STEEL, THE PERFECT MATERIAL FOR A SUSTAINABLE, CIRCULAR AND RE-USABLE ECONOMY

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ABSTRACT

Decarbonization of the steel industry is key to reach the climate goals set in Paris. ArcelorMittal has a clear roadmap to reach carbon neutral steel production from iron ore by 2050, subdivided in two pathways: Smart Carbon and Innovative Direct Reduced Iron (DRI). Some of the most widely used foundation materials already have a low environmental footprint due to the production from scrap in an Electric Arc Furnace. There are several other optimizations possible to reduce the carbon footprint even further. Steel re-used several times in temporary applications, thus reducing the environmental impact each time the sheet piles are reused. At the end of life, when they cannot be reused anymore, all the remaining steel can be recycled. This creates the perfect circle for infinite use of steel, without any degradation of the material properties.

Keywords: ArcelorMittal, Smart Carbon, Innovative DRI (Direct Reduced Iron), steel sheet piles, reduce, reuse, recycling

INTRODUCTION

Steel is one of the most frequently used materials in the world, with almost 1.9 billion tons produced every year. The sheer scale of global steel production means the industry accounts for approximately 7% of the world's annual greenhouse gas emissions (Climate Action Report 2, 2021). Considering that global steel demand is forecast to increase to around 2.6 billion tons by 2050 (AMCSO, 2022), the steel industry has an important contribution to make if the world is to meet the objectives of the Paris Agreement and limit global temperature rise to 1.5 degrees Celsius above pre-industrial levels. The steel industry has the responsibility to work towards carbon neutral steel production. ArcelorMittal Europe has committed to reduce CO2 emissions by 35% by 2030, with a further ambition to be carbon neutral by 2050, in line with the EU's Green Deal (European Commission, 2021) and the Paris Agreement (United Nations, 2015). The challenge the industry faces is enormous, and yet to make this transition, our future world will need more steel, not less. For the steel industry, nothing short of a transformation is needed.

Steel is not only a material which is critical to building the infrastructure of our world — being a leading material in the production of buildings, infrastructure, cars, etc. — but it is also one with leading circularity credentials, with current recycling rates around 85 to 95%. Therefore, as meeting the objectives of the Paris agreement requires a permanent, fundamental shift in the way we consume and produce goods, the drive to decarbonize aligns with the shift to a truly circular economy — one that seeks to eliminate waste through the continual reuse of resources. The major advantage of steel recycling is that it is infinitely recyclable without loss of quality (downgrading). Often even upgrading of the steel is achieved during the recycling process.

Steel is critical for the transition toward a carbon neutral and circular economy, and it plays an integral part in the energy transition and electrification. It has a lower carbon footprint compared to competing materials, and it is therefore a key enabler in decarbonizing many other technologies like wind turbines, efficient transformers and lighter weight vehicles. A study by Boston Consultancy Group (BCG) and the German Iron and Steel Institute (VDeh) found that the CO2 emissions reductions enabled by steel outweigh emissions from steel production by 6 to 1 (BCG and VDeh, 2013).

STEEL PRODUCTION METHODS

The two main production processes currently used are steel production from iron ore in a Blast Furnace-Basic Oxygen Furnace (BF - BOF) and production from scrap in an Electric Arc Furnace (EAF). The Blast Furnace is used to produce pig iron by continuously supplying iron ore, cokes and limestone through the top of the furnace. Hot air is simultaneously blown into the lower section of the furnace, so that chemical reactions take place throughout the furnace as the material falls downward. At the bottom of the furnace molten pig iron is removed and waste gases exit at the top of the furnace.

Inside the pig iron, the carbon content is around 4-5%. In the Basic Oxygen Furnace the molten pig iron from the BF is transformed into steel. The furnace is filled with 15 to 25% scrap after which the hot iron is added to the furnace. By blowing high purity Oxygen through the molten pig iron, the carbon content is lowered and unwanted chemicals are removed. Slags are formed at the top of the furnace to absorb any remaining impurities and the created low-carbon steel is poured in a ladle for casting. Figure 1 shows the main input and output of a BF-BOF Process.

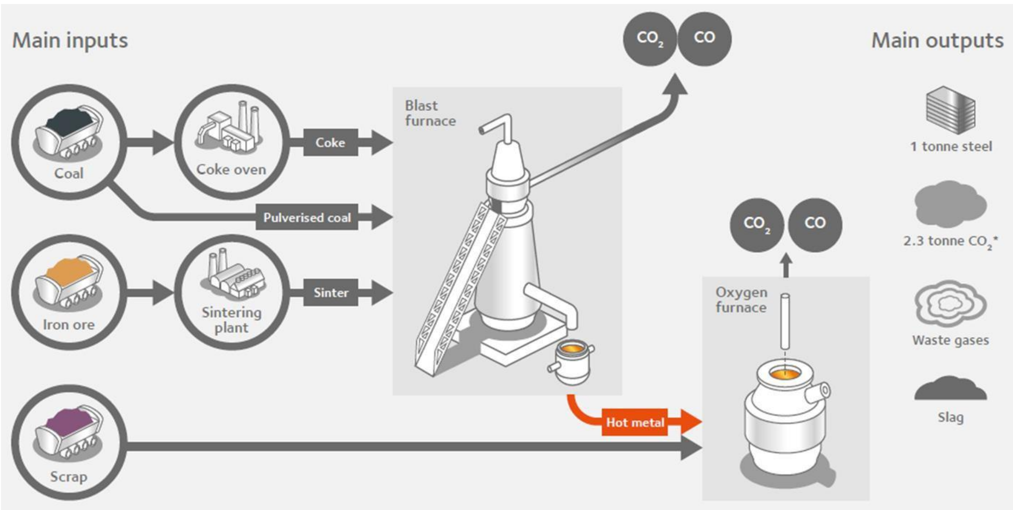

Fig. 1 – Steelmaking at an integrated plant (using iron ore)

In a scrap based Electric Arc Furnace no iron ore is used. Scrap is sorted on quality, and put in different layers into the basket. The basket is pre-heated with hot furnace off-gases to recover energy and increase efficiency. The furnace is then charged with scrap from the basket, and the electrodes are lowered into the scrap. The electrode creates a short-circuit current of thousands of amperes, and by partial withdrawal of the electrode the arc is created and the steel is melted. The contaminants in the scrap are removed with the steel slag floating on the surface. The molten steel continues to be processed in a Ladle Furnace, allowing addition and removal of elements in order to obtain the correct steel quality and homogeneity. Figure 2 shows the main input and output of an EAF Process.

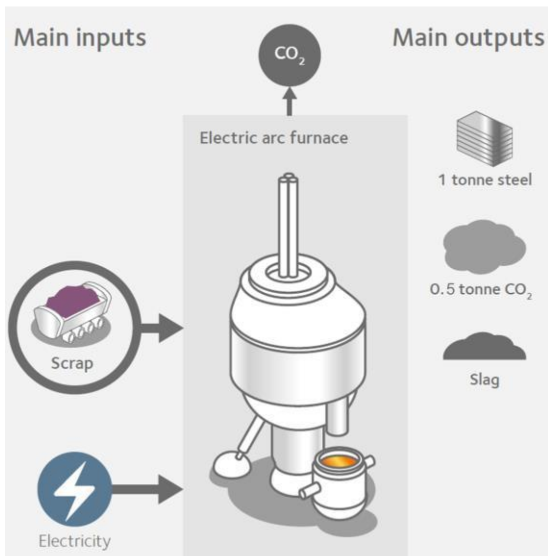

Fig. 2 – Scrap based EAF steelmaking

Part of the answer to steel's decarbonization challenge is through the increased use of scrap or recycled steel. Iron ore reduction in the BF-BOF accounts for the vast majority of carbon emissions coming from steelmaking. Based on analyses from published Environmental Product Declarations (e.g., AM EPD, 2018, 2019, 2020) the scrap based EAF production has a factor 4 to 5 lower carbon footprint, so it is more environmentally friendly. However, the global amount of steel that can be produced in a scrap based EAF is limited by the availability of end-of-life steel. Steel is used in many fields of applications with different service lives, from packaging products with a short life span to the automotive industry with a medium life span and building and infrastructural projects with a long lifespan (up to 100 years). As the available scrap depends on the rate of demolishing and rebuilding of existing applications, an offset in time exists between the available scrap and the current steel production. Due to the ever-increasing demand for steel, the available steel scrap will not be sufficient to replace the production from iron ore completely, see Figure 3.

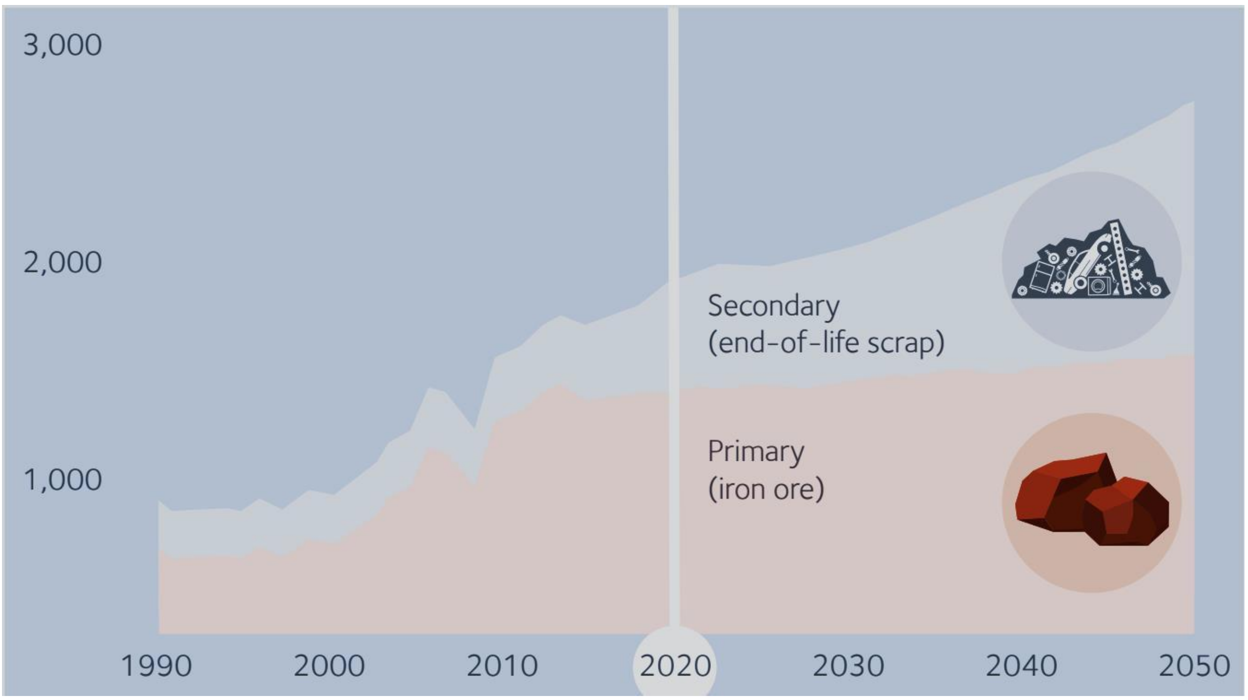

Fig. 3 – Steel demand vs scrap availability (Climate Action Report 2, 2021)

Today, around 25% of steel is produced by recycling scrap in an Electric Arc Furnace. While this percentage is forecast to rise to 50% by 2050 (AMCSO, 2022), the quantity of scrap required for the steel industry to fully convert to scrap-based, secondary steelmaking could only be available at the end of this century. Therefore, the challenge of decarbonizing steelmaking involves finding fundamentally new ways of making primary steel and reducing iron ore with alternative reductants to fossil fuels.

In order to decrease the carbon footprint ArcelorMittal is looking at three pillars: Reduce, reuse and recycle. The first step is to reduce the carbon footprint of the steel production and optimize steel solutions. The second step is to design in such a way that the materials can be reused as much as possible. The last step is to make sure that all the steel that is not reused will be recycled. This recycled steel will serve as input for the steel production in the EAF.

REDUCE

ArcelorMittal has developed the industry's broadest and most flexible suite of low-emissions steelmaking technologies based on iron ore, and is integrating it into two pathways: Smart Carbon and Innovative Direct Reduced Iron (DRI). Both are revolutionary for the production of steel and hold the potential to deliver carbon-neutral steelmaking. Smart Carbon aims to reduce the carbon emissions within the Blast Furnace – Basic Oxygen Furnace process itself. Innovative DRI looks at the option to convert the BF-BOF process towards a Direct Reduced Iron facility in combination with an Electric Arc Furnace (DRI-EAF). This is a necessary intermediate step to come to a carbon neutral steel production facility based on hydrogen. No single solution exists. Different technology pathways, or a combination, are likely to be developed in different parts of the world depending on how public policy shapes the availability of alternative energy sources.

REDUCE - SMART CARBON

Smart carbon will use two types of circular carbon. The first option is to partially replace the use of coal in a blast furnace with alternate sources of circular carbon from waste streams, such as sustainable biomass residues (Torero). The Smart Carbon route also allows for integrating carbon capture and reuse (CCU) or storage (CCS) technologies, meant to capture carbon emitted during the steelmaking process. Potentially, the route can be made carbon-negative (i.e., the process has a net effect of removing CO2 from the atmosphere). Furthermore, the end-of-process carbon that is captured could then be recycled and utilized by the chemicals industry, helping to produce carbon-neutral biomaterials (Carbalyst®). The key input is the carbon monoxide waste gas from blast furnaces, which is produced as a by-product from steelmaking and otherwise would have been burnt to release carbon dioxide. A visual representation of the different steps in the Smart Carbon Route is given in Figure 4.

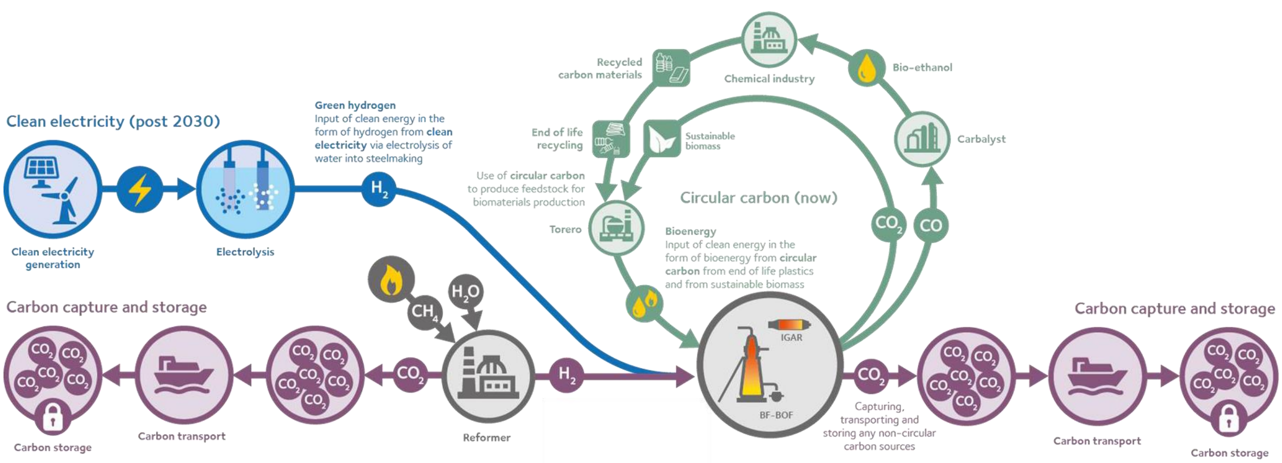

Fig. 4 – The Smart Carbon Route (Climate Action Report Europe, 2020)

Torero

An important component of the Smart Carbon low-emissions steelmaking pathway is the potential replacement of coal with circular carbon sources including sustainable biomass in the form of forestry residues and agricultural waste, and even waste plastics. By making this change, it would reduce the levels of CO2 in the atmosphere as fossil coal will remain in the ground. Using sustainable biomass from agricultural waste as energy input would still lead to CO2 emissions, but these waste products would already emit CO2 as part of the natural, circular carbon cycle as they decompose at the end of their natural life. Hence this energy source is classified as carbon-neutral.

To prove the viability of Torero, an industrial-scale demonstration plant is under construction that converts (otherwise unusable) waste wood into renewable energy through a process called torrefaction. The demonstration plant in Ghent, Belgium, involves two reactors, each of which will produce 40,000 tons of bio-coal annually. Construction started in 2018 and the first reactor will be ready in Q1 2023. Reactor 2 will be ready in 2025. When in full production the project is anticipated to reduce Ghent's CO_2 emissions by 225,000 tons per year. Figure 5 shows the different production steps of the Torero plant.

Fig. 5 – Torero plant production steps

Carbon Capture and Utilization or Storage

The progress in carbon capture and utilization technologies could give steelmakers a new role in supporting a lower-carbon future. The search goes on for effective new carbon capture and storage (CCS) technologies that can lock away carbon so that it never enters the atmosphere. ArcelorMittal has committed to several joint activities including the development of logistics, exploring potential commercial models, and the promotion of Carbon Capture and Use (CCU) and CCS, as an important part of the successful decarbonization of European industry. When applied to steelmaking, the process involves the capture of the CO_2 contained in blast furnace waste gases using a chemical solvent, extracting the CO_2 from the solvent and putting it under low pressure. This allows the CO_2 to be reused in furnaces or stored away. The process also yields heat, which can be harnessed to reduce the operating cost of furnaces. By using the DMX™ process, it reduces the energy intensity of carbon capture by nearly 30%. This is made possible by using heat-recovery methods as well as the DMX™ demixing solvent. Not only is the solvent more chemically stable than the aqueous monoethanolamine (MEA) solution commonly used in CCU/S today, it also has a higher capture capacity, making it both more efficient and cost-effective.

The 3D Project, launched in 2019, involves building a DMX™ Demonstration plant at Dunkirk. By demonstrating that the process can successfully be applied on an industrial scale, the project could significantly cut the costs of CCU/S, making it replicable across heavy industrial sites. The 3D Project will also play an essential part in the design of the future European Dunkirk-North Sea Cluster, which aims to capture, pack, transport and store 10 million tons of CO_2 per year and should be operational by 2035. The CO_2 extracted from the process is extremely pure (99.7%) and can be pressurized at up to 7 bars to facilitate subsequent transport by boat or pipeline. Figure 6 gives an overview of the 3D project for the CCU/S.

Alongside the search for carbon capture and storage, it is also necessary to develop carbon capture and utilization (CCU) technologies. Unlike CCS, which treats CO_2 as waste, CCU converts it into commercially viable products such as bio-oils, chemicals, plastics and fuels. These products can replace products made from fossil fuels with the net effect of reducing greenhouse gas emissions. In effect, by getting more value from the used carbon, CCU could help the economy as a whole to use less carbon, thereby reducing the carbon emissions.

In November 2016, the European Commission took an important step and officially indicated that, under the Renewable Energy Directive 2 (RED, 2018), liquid ethanol produced from industrial carbon waste would be recognized as ‘advanced’ biofuel — a form of renewable energy — since its use displaces carbon emissions from fossil fuels. Biofuel has an important role to play in a lower-carbon economy. And whereas the first-generation biofuels were typically made from crops, the Carbalyst® process does not put pressure on agricultural land or deforestation.

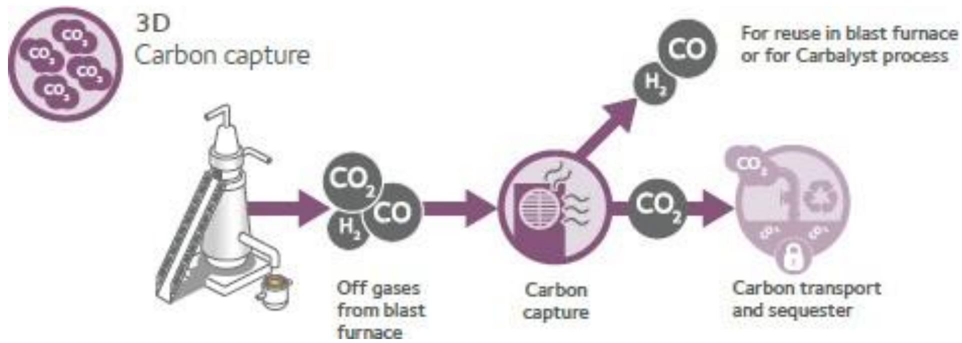

Fig. 6 – Carbon Capture and Utilization or Storage overview.

Carbalyst

Carbalyst®, also known as Steelanol, is the flagship carbon capture and reuse technology project. The technology involves capturing carbon-rich waste gases emitted from the blast furnace during the steelmaking process and converting them into recycled carbon chemicals. The carbon rich waste gases consist mostly of carbon monoxide, carbon dioxide and hydrogen. These waste gases are no longer considered as waste, but as raw materials. The bioreactors will convert industrial gases captured during the steelmaking process into sustainable ethanol. Nowadays already more than 5% of the gasoline is green ethanol. It can also be used in the chemical sector for cleaning agents and plastics.

The conversion of the waste gases into advanced ethanol is done by micro-organisms. It starts with the capture of the gas from the Blast Furnaces. This gas will be pre-treated, put under pressure and provided to the micro-organisms as fine bubbles. Those micro-organisms grow in the bioreactors, which are gigantic brewing vessels filled with water, micro-organisms and all kind of nutrients the micro-organisms need to grow optimally and to produce ethanol. The produced ethanol is purified to obtain a level of quality that makes it possible to use it as a fuel or as raw material for the chemical industry. To make the process even more sustainable, it is combined with a unique water treatment installation that uses water cyclically and recovers the valuable nutrients. Figure 7 shows an overview of the different steps in the Carbalyst® process.

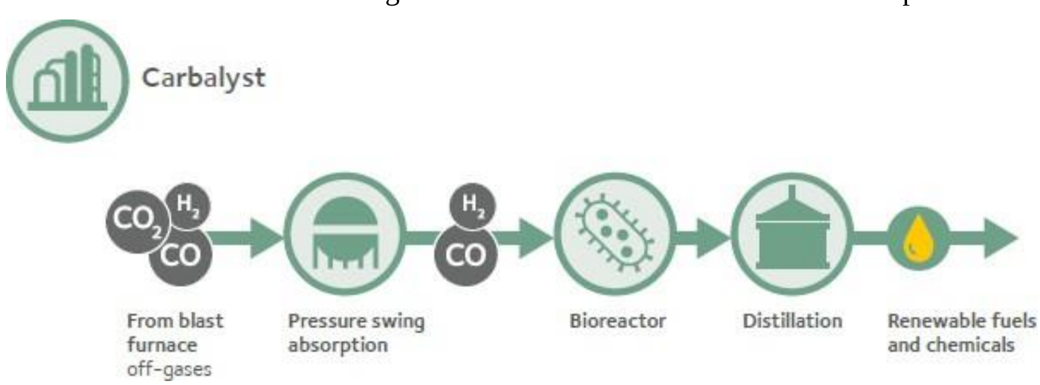

Fig. 7 – Carbalyst Plant production steps

The first Carbalyst® project is an industrial-scale demonstration plant at the production facility in Ghent, Belgium. The plant reduces the CO2 emissions by 125,000 tons per year, but also results in the production of 80 million liters of advanced ethanol per annum, almost half of the total current demand for fuel mixing in Belgium. This bio-ethanol can be blended with traditional gasoline as a low-carbon alternative fuel for the transport sector. Commissioned at the end of 2022, this new groundbreaking installation is the first one in Europe.

REDUCE - INNOVATIVE DRI

Whereas the Smart Carbon pathway is applicable to the blast furnace - basic oxygen furnace steelmaking route, the Innovative DRI pathway applies to the direct reduced iron (DRI) – electric arc furnace route (EAF). In addition to scrap, the other possible metallic input in EAFs is direct reduced iron (DRI). This is made through the direct reduction of iron ore using natural gas. In the DRI process, iron oxide pellets are reduced to metallic iron, by extracting oxygen using natural gas. The natural gas is split into hydrogen and carbon monoxide before the reaction chamber, after which it binds the oxygen in the iron ore to create water and carbon dioxide as byproducts. In this way, over 55% of the reduction process is done with hydrogen, leading to lower carbon emissions compared to the BF-BOF process.

Historically there has been limited use of the DRI-EAF route other than in regions with a very low natural gas price. However, to reduce the emissions, the transition to natural-gas based DRI-EAF will be a first step with a proven technology. This technology has the potential to further innovate and decarbonize steel production by using green hydrogen. While this route holds great potential, the renewable energy infrastructure required to create sufficient volumes of carbon-free, 'green' hydrogen is still lacking. Therefore, until the infrastructure emerges to make affordable green hydrogen at large scale, blue hydrogen (sourced by extracting hydrogen from natural gas) is used as an intermediary step. This can be combined with carbon capture and utilization or storage technology to capture CO2 produced in DRI production while still using natural gas.

In Europe, the strategy is largely focused on the Innovative DRI pathway. This reflects the commitment in Europe to prioritize the availability of green hydrogen at competitive prices. Countries including Spain and Germany plan to accelerate the availability of renewable energy that will support the introduction of green hydrogen. This is the foundation of zero carbon-emissions through the DRI-EAF (Direct Reduced Iron-Electric Arc Furnace) route. A visual representation of the different steps in the Innovative DRI Route is given in Figure 8.

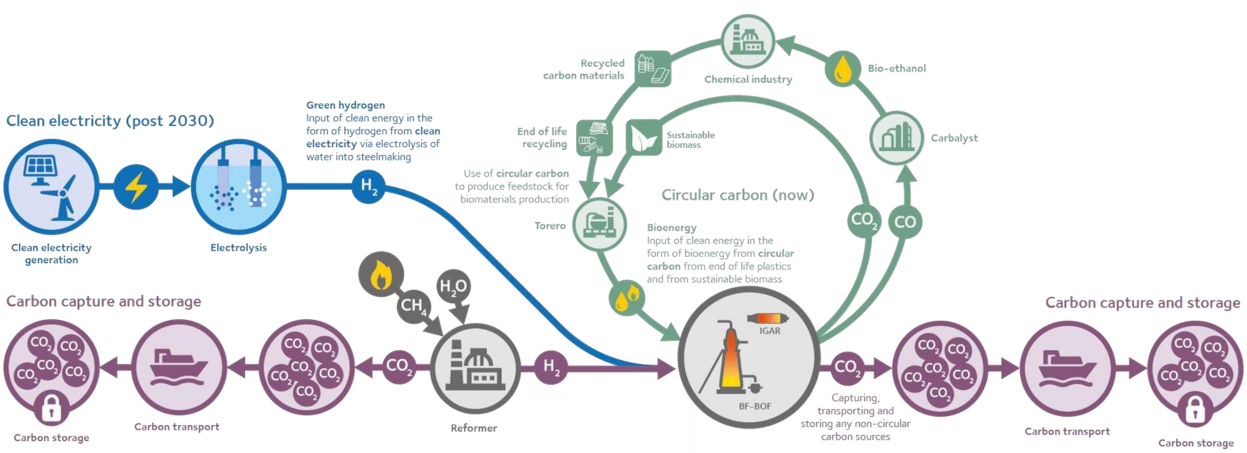

Fig. 8 – The Innovative DRI Route

Hydrogen DRI EAF

Technologies can be developed to increase the proportion of hydrogen fed into the shaft furnace up to 100%. Where renewable energy is used to produce hydrogen for use in this way, it directly displaces CO_2. However, where insufficient levels of renewable energy are available, industry will need to use ‘blue’ hydrogen, derived directly from fossil fuels or industrial gases and combined with carbon capture and storage (CCS) to ensure carbon neutrality. The aim is to achieve the separation of H_2 with a purity of more than 97% from the waste gas of the existing plant using a process known as ‘pressure swing absorption’. This allows for the development of technological solutions at industrial scale to reduce iron ore with only hydrogen and in absence of carbon. Many technical and practical challenges are ahead, which only can be solved in an operational plant. This has never been done up to now due to lack of hydrogen infrastructure.

Currently the only operating DRI-EAF facility in Europe is located in Hamburg, Germany. It is already one of Europe’s most energy efficient steel plants, using natural gas to reduce iron ore to make DRI, which is then fed into an EAF alongside scrap input. The site is therefore chosen as flagship for the Innovative DRI technology pilot. It is designed to test the ability to replace the use of natural gas with hydrogen to reduce iron ore and form DRI on an industrial scale, as well as then testing how that carbon-free DRI reacts in an EAF. The process of reducing iron ore with hydrogen will first be tested using grey hydrogen generated from the capture of waste gases at the steel plant by pressure swing absorption. It is scheduled that the plant will be operational before the end of 2025, initially producing an annual volume of 100,000 tons of DRI. The plant will be the world’s first direct reduction plant on an industrial scale, powered by hydrogen. If the hydrogen is produced via the electrolysis of water, with electricity derived from renewable sources, it would make zero carbon DRI. If this is then fed into an EAF running on renewable electricity, it would lead to zero carbon steel.

From 2025, the world's first full-scale zero carbon emissions plant will be operating in Sestao, Spain. Construction for a new DRI plant in Gijón, Spain, has started in combination with a new hybrid EAF that will run on green hydrogen and renewable electricity. It will produce 1.6 million tons of zero carbon emission flat steel products for the automotive and construction sectors and general industry.

REDUCE - ELECTRIC ARC FURNACE ON RENEWABLE ELECTRICITY

ArcelorMittal Europe has announced plans to build four new DRI-EAF facilities to replace existing BF-BOF furnaces across Europe. Within the DRI-EAF process, the last production optimization can be made in the electric arc furnace. This furnace can be used for production of steel from both circa 100% scrap metal and from direct reduced iron. Both base materials have to be melted in an Electric Arc Furnace in order to create steel. Since almost no oxygen is left to remove from the iron or scrap, the direct carbon dioxide emissions are also limited. However, the amount of electricity required to melt the material is high. By sourcing 100% renewable electricity from the power grid, the environmental footprint of the EAF drops significantly with 30% or more. The renewable electricity can be (partly) generated onsite by wind turbines and solar panels. The remaining demand for electricity will be supplied from other renewable sources, together with ‘Guarantee of Origin’ certificates, which are audited by an external third party. As renewables increasingly become part of electricity grids, balancing generation and consumption is key. The production site can use a “time shift” process to regulate the power consumption of the electric arc furnace, to absorb surplus electricity from nearby wind power generation. Reducing the indirect carbon emissions from energy sources (scope 2 emissions) means mainly focusing on sourcing low-carbon electricity. This will be an increasing challenge as the transition from BF-BOF technology to scrap and DRI-EAF technology will result in electricity becoming a greater part of the energy mix used to make steel. The main focus will be on purchasing renewable energy certificates and by establishing direct power purchase agreements (PPA) with suppliers from renewables projects.

REDUCE - STEEL FOUNDATION OPTIMIZATION

For foundations of quay walls, embankments, tunnels, high rise buildings and many more infrastructural works, steel foundations are one of the preferred solutions. With the current goals of decarbonizing and reusing the foundation solutions, steel will become more and more important. The decarbonization pathways within the steel production are one way, but within steel foundations other factors can be taken into account. The mostly used steel elements as foundation materials are sheet piles, tubes, beams and anchors. Sheet piles and beams from Luxemburg are produced in an EAF with scrap material as input. This has a significant environmental advantage compared to production from blast furnace. With the option to produce the steel with renewable electricity, the environmental footprint will be lowered even further, see Table 1 for a comparison of the different production methods. The CO_2 emissions are compared per ton of finished products, like sheet piles or beams.

Table 1. Global Warming Potential (kg CO_2-eq./t) for steel products (modules A1-A3, according to EN15804)

Production method	Estimated GWP (kg CO_2-eq./t)
BF-BOF, without Smart Carbon	± 2000 - 2800
DRI-EAF, Natural Gas	± 1000 - 1500
EAF scrap, regular electricity	± 500 - 750
EAF scrap, green electricity	± 300 - 400

Investments to decarbonize steel production are ongoing, however, the best way to reduce the environmental footprint of the project is to optimize the weight of the steel solution. The emissions are expressed per ton of steel, so any optimization in weight will lead to an equivalent optimization in environmental footprint for the project. The steel profiles can often be optimized by choosing a higher steel grade in combination with an optimized section. For example, 1.6 m wide steel sheet piles can be chosen with a steel grade S430 GP or even S460 AP. The environmental footprint of these higher steel grades is comparable to the most commonly used steel grade S355 GP (AM EPD, 2018). Therefore, an optimized section in a higher steel grade will lead to a significantly lower weight, lower environmental footprint and lower costs. Another design optimization is to design the steel foundation for reusability. This can mean that the initial section is a stronger profile compared to the most optimal section, but since it has a temporary function, the extra strength and improved durability help in reusing the profile as much as possible. Project owners, designers and contractors within the construction and infrastructural market all can influence the optimization of a design. Project owners can optimize their operational long-term strategy to decrease the environmental impact over the lifetime of the structure. Through monitoring and maintenance, existing steel structures can be analyzed and verified whether they still meet the requirements. The monitoring can provide accurate information on the state of the structure, the forces involved and their impact on the steel structure. This can lead to the discovery of hidden unused capacity within the structure, creating room for optimizing the use of the structure and extending the lifetime.

RE-USE AND RECYCLING

The major benefit of steel sheet piles is not only the low carbon footprint in production, but also the possibility to reuse the same profile multiple times. This proven concept of reusing steel sheet piles is most known in temporary applications, like construction pits, cofferdams or deeper excavations for tunnels, highways, etc. It is often even possible to reuse the temporary sheet piles multiple times within the same project, if the phasing of the project allows it. This drastically decreases the environmental footprint of the project. Another option which is becoming increasingly accepted by project owners, is to install used sheet piles in permanent applications.

The used sheet piles have the same strength and load bearing functionality as newly produced sheet piles. After long service lives of 100 years, the sheet piles can still be extracted from the soil. Although reuse of such old piles is not to be expected, they can still be recycled and serve as input for the newly produced sheet piles in the EAF. This creates the perfect circle for infinite use of steel, without any degradation of the material properties.

SUMMARY AND CONCLUSIONS

Steel is a material that is critical to building the infrastructure of our world, being a leading material in the production of buildings, infrastructure and energy transition. Decarbonization of the steel industry is key to reach the climate goals set in Paris. ArcelorMittal has a clear roadmap to reach to carbon neutral steel production from iron ore by 2050 subdivided in two pathways: Smart Carbon and Innovative DRI. Both hold the potential to develop carbon neutral steel production in the coming decades. The most widely used foundation materials, steel sheet piles and beams, already often have a low environmental footprint due to the production from scrap in an Electric Arc Furnace. Several other optimization means are possible to reduce the footprint even further. Steel sheet piles can be reused multiple times in temporary applications, thus reducing the environmental impact each time the sheet piles are reused. At the end of life, when they cannot be reused anymore, all the remaining steel can be recycled. This creates the perfect circle for infinite use of steel, without any degradation of the material properties.

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