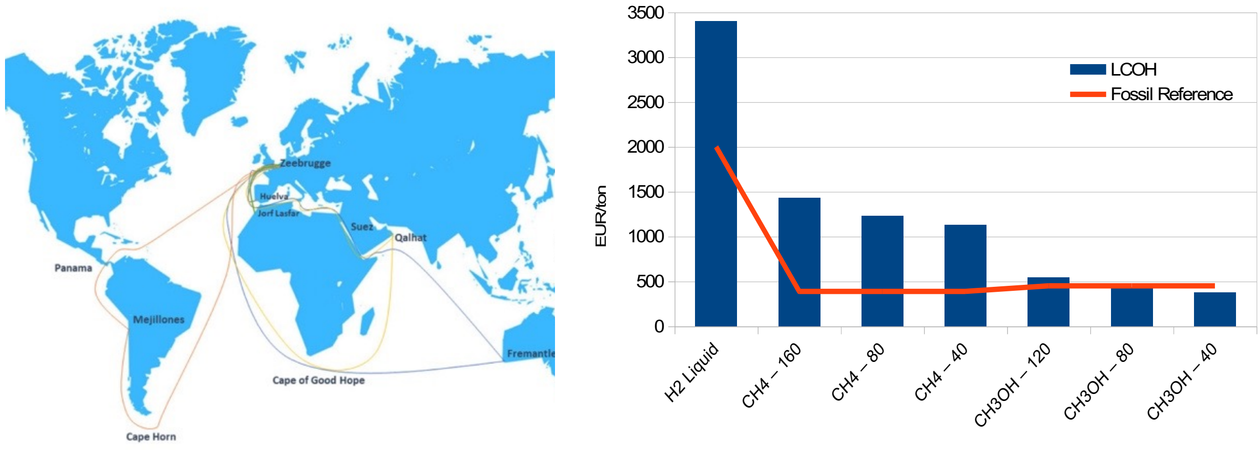
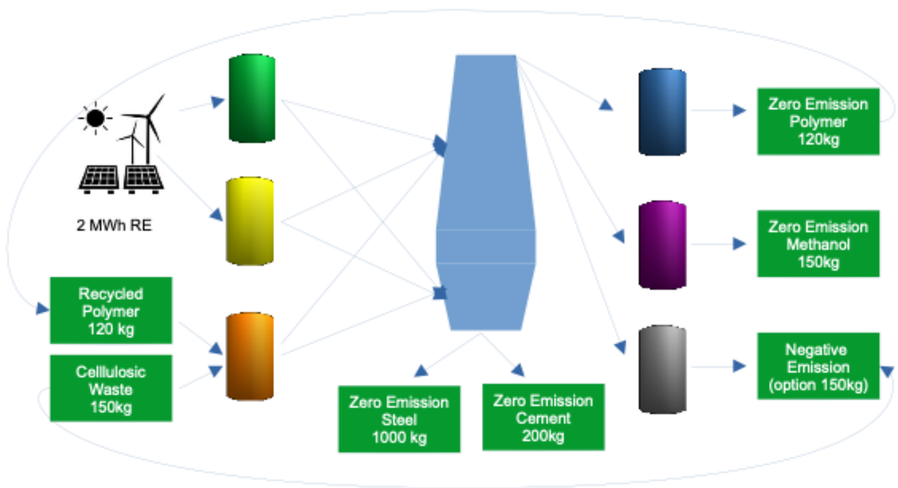


Fig. 29: Average Levelized cost of Hydrogen (H2), methane (CH4) and methanol (CH3OH) in Zeebrugge (B), produced in Chili, Oman, Australia, Morocco from renewables (as function of cost of CO2 : 160 EUR/ton, 80 EUR/ton and 40 EUR/ton)[34]



	Today Steel Emissions Kg / ton steel	Electrification HT Heat	Hydrogen injection	Torrefaction & Gasification	Gasfermentation	CCE	BECCS (option)	Carbon Neutral Steel emissions Kg / ton steel
BF/BOF	1600	-350	-300	-350	-400	-200	(-150)	0 (-150)
DRI/EAF	1100	-250	-200	-250	-200	-200		0

Fig. 30: Integrating 5 key enabling technologies allows to move existing BF and DRI plants to move to carbon neutral steelmaking.

- The biological CO2 from cellulosic biomass waste can as bonus be captured for BECCS (negative carbon emissions)

The key enabling technologies (KET) as integrated in figure 30 have a number of elements in common:

- all technologies exists at commercial scale or are currently in demonstration
- all technologies are scaled and scalable related to realistic supply constraints.
- all technologies can be stepwise integrated with both existing or new BF and DRI plants
- all KET can be deployed in parallel. There is no risk for carbon lock-in by starting with one technology. On the contrary, the combination of multiple KETs is creating additional synergy gains which will accelerate the deployment.

A new narrative for Carbon Neutral Steelmaking

Until now, two narratives for Carbon Neutral steelmaking were launched: the CCS narrative and the Hydrogen narrative which both are competing with each other (point A and B in figure 30).
The CCS narrative was at the base of the ULCOS project in 2005 in Europe. It states that carbon is a mandatory resource and that steelmaking always will produce a lot of CO2. Large scale CCS integration is enabling to move to carbon neutrality at the lowest cost. It allows to continue the current infrastructure and to keep the jobs. In this way, CCS is promoted as a contributor to the “Just Transition”[41].

More recently, the Hydrogen narrative was launched. It promotes the radical change away from carbon to hydrogen produced with renewables. Although the costs of the transition are high in case only renewables are considered, it is believed that banning carbon feedstock is the most desirable abatement option.

Both narratives however have the same issues: lack of robustness and increasing marginal costs while scaling up.

Lack of robustness:
The CCS and the Hydrogen narrative are believing in a deterministic world with only 1 endgame (e.g. “continuous storage of fossil CO2”; “green hydrogen economy”). There is no flexibility to adapt the path for future “black swans”. A relevant example of Black Swan is the believe in hydrogen fuel cells as future transport technology until recently the battery technology popped up as a game changer. For steelmaking, the gas

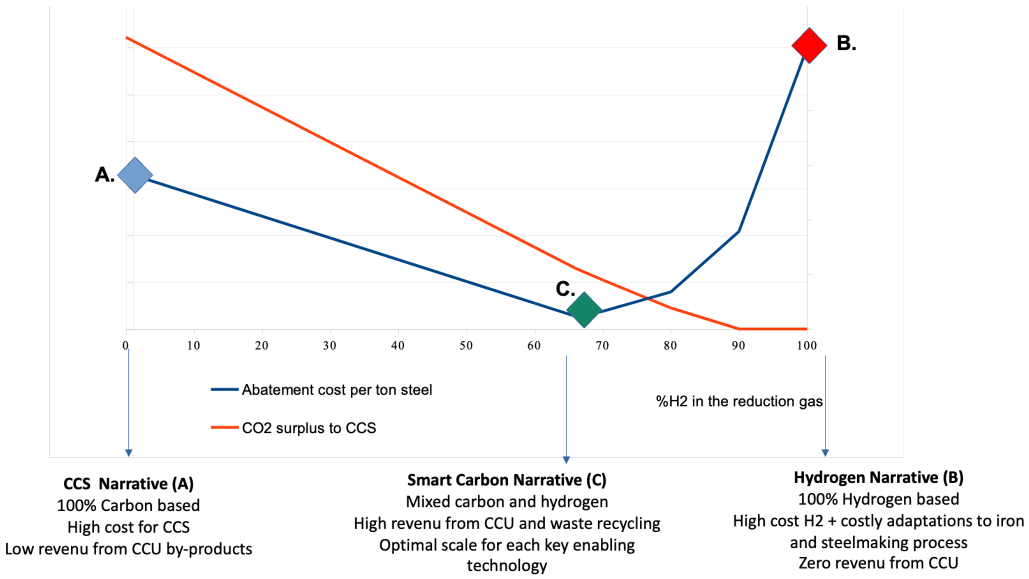


Fig. 31: The traditional CCS (point A) and Hydrogen (point B) narratives result in high cost and low flexibility (thus risks). The novel Smart carbon narrative is flexible and combines 5 strategies at their lowest cost point

fermentation of steel waste gas was also such a black swan: it popped up after the ULCOS project and opened suddenly the opportunity of CCU at large scale.

Increasing marginal costs while scaling up:
Both narratives are also suffering from the "Law of Diminishing Returns". This means that the first abatement steps can be relatively cheap, but the larger the deployment the higher the costs and the lower the returns. Green hydrogen production on site for flexible injection can be relatively cheap for the first 50 or 100MW, but in order to run 3 GW electrolysers 24/7 with renewable power, transport over long distance and (seasonal) hydrogen storage will be required. This will come at a cost which is increasing the more we move to 100% hydrogen based steelmaking. Same is true for CCS : a fraction of the CO2 can be captured at low cost and can be stored or used locally. But 100% capture of all CO2 and storage during decades will result in exponential increase of the marginal storage costs.

Although IPCC confirms that without CCS the CO2 abatement costs over the period 2015-2100 will be 138% higher versus solutions with CCS[41], CCS never got the necessary incentives and political will due to the 2 above mentioned reasons. The lack of flexibility created the fear that supporting CCS would lead to carbon lock-in (for example by keeping the coal fired power plants). Financing CCS risked to make the deployment of renewable power more expensive and thus policy makers feared to have to pay twice. Since 2005, except in USA, no significant progress was made related to CCS.

The same risks to happen with the Hydrogen narrative. EU is allocating massive amounts of financial support to the initial investments in hydrogen but this will be not enough. Limited potential to deploy locally renewable power will result in high costs. All experts believe that the Green Hydrogen narrative will be more costly compared to Blue Hydrogen (the CCS narrative) and will require financial support during decades. The result is loss of competitiveness, jobs and higher contributions from taxpayers (directly or indirectly due to more costly energy and products). This lack of justness risks to create resistance against the whole Climate Transition plan.

Need for a new compelling steel narrative:
The two conflicting narratives are paralyzing the climate actions in the steel industry and are blocking the necessary investments to move to carbon neutrality.

Steelmakers need to develop a new compelling narrative based on the Smart Carbon pathway (point C in figure 31). Steel sector can be at the center of the future eco system guided by values as "zero waste", "cradle to cradle" and "high returns thanks to specialization". The optimum is not or only carbon (point A) or only hydrogen (point B), but in the combination of both (point C). This results in lower costs for CO2 capture (the red curve), more flexibility to integrate variable renewables, higher added value thanks to the production of chemicals, higher return to society by promoting circular economy and job creation.

Summary

This article gives an overview of the challenges and opportunities to transform the steel sector to carbon neutrality. The main technological steps are described and the constraints for implementation in a 2050 carbon neutral world are identified.

Starting from the traditional and conflicting narratives for carbon neutral steelmaking, which are the CCS narrative and the Hydrogen narrative, it is shown that steelmakers need to develop the new compelling Smart Carbon Narrative based on a flexible combination of carbon and hydrogen inputs from renewables and from waste resources at the entry and production of high valuable chemicals with CCU (carbon capture and use), CCE (carbon capture and export) and BECCS (bio-energy CCS)

The Smart Carbon narrative will bring the steel sector at the center of the Carbon Neutral Eco system with a more "Just Transition" which creates jobs and prosperity for our society.

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