GMK CENTER

Decarbonization of the steel industry:

a challenge for the coming decades

The sponsor of the study

METINVEST

The strategic vision of Metinvest Group is based on the principles of sustainable development, ensuring a balance of economic issues, social progress and responsibility for the environment. Today the combat against climate change and decarbonization of the economy are in the first place globally. This is a difficult task without single-valued algorithm. Therefore, Metinvest Group decided to contribute to the search for possible ways to decarbonize the Ukrainian iron & steel industry and the Ukrainian economy as a whole and became a sponsor of the study "Decarbonization of the steel industry: a challenge for the coming decades".

The partner of the study

HORST WIESINGER
CONSULTING

Deep study of decarbonization technologies, their features, and possible consequences for the industry became possible thanks to the involvement of the Austrian consulting company Horst Wiesinger Consulting as a partner in this study. The expertise of Horst Wiesinger Consulting specialists allowed a systematic approach to the study of such a complex issue as decarbonization of the steel industry. Horst Wiesinger Consulting has significant experience in implementing energy efficiency projects on iron & steel plants. The company is also a consultant for R&D projects.

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Dr. Horst Wiesinger, founder and CEO of Horst Wiesinger Consulting Head of Supervisory Board of GMK Center

Horst WIESINGER:

"Decarbonization — challenge for the coming decades"

Over the past 50 years, the steel industry has been under pressure of environmental challenges. At first, concerns were raised over visible pollution (smoke, dust). This could be seen on the example of the first official air pollution control regulation, Technical Instructions on Air Quality Control, adopted in Germany in 1964. These instructions set emission limits for dust, sulfur dioxide, nitrogen oxides and other compounds. Although the document was binding in Germany only, many European countries decided to follow its recommendations.

Public interest in environmental issues substantially increased following accidents at chemical plants. In July 1976, an industrial accident at a chemical plant near Seveso, Italy, resulted in a release of dioxin. In December 1984, an accident at a chemicals plant in Bhopal, India, released poisonous gases, killing 3 thousand people.

Following these events, the European Commission started to collect environmental data on industrial production. It resulted in the adoption in 1996 of Council Directive concerning integrated pollution prevention and control. Directive 2008/1/EC of 2008 substantially amended the previous document. The main idea of the document is that the emission permit is granted only if a plant complies with the 'best available techniques.' The 'best available techniques' are described for all sectors, including steel production.

The 'best available techniques' lack requirements for CO_2 emissions, which are becoming increasingly important. In 2015, the Paris Agreement on Climate Change was signed. However, two years later, in 2017, the USA left this agreement. The parties agreed to keep the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C.

The EU is moving towards the carbon-free economy in the framework of the Paris Agreement. A discussion of possible goals and tools of the reduction of CO_2 emissions is expected to end in 2021 so as to start a transition. The discussion's effectiveness is proved by the conclusion of the European Green Deal. It is a strategy for the EU to achieve a climate-neutral economy by 2050.

This ambitious goal could be achieved only in interaction of governments and plants. Carbon-free technologies, represented mainly by individual solutions and research projects, are at a fledgling stage. In the steel industry, the first wave of cutting-edge technologies on an industrial scale could be expected after 2035 at the earliest.

Funding of decarbonization remains the key problem affecting the industry. For steelmaking companies, decarbonization primarily means a growth in capital investment. The EU is ready to partially compensate for these costs as part of the European Green Deal, realizing that it is impossible to implement such global project without government support. It is also apparent that decarbonization will increase the cost of production and, as a result, cause a loss of competitiveness of European steelmakers. To solve this problem, the EU is going to introduce a carbon border adjustment mechanism, a special tax on cheaper imports from countries with less stringent CO_2 emission standards.

The defined CO_2 reduction target can only be met by the full commitment of the global industrial community involving all CO_2-emitting sectors. It is evident that the target can only be met by a consorted and holistic approach of the world community and would need a rather long transition period. ■

Yuriy RYZHENKOV:

"Decarbonization of the steel industry to encourage decarbonization of other sectors"

Yuriy Ryzhenkov,
Metinvest Group CEO

The steel industry will play a key role in achieving carbon neutrality in Ukraine. Metinvest, as the country's largest steel producer, is clearly aware of its responsibility for this process. We are confident that our Group will take a lead in decarbonization of Ukrainian industries, setting an example for others on the path to this important target.

Environmental protection is one of the core values of the Metinvest Group. For many years, we have been working to provide up-to-date, energy-efficient and eco-friendly production at our assets. **Over 15 years, Metinvest has invested UAH 80 billion in environmental projects.** Furthermore, we are annually increasing green investments. In 2020, every third dollar of our investment was spent on environmental projects. This is yielding results, as we are gradually reducing our environmental impact through contributing to combating climate change.

The measures taken by the Group are aimed at mitigating the environmental footprint at all stages of the production process. To this end, Metinvest applies an integrated approach to automated environmental protection, enabling to manage environmental performance and risks in the medium- and long-term perspective, standardize environmental business processes, forecast and proactively identify potential environmental risks.

Our efforts in environmental activity have been highly appreciated by the international community. Metinvest is among the world's 10 top steel producers in terms of environmental risks.

The Metinvest Group is a global player that operates in accordance with the best practices. We must therefore take a lead in achieving the declared strategic goals for decarbonization and carbon neutrality.

Achieving carbon neutrality is a challenging task that requires a complete restructuring of production processes. At the same time, breakthrough technologies are under development. To enhance the resilience of our business, we intend to participate in R&D projects to develop and introduce advanced decarbonization technologies.

Metinvest is currently developing a 10-year roadmap to cut CO_2 emissions. We are very careful about every step we take to achieve carbon-neutral production in the long run. These ambitious transformations should not harm sustainability of our business. Understanding that Metinvest is the largest employer and taxpayer, apart from technological solutions, we address issues within the interests of stakeholder groups such as our employees and local communities.

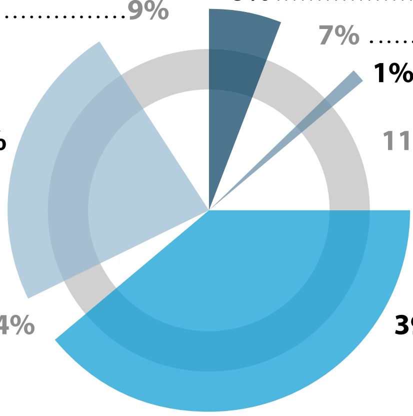
Decarbonization poses a number of challenges for steelmaking companies. To make all stakeholders understand business needs, potential risks and implications of decarbonization, we consider it important to raise awareness of the parties concerned. With that in mind, Metinvest sponsored this study.

Awareness-raising will help improve communications and relationships, including between businesses and the government. This is the only way for building new 'green' industries and a new economy. Steel producers make steel for wind turbine towers, new light-weight alloys for vehicles, structures for construction. Hence, a success of decarbonization of the steel industry will encourage decarbonization of other sectors. ■

The steel industry strives to achieve carbon neutral status

The Paris Agreement, adopted in 2015, marked a turning point in global environmental and economic policies. The signatories agreed to cut human-related greenhouse gas emissions to zero as soon as in this century. This target changes the approach to economic policy, because it implies radical restructuring of business models, technologies, supply chains, and competition conditions in a number of industries. The set targets will have a stronger impact on the energy sector, transport, housing and utilities, as these are the industries with the highest CO_2 emissions. These three industries together account for 71% of total emissions. The steel industry ranks sixth on this list, with only 6% share in emissions.

Global CO_2 emissions by sector in 2019



Source: IEA

2.27
Gt of CO_2
direct emissions from the iron & steel industry in 2019

1.83
t of CO_2
average carbon intensity (scope 1+scope 2) per ton of steel in 2019

Source: IEA

According to the IEA, global direct CO_2 emissions from the steel industry in 2019 were 2.27 gigatons. This is the amount of emissions directly related to iron & steel production processes (scope 1). Average direct carbon intensity per ton of steel — 1.21 tons of CO_2. According to the IEA, average indirect carbon intensity, i.e. emissions associated with generation of electricity that consumed during the production process (scope 2), amount to 0.62 tons. In other words, total direct and indirect carbon intensity were 1.83 tons per ton of steel in 2019, which corresponds to the World Steel Association's statistics.

The steel industry is under pressure to reduce emissions, both on the part of the government that sets respective targets and on the part of consumers and investors.

GHG emission reduction is the global target that implies a cut in emissions along the entire value chain. Some consumers, e.g. car manufacturers, therefore demand 'green' products. As a result, a new 'environmental norm' is being formed, which will be implemented in future production standards.

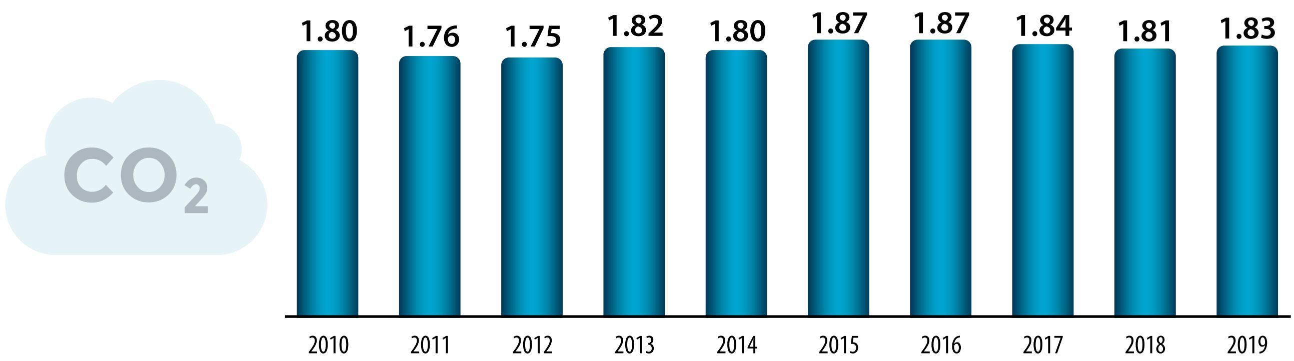
Tough emission reduction targets could damage the long-term sustainability of steelmaking companies. Hence, financial institutions require businesses to have a clear understanding of their zero carbon transition plans.

This pressure poses risks to steelmaking companies, since the industry has limited opportunities to curtail emissions. Steelmakers must therefore map out decarbonization strategies in order to adapt and stay competitive. ■

Decarbonization of the steel industry requires breakthrough technologies

The steel industry has a limited potential for reducing CO_2 emissions. Despite the applied policies, the average carbon intensity have remained at 1.8 tons over the recent decade.

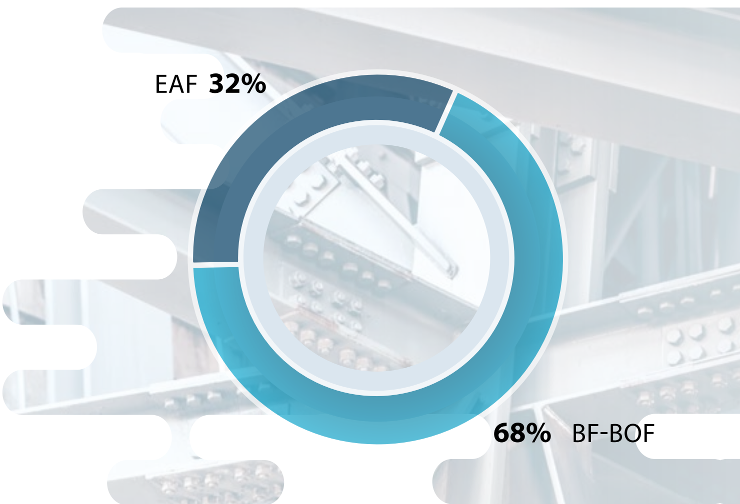
Global average carbon intensity per ton of steel (scope1 + scope 2), t



Source: WSA

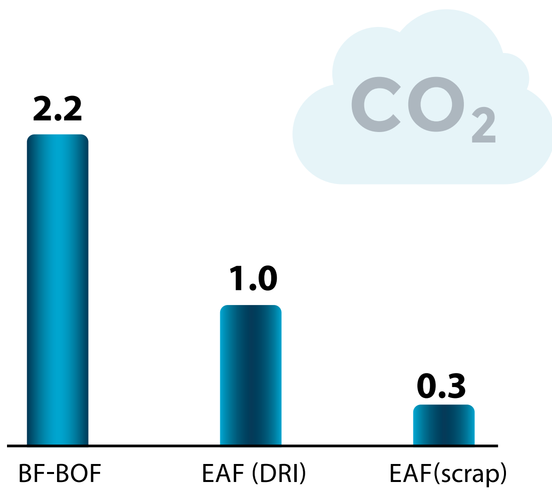
This fact can be explained by the specifics of production capacities and technologies applied. 68% of installed capacities in the industry is based on the traditional BF-BOF route. Another 32% use the electric-arc furnace route (EAF). Greenhouse gas emissions from the BF-BOF route are significantly higher. ►►

Structure of capacities by basic steel production technologies



Source: OECD

Carbon intensity per ton of steel by technology route, t

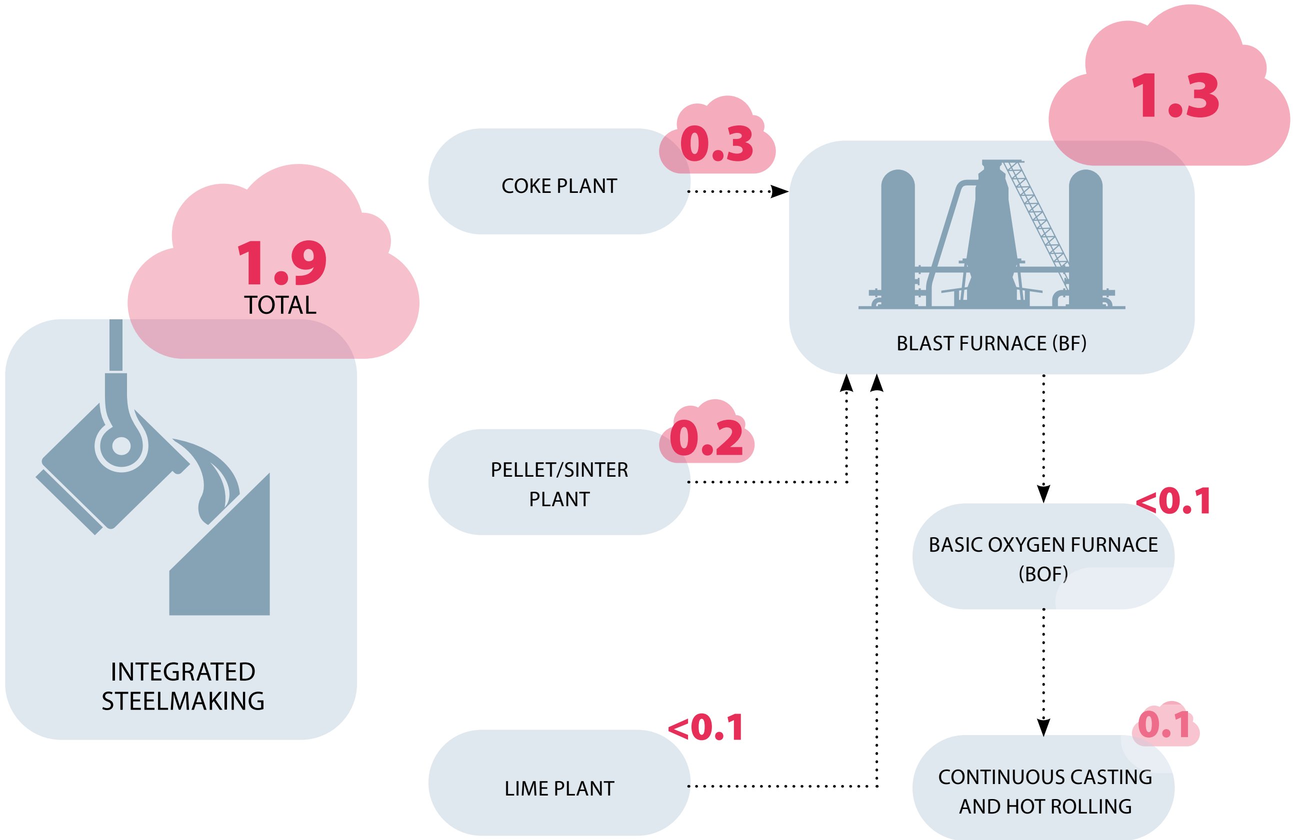


Source: WSA

The reason for higher emissions in the BF-BOF technology is the use of coal (as coke or feedstock for pulverized coal injection units) and natural gas. Coal and gas are both carbon sources. Carbon plays an important role in steel production at iron and steel works. Firstly, it is a reduction agent in blast furnaces, which removes oxygen from iron ore necessary for the production of pig iron. Secondly, carbon is a source of energy enabling achieving of high temperatures required for steel production. Thirdly, carbon is a necessary component of steel (up to 1% in the composition of high-carbon steels).

Blast furnace production is a key source of CO_2 emissions of a steelmaking company that uses the BF-BOF route, with a share of 68% in total direct emissions.

Sources of CO_2 emissions at integrated iron and steel works (BF-BOF) in the case of EU plants, ton CO_2 per ton of steel

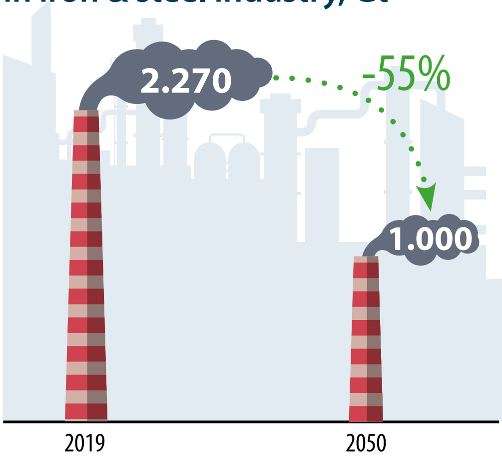


Source: University of Cambridge Institute for Sustainability Leadership

Blast furnaces emit 1.3 tons of CO_2 per ton of steel. Iron is reduced from iron ore in blast furnaces. Coke plants rank second in CO_2 emissions (0.3 tons of CO_2 per ton of liquid steel). CO_2 emissions of coke plants are associated with high-temperature heating of coking coal, which is 100% carbon. Sintering and pelletizing plants rank third in carbon dioxide emissions (0.2 tons of CO_2 per ton of liquid steel). In other words, the BF-BOF route does not have a significant potential for cutting emissions.

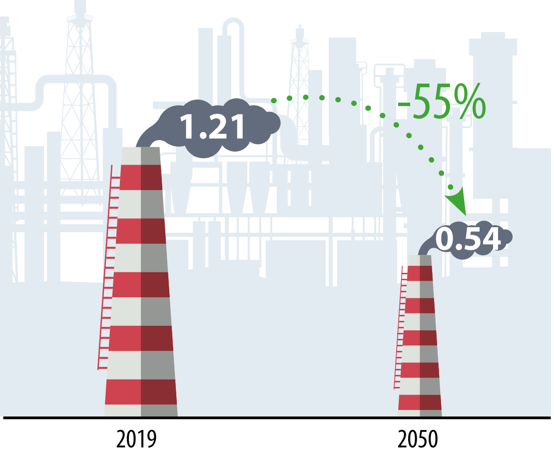
According to the IEA, the industry needs to achieve a 55% reduction in emissions by 2050 so that to achieve carbon neutrality targets by 2070. World Steel Dynamics says that the steel output in 2050 will remain at the level of 2019, 1.85–1.87 billion tons. That means that by 2050 carbon emissions per ton of steel should also drop by 55%.

Direct CO_2 emissions in iron & steel industry, Gt



Source: IEA

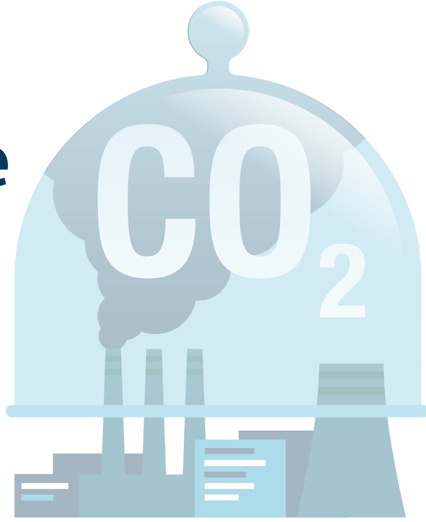
Direct CO_2 emission per t of steel, t



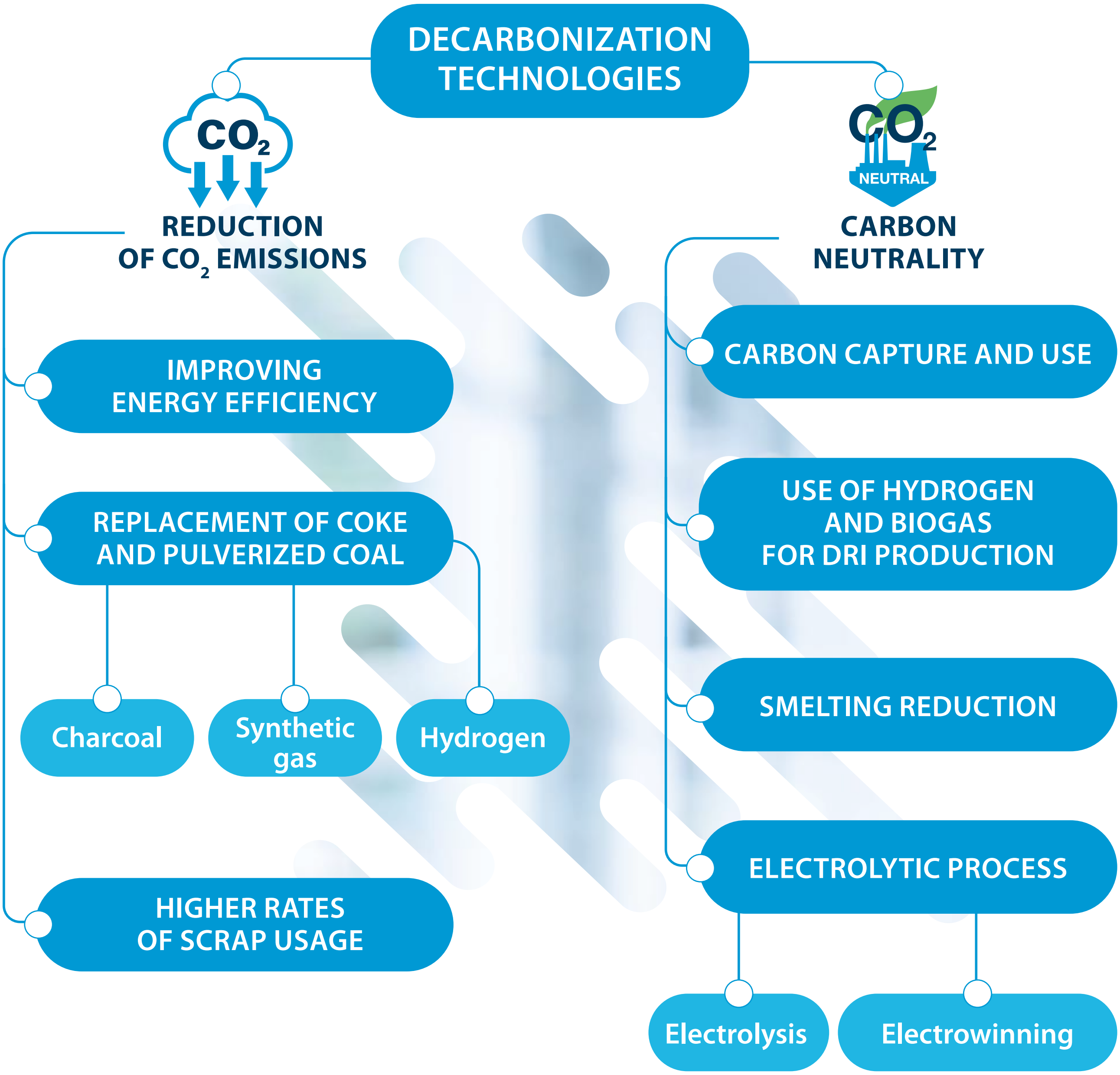
Source: IEA, GMK Center estimations

According to a leading engineering company, Primetals, the application of best practices will decrease emissions by no more than 25–30%. This is not enough to meet the required GHG emission reduction targets. Innovative breakthrough technologies are needed for carbon-free iron & steel production. These technologies are currently under development. ■

Carbon-free production technologies — at the stage of development



Depending on the decarbonization potential, technologies that reduce CO_2 emissions are distinguished from technologies that are led to carbon neutrality. Emission-reducing technologies are already commercially available, whereas carbon-neutral technologies are at various stages of R&D.



Reducing of CO_2 emissions technologies

IMPROVING ENERGY EFFICIENCY

Improving energy efficiency requires improvement of equipment performance and its gradual upgrading in accordance with the best available technologies (BAT). According to the IEA estimations, the improved operating performance could save about 20% of energy costs per ton of steel, which would also have positive economic benefits.

BAT include:

a) technologies for the use of excess energy, which is usually emitted into the environment, in production processes;

b) technologies reducing the use of fuel in iron & steel production;

c) technologies for generating electricity from excess heat.

Possible ways for improving energy efficiency of steel production, according to the IEA:

• **Installation of waste-heat utilization systems,** that enables to decrease energy consumption by electric arc furnaces and basic oxygen furnaces. • **Dry coke quenching.** Enables to use heat of hot coke coming out of coke ovens to generate electricity and to reduce fuel consumption of coke ovens. Furthermore, dry coke quenching improves the quality of produced coke.

• **Installation of top-pressure recovery turbines** that use pressure and heat of blast furnace gas for electricity generation. Such turbines enable to make 30–40 kWh of electricity per each ton of pig iron in a wet dust cleaning system for exhaust gases. The volume of electricity generation can be increased to 50–60 kWh in dry dust removal.

The quality of raw materials is an additional factor of efficiency of production processes. Specifically, the higher iron content of iron ore, or the higher level of agglomeration of iron ore means, that the less energy is needed for iron ore reduction.

Another way to reduce energy consumption is to raise scrap usage rate in BOF production. The widespread use of this strategy is however constrained by the limited availability of scrap reserves.

REPLACEMENT OF COKE AND PULVERIZED COAL

Charcoal

Charcoal was initially used to make pig iron. Coal coke started to be used in the 18th century after the invention of coking technology (coal-based production of pig iron turned out to be impossible because of large amounts of harmful impurities, sulfur and phosphorus).

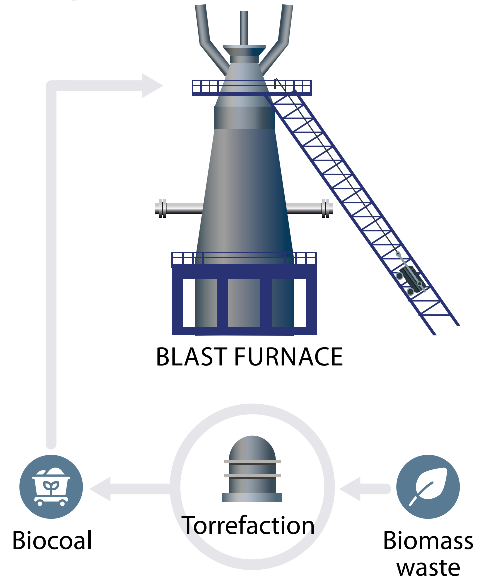
To date, Brazil uses charcoal for the production of pig iron. Local steelmakers grow eucalyptuses on special plantations to make charcoal. New young plants are immediately planted instead of the cut-down trees. The eucalyptus resource renews every 6–7 years. Over this time, the tree grows up to 12-meter high and the trunk diameter reaches 200 mm.

Brazilian companies use mini blast furnaces to produce pig iron. Because of fragility, charcoal cannot be used in large blast furnaces that are more energy efficient.

Among the advantages of charcoal are low ash content, high quality of pig iron (low content of sulfur and phosphorus, absence of impurities of titanium, chromium and zinc coming from coke ash), low slag yield (120–150 kg/ton of pig iron against 230–300 kg/ton in coke-based production). Although replacement of coke with charcoal allows to cut CO2 emissions by 32–58%.

It is not suitable for all regions. ►►

Torero process scheme



Firstly, the cultivation of suitable forests is not available everywhere. Secondly, the large sizes of available blast furnaces do not allow the use of charcoal. Thirdly, a switch to small blast furnaces will increase energy costs and decrease competitiveness.

ArcelorMittal has a Torero project for converting waste wood into a biocoal that replaces fossil powdered coal in a steel mill blast furnace.

Carbon monoxide (CO) in the blast furnace exhaust fumes is microbially fermented to bioethanol using Steelanol technology (production of biofuels through an innovative gas fermentation process).

A Torero demonstration unit is under construction at ArcelorMittal's asset in Gent, Belgium. Torero investment is estimated at €40 million, including €11.5 million under the EU Horizon 2020. The demonstration unit is to convert 120 thousand tons of waste wood per annum.

Synthetic gas

IGAR (Injection de Gaz Réformé) is ArcelorMittal's project. It is aimed at capturing waste CO_2 from the blast furnace and converting it into a synthetic gas (syngas) that can be re-injected into the blast furnace to reduce iron ore.

This approach helps reduce carbon dioxide emissions in two ways:

• firstly, through the capture of CO_2;

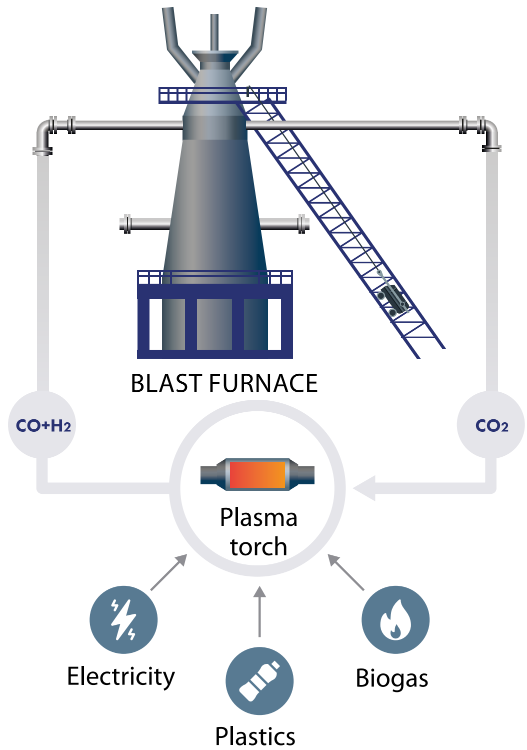
• secondly, through the use of CO_2 in steelmaking (the synthetic gas produced from CO_2 partially replaces coke, thus reducing the need for coke and coal production).

According to preliminary estimates, CO_2 savings from IGAR for a steel mill are expected at **0.1–0.3 ton of CO_2 per ton of steel.**

The syngas consists of two components, carbon monoxide (CO) and hydrogen (H_2). These components are a result of the dry reforming process — a mixture of CO_2 and natural gas (CH_4) is heated to very high temperatures using a plasma torch. ArcelorMittal hopes to use biogas or waste plastics in place of natural gas. And with the plasma torch running on clean power, the entire process provides substantial emission reductions.

In 2017, the IGAR project passed a series of tests. ArcelorMittal will launch a pilot project to construct a plasma torch in Dunkirk, France, in 2021–2022. The project is supported by the French Environment and Energy Management Agency (ADEME). **IGAR investment is estimated at €20 million.**

IGAR process scheme



Hydrogen

Hydrogen can be fed into the blast furnace instead of coal/coke. Like carbon, hydrogen can reduce iron from iron ore. The advantage of hydrogen is that when it is used, steam is emitted instead of CO_2. According to Primetals estimations, the potential for reducing carbon dioxide emissions through hydrogen injections into a blast furnace is up to 20%. This technology is currently being tested for use.

Thysenkrupp started to use hydrogen in blast furnaces instead of powder coal. In November 2019, the first test was conducted to inject hydrogen into one of 28 lances at the blast furnace No. 9 in Duisburg.

In February 2021, the company completed the first testing phase and announced its readiness to test all 28 blast furnace tuyers in 2022. The tests time frames have been shifted due to the COVID-19 pandemic (it was previously scheduled to extend the use of hydrogen to the other three blast furnaces by 2022).

The project budget is **€2.7 million**, of which 40% is funded by the Federal State Government of North Rhine-Westphalia. Hydrogen consumption per ton of pig iron is 11.7 kg (131 m^3).

Hydrogen for the project is supplied by Air Liquide, a world leader in gases for industry. Hydrogen was supplied by truck at the first stage of testing, whereas the construction of a hydrogen pipeline will be required at the second stage. The use of hydrogen will reduce CO_2 emissions per ton of pig iron by 19%.

Thysenkrupp has partnered with RWE to jointly produce ‘green’ hydrogen. Supplies of hydrogen from the RWE electrolysis plant are expected to start in the mid-2020s. By that time, the company intends to build a DRI plant.

Thysenkrupp also agreed with an energy company, STEAG, to carry out a feasibility study for the construction of a water electrolysis plant for hydrogen production. The plant is to be built at the STEAG production site in Duisburg. At the first stage, hydrogen is planned to be used in blast furnaces, and for the production of DRI in the future. With a capacity of 500 MW and 75 thousand tons of ‘green’ hydrogen per annum, the projected plant will be able to meet the needs of the DRI plant, which Thysenkrupp is going to build until 2025.

STEEL PRODUCTION IN ELECTRIC-ARC FURNACES THROUGH THE USE OF SCRAP (RECYCLING) AND AN INCREASE OF SCRAP RATE USAGE IN BASIC OXYGEN FURNACES

Steel is a highly recyclable material. To date, 85% of used steel products are recycled on average, while the recycling rate varies significantly depending on a scrap source, from 50% for construction rebar steel to 97% for industrial equipment.

Scrap is the main raw material for electric arc furnaces. In the meantime, it can also be used in BOF steelmaking, increasing its energy efficiency. In the BOF and OHF routes, it is possible to use up to 30% of scrap in the charge composition. This enables to reduce CO_2 emissions along the BF-BOF route by 3%.

Production of steel from scrap in electric arc furnaces reduces energy consumption by 55–60% compared to production from iron ore. Therefore, CO_2 emissions in steel production in electric-arc furnaces (0.3 tons of CO_2 per ton of steel) are significantly lower than those in the BF–BOF route (2.2 tons of CO_2 per ton of steel).

Availability of scrap is a factor limiting the development of steel production in electric arc furnaces. According to Worldsteel, the volume of available scrap will grow and reach 1 billion tons in 2030 and 1.3 billion tons in 2050. Hence, the development of EAF steelmaking will require an increase in the volume of scrap and improvements of techniques for its sorting. Particularly acute is the problem of removing copper impurities, which degrades the quality of steel products.

A transition to renewables is also needed for efficient decarbonization of EAF steel production. This will help remove CO_2 emissions from electricity production.

The area related to the use of scrap in steel production is covered by PEM (Primary Energy Melter), a project of ArcelorMittal and the SMS group. The project is based on melting of low-quality scrap using metallurgical/natural gas. The first PEM unit was installed at a test facility in Gent in 2012.

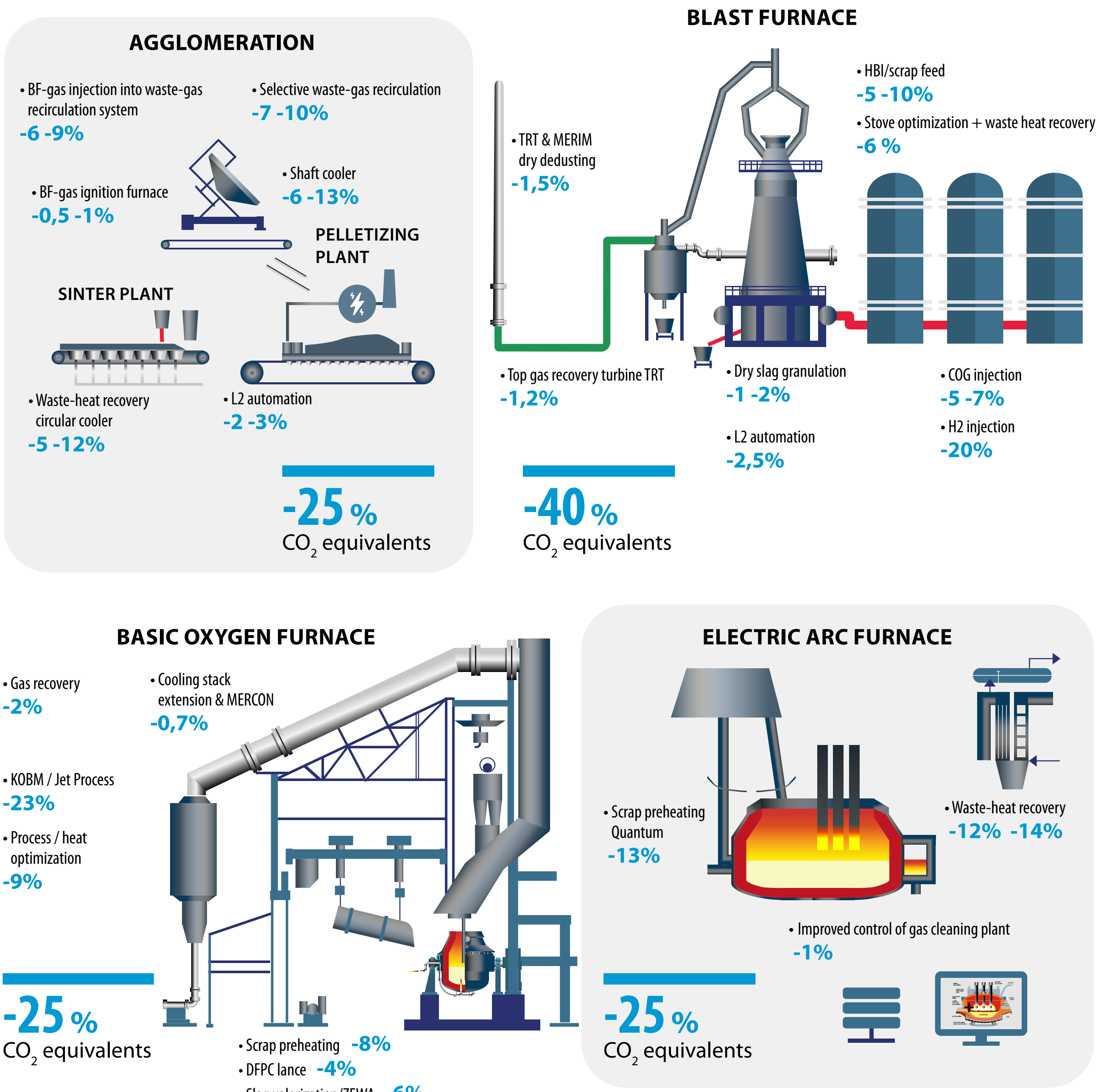
PEM technology increases the use of scrap in the basic oxygen furnace, because scrap is fed in the molten state and therefore does not require additional energy for heating.

The use of PEM technology in the basic oxygen furnace will reduce carbon emissions due to: ►►

a) reduction in the use of natural raw materials (iron ore, coking coal, coke, fluxes);
b) re-use of metallurgical gases (blast furnace, coke oven gas, etc.).

The use of PEM technology in EAF steelmaking will help optimize energy costs. According to the SMS Group, 10% of electricity in electric-arc furnaces is used for excess heating, unnecessary for scrap melting. Therefore, switching to natural gas-based scrap melting can reduce primary energy consumption by 32% and thus generate **expected CO_2 savings of 35%** (from 330 to 215 kg/t of steel).

Existing capabilities to reduce CO_2 emissions in Iron&Steel production



Source: Primetals

Technologies to achieve carbon neutrality

CARBON CAPTURE AND STORAGE/USE

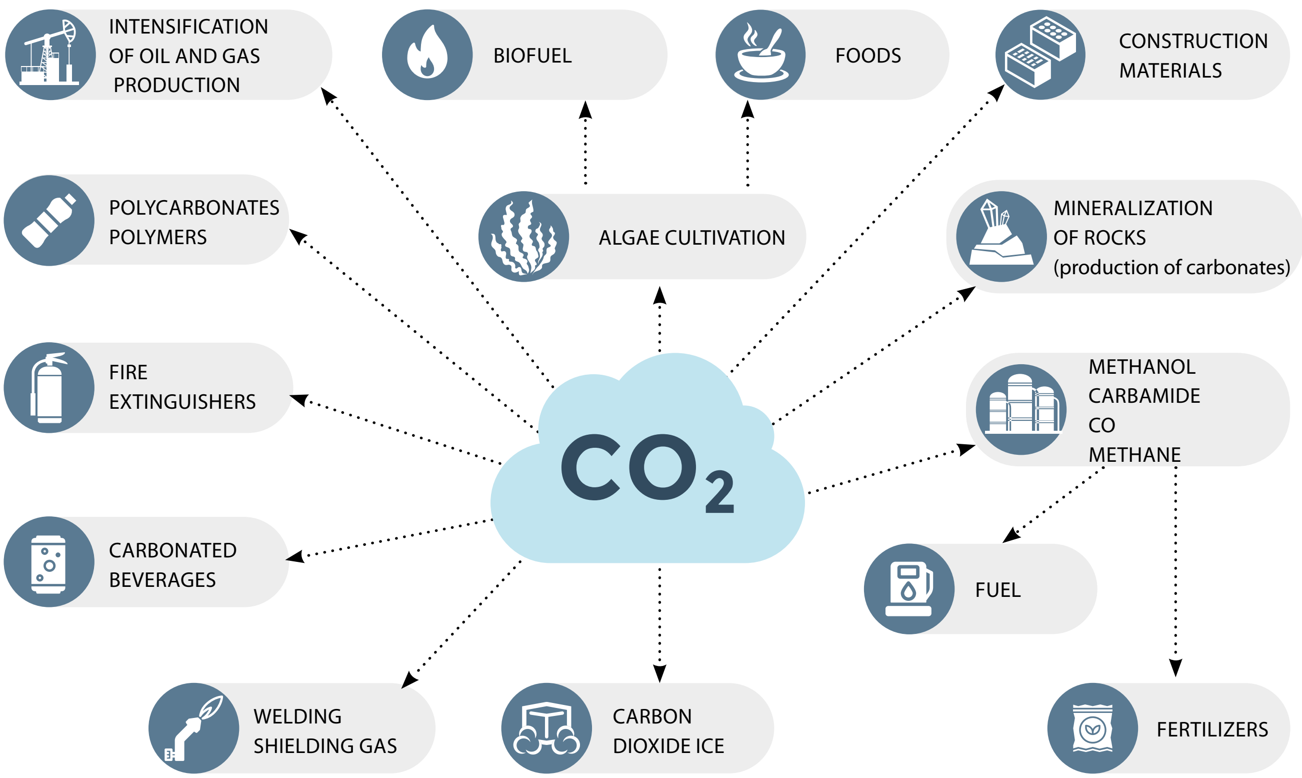
Carbon capture and storage (CCS) is the process of capturing and storing carbon dioxide at safe sites (as a rule, underground storage sites) before it is released into the atmosphere.

Carbon capture and use (CCU) is a similar process that differs in one feature — CO_2 is not simply stored at special storage sites, but is used in other industrial processes (e.g., in methane or polymers production). This is an advantage of the CCU technology, as CO_2 generates sales revenue and increases the economic viability of carbon capture.

Abandoned oil, gas and coal fields, as well as deep saline formations (sedimentary rocks, of which pore spaces are filled with high-salt water) can be used as carbon dioxide storage sites. To date, most of captured CO_2 is pumped into active oil fields to increase the well yield.

The disadvantage of some concepts for the use of CO_2 is that captured and processed CO_2 is later released into the atmosphere when products are used (e.g. when fuel is burnt). Therefore, the principal goal of CO_2 capture and use should be the production of products that do not emit CO_2. Establishment of a closed cycle is an alternative: a product is made of CO_2 (e.g. plastic), which at the end of its life is used in production at a steelmaking plant (e.g. as fuel) and at the same time CO_2 is captured. ►►

Areas of CO_2 utilization



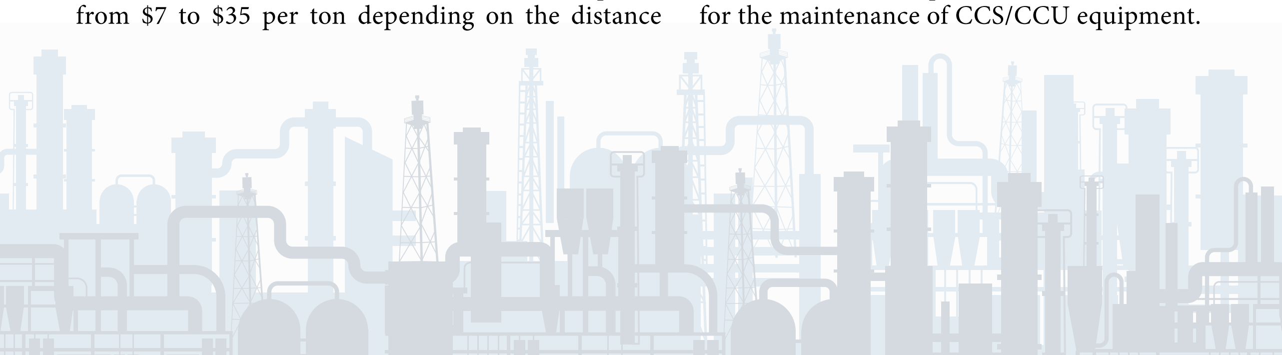
Source: US Department of Energy's National Energy Technology Laboratory, Ministry of Economy, Trade and Industry of Japan

According to estimations by the University of Cambridge Institute for Sustainability Leadership, the cost of CO_2 capture and storage may range from \$25 to \$190 per ton (including expenses for CO_2 capture from exhaust gases, transportation to the storage site and storage). Capture expenses depend on the composition of exhaust gases: the lower the CO_2 content in emissions, the higher the capture value. The capture process requires heating to 120°C, through either the use of electricity or transmission of residual heat from production.

According to the Global CCS Institute, expenses for transportation and storage of captured CO_2 vary from \$7 to \$35 per ton depending on the distance between capture and storage sites, type of storage and its accessibility. Electricity is needed for CO_2 compression for transportation and storage.

Nowadays, the use of CCS/CCU technologies in the steel industry is complicated by several sources of emissions, which makes it difficult to capture more than 60% of CO_2. A possible solution to the problem is to switch to the smelting reduction technology that allows concentrating emissions in one source. An alternative is to enhance the use of blast-furnace gases in steelmaking and capture remaining carbon emissions.

Other bottlenecks are a shortage of sites suitable for storing captured CO_2 and increasing operating costs for the maintenance of CCS/CCU equipment.



USE OF BIOGAS OR HYDROGEN INSTEAD OF NATURAL GAS IN THE PRODUCTION OF DIRECT REDUCED IRON

Direct reduction of iron is the process of producing alternative raw materials for electric arc furnaces: iron ore pellets (direct reduced iron, DRI) and hot briquetted iron (HBI). To this end, rich iron ore (with at least 67% Fe content) is used, which is reduced at high temperatures to 90% Fe content or higher. Natural gas (up to 400 cubic meters per ton of DRI) is used as a reduction agent.

Direct reduction of iron, followed by steel smelting in electric-arc furnaces, emits 50% less CO_2 compared to the BF-BOF route. Like in Ukraine, direct reduction of iron is not widely used in the EU because of the lack of cheap gas. Production of both DRI and HBI is concentrated mainly in the Middle East, North Africa and Latin America.

The main idea of cutting emissions is to substitute natural gas with biogas or hydrogen. The possibility of using hydrogen to reduce iron raises no questions, as during the natural gas-based DRI process hydrogen reduces up to 50% of iron, while the rest is reduced by carbon.

There are several types of technologies that use hydrogen to produce direct reduced iron.

A transition to hydrogen for the purpose of decarbonization poses a number of challenges. First and foremost, hydrogen should be produced with no CO_2 emissions. This could be achieved with the help of either CO_2 capture or the use of alternative sources of electricity. 3–4 MWh of 'green' electricity per ton of steel will be required to produce hydrogen from water by electrolysis. Production of hydrogen from natural gas under the current steam methane reform will require the capture of 0.5 tons of CO_2 per ton of steel.

A separate aspect is the need for large storage facilities for hydrogen. In the opinion of the University of Cambridge Institute for Sustainability Leadership, steel companies will have to maintain at least a five-day supply of hydrogen to ensure continuity of the production processes.

Significant reduction of CO_2 emissions in the DRI-EAF route requires changes in other production processes. Firstly, it is an alternative clean source of energy to sinter/pelletize iron ore. Potential options are electricity and biofuel. Secondly, although CO_2 emissions of electric-arc furnaces are relatively low (0.1 ton of CO_2 per ton of steel), there is a potential for further reduction. Thirdly, alternative clean energy sources are also needed for furnaces heating up billets before rolling.

Hydrogen-based direct reduced iron

Technology	How it works	Pros	Cons
Shaft furnace direct reduction	Hydrogen is used to reduce iron ore pellets to direct reduced iron at 800° C.	- small plants can be used - easy control of the production process - possibility of installing equipment at available facilities with the further use of direct reduced iron in BOF and EAF steel production	- based on the use of iron ore pellets, CO2 is emitted in the production process (the emissions level depends on the fuel used) - 100% relies on 'green' electricity supply - requires supplies of 'green' hydrogen, for the production of which large-scale electrolyzers need to be developed
Hydro-gen-based di-rect reduced iron — fluidized bed	Similar to the shaft furnace technology, with the only difference is that finely processed iron ore powders (fines) are used instead of pellets.	- a cut in CO_2 emissions and pelletizing costs - higher iron content in the final products (95% against 90% as in the shaft furnace method)	- 100% depends on supplies of 'green' hydrogen and 'green' electricity - less developed than shaft furnaces, requiring higher investment
Suspension ironmaking	The process begins with the ultrafine grinding of low-grade iron ore to produce iron ore concentrate. Iron ore concentrate is then reduced using hydrogen in a high-temperature flash reactor for just a few seconds, directly producing steel once carbon is added.	- direct reduction of iron ore to steel in one reactor, removing the need for ironmaking, sintering or pelletizing etc. - fewer impurities in produced steel	- the technology is at an experimental stage - requires significant investment - ultrafine grinding of iron ore requires high energy intensity and increased plant maintenance
Plasma direct steel reduction	Iron ore, raw or in the form of fines or pellets, is reduced using hydrogen plasma in a plasma steelmaking reactor. Hydrogen plasma is a hydrogen gas that has been heated or electrically charged to separate it into its constituent particles.	- the process removes the need for preprocessing of iron ore - lower reactor temperatures in the production process - it is highly integrated with other methods (e.g. smelting reduction)	- the technology is at a very early stage of development, with a full reactor design yet to be developed

Source: Roland Berger

SMELTING REDUCTION

Smelting reduction will help draw out coke and sinter plants and blast furnaces from the production process. There are several types of smelting reduction, but the general process includes **two stages:**

- **at the first stage**, iron ore (e.g., lump ore or iron ore pellets) is fed into a reducer and then reduced to a DRI-like condition with the help of gas. Gas comes from the second unit (smelter-gasifier furnace), in which coal gasification takes place;
- **at the second stage**, partly reduced iron ore enters into the smelter-gasifier furnace and then final reduction and melting takes place through interaction with gasified coal.

The process results in the production of pig iron, which can be converted into steel in the basic oxygen furnace.

Advantages of smelting reduction:

- **20% decrease in energy costs;**
- substitution of coke with coal, not necessarily coking coal;
- one source of CO_2 emissions is formed due to the integration of several production processes into one. This allows to capture up to 90% of carbon dioxide emissions.

ELECTROLYTIC IRON PRODUCTION (BASED ON ELECTRICITY FROM RENEWABLE SOURCES)

The method is at the stage of laboratory tests. There are **two types of this method**

Electrolysis

The dissolution of iron ore in an electrolyte (molten oxide or a mixture of oxides, e.g. calcium oxide, aluminum oxide, magnesium oxide) at the temperature of about 1,600°C. Then an electric current is passed through the solution. As a result, reduced iron is accumulated on the cathode, and oxygen on the anode. The final product of electrolysis is liquid steel.

Electrowinning

Iron ore is ground into an ultrafine concentrate, leached and then reduced in an electrolyzer at around 110°C. The resultant iron plates are fed into an electric-arc furnace.

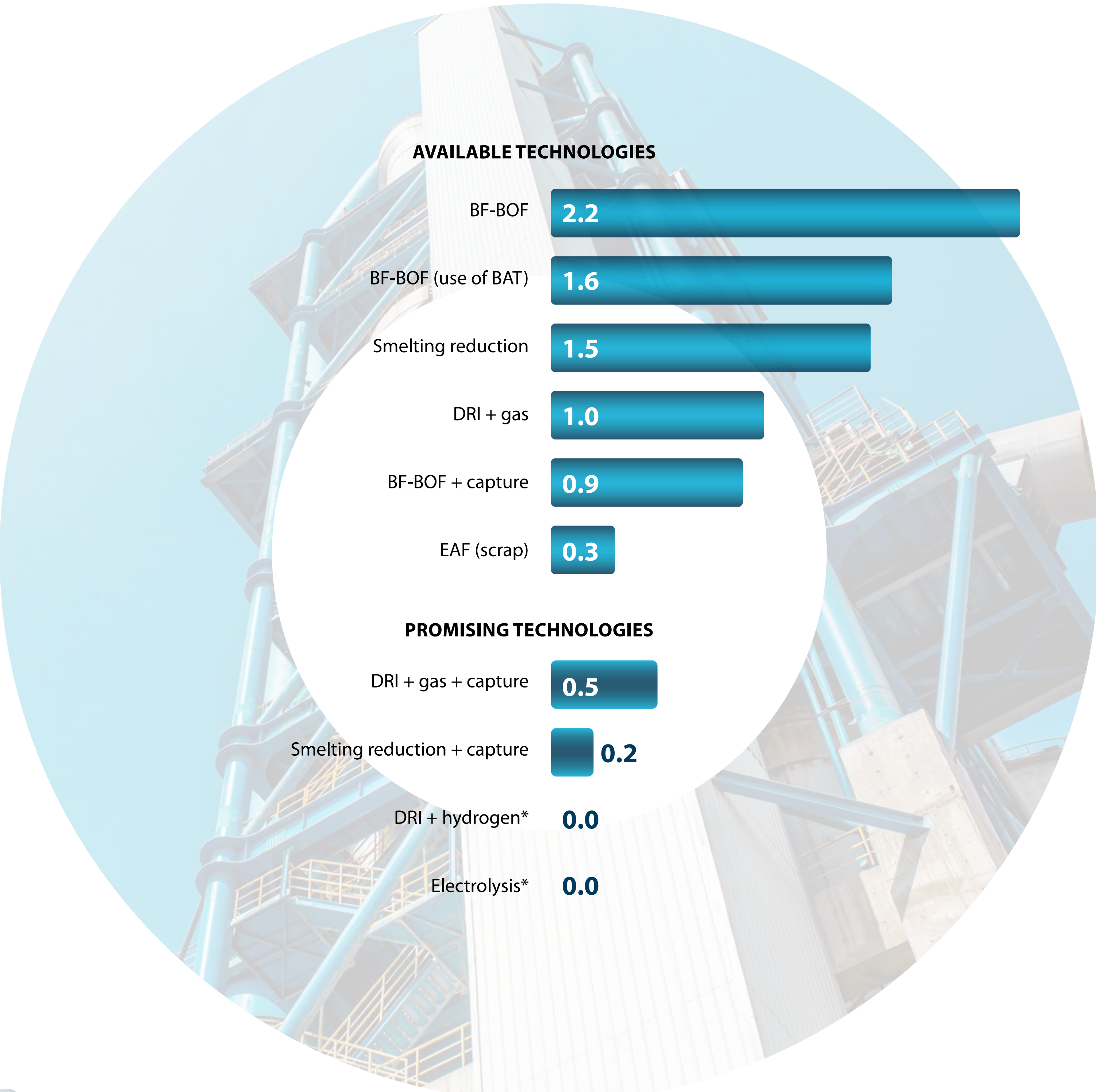
For both types, the electrolyte composition, temperature, and anode material are the subject for further research.

The electrolytic process may become the most energy efficient method of steel production in the future, because it excludes some production stages typical for other technologies (production of coke, iron ore pellets, sinter are, hydrogen, etc.). According to the IEA, **electrolysis-based production will require 15-30% less electricity per ton of steel** compared to hydrogen-based DRI production. **Electrolysis-based production will also require less capital investment, since it does not require much equipment.**

At the same time, the electrolytic technology is still being tested in laboratories. The process is also relatively inflexible compared to hydrogen-based direct iron reduction, as it cannot be easily stopped.

The process needs a constant source of electricity (in the context of decarbonization, electricity must come from renewable sources). The main problem is the high price for 'green' electricity, its insufficient volumes, inconstant green energy generation against the lack of storage capacities.

CO_2 emissions per ton of steel by different technologies (scope 1 + scope 2), t



** subject to the use of electricity from renewable energy sources and hydrogen produced without CO_2 emissions*

Source: IEA, University of Cambridge Institute for Sustainability Leadership, оценки GMK Center

Some difficulties restrict decarbonization opportunities

Achieving the carbon neutrality targets for global steel production is possible only on a long-term horizon. Decarbonization of the steel industry is complicated for reasons that can be divided into the following **two groups: technological and economic.**

Technological

1 Large number of emission sources

An integrated iron and steel works may have more than 1,000 emission sources, including unorganized ones. Measures to improve efficiency and cut emissions need to be carried out at each of them. Used raw materials (iron ore, coke), which cannot be replaced using the available technologies, may also be a source of emissions.

2 Need for breakthrough technologies

According to McKinsey, 45% of CO_2 emissions of a steel mill are caused by high temperature heating, which is impossible to achieve without fossil fuels. Alternative technologies are just being developed. The risks for the industry are posed by the fact that the national emission reduction targets have already been set, whereas the time frames for the emergence of new technologies are not determined

3 Radical changes and unreadiness of supply chain

Different stages of steel production are deeply integrated into each other. A change in one stage therefore prompts a change in the others. Hydrogen-based technologies may face a deficit of raw materials, because there are currently no solutions for hydrogen production at the required scale, as well as for storage and supply systems.

4 Availability of energy resources

Alternative technologies for steel production will entail a much higher increase in electricity consumption, and this electricity should be environmentally friendly. Also, investment will be needed to expand the electricity supply system.

Economic

1 High need for investment

A change in technologies at integrated iron and steel works will imply complete restructuring of operating production facilities. In terms of investment amounts, a change in technologies is comparable to the construction of new plants. There is a considerable uncertainty regarding the amounts of required investment, since emerging technologies are not yet commercially available.

2 Higher production cost

Low-carbon technologies increase the cost, e.g. electricity and hydrogen expenses. In other words, the launch of decarbonization technologies will mean a loss of competitiveness. In this context, governments strive to adjust competitiveness through the implementation of respective policies. These policies can be a hidden tool of protectionism.

3 Adverse social implications

The steel industry is basic even for developed countries and has a high social importance. Giving up coal and coke, use of EAF instead of the BF-BOF route will trigger a significant reduction in the need for labor force. Staff cuts will be associated with social risks in the regions.

4 Dependence on the government

Achieving carbon neutrality goals will be entirely dependent on government incentives. Asynchrony of national policies of different countries will create risks for competitiveness of companies, notably from emerging economies. ■

Decarbonization requires significant investment

Since achieving carbon neutrality is only possible through radical changes in production technologies and supply chains, this will require significant CAPEX comparable to the construction of new production facilities. **The amount of investment in decarbonization projects until 2050 is estimated at an average of $1,000 per ton of steel, ranging from $600 to $1,850.**

Estimated amounts of capital investments in decarbonization projects

Source	Object	CAPEX, $ bln	Per ton of steel*, $
Estimations by international consulting companies and associations			
McKinsey	CAPEX in the global industry until 2050, baseline scenario	3,000	1,850*
IEA	CAPEX in the global industry until 2050, Sustainable Development Scenario	1,400	866*
McKinsey	CAPEX in the EU industry until 2050	120	1,000*
Roland Berger	CAPEX in the EU industry until 2050	120	1,000
Corporate projects data			
Voestalpine	DRI+H_2 with a 7.5 million ton annual capacity	8.4	1,120
	Infrastructure	27.6	3,680
ArcelorMittal Europe	Carbon capture units	18–30	1,000–1,500
	DRI+H_2	36–48	
	Infrastructure	up to 240	up to 4,600
H2 Green Steel	DRI+H_2 in Sweden with a 5 million ton capacity	3.0	600

** per ton of rated BOF steel production capacity*

Source: companies' data, media, GMK Center estimations

The preparations of supply chains — green hydrogen industrial-scale production and green electricity — will require much more investments than iron & steel production facilities. Based on the announced projects, the amounts of infrastructure CAPEX average $3,700–4,600 per ton of steel.

Investment difficulties:

1. The industry's current debt is high and **makes it difficult to raise such significant amounts of funding.** In 2019, the industry's average Net Debt/EBITDA reached a threshold rate of 3.0.
2. **Low margins are due to the expected weak growth in demand,** $90 EBITDA per ton of steel on average, which gives a long payback period, with an investment of $1,000 per ton of capacity.
3. **Excess capacities in the industry** also pose a problem that enhances competition, causes volatility in the markets, puts pressure on companies' financial results, and increases investment risks.
4. The need for application of breakthrough technologies in the process of decarbonization is determined by administrative pressure, and emission reduction targets set by the government — not by economic factors. The government should therefore be a co-funder. **Environmental policymakers in most countries are not ready to launch the necessary tools for funding decarbonization.** ■

Decarbonization prompts an increase in production cost

Low-carbon steelmaking technologies were not widely used in the past, as they are associated with higher production costs. Low-carbon steel production will cost 10–80% more per ton of steel compared to traditional BF-BOF route.

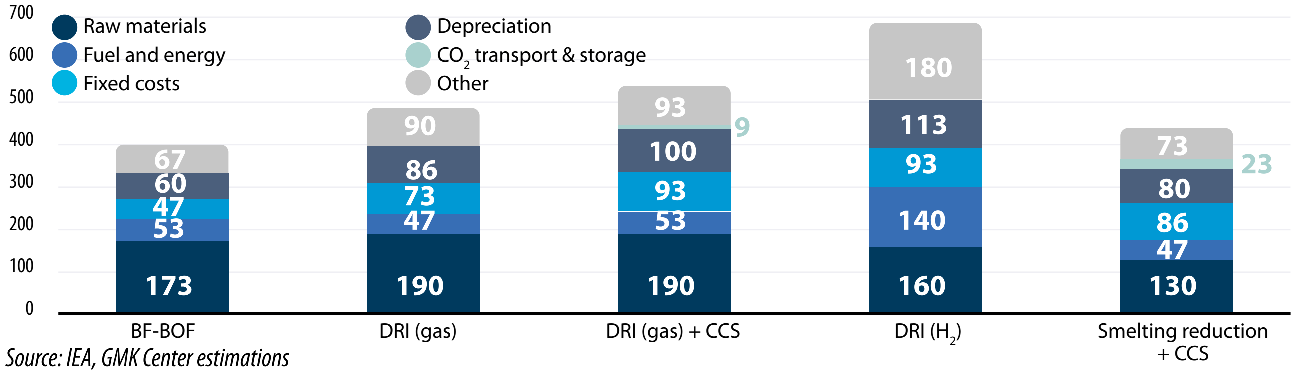
Cost of steel production growth rate by breakthrough technologies, as compared to the traditional BF-BOF route

Technology	Calculation source	Growth rate, %
Gas-based DRI	IEA	+22%
	Voestalpine	+30%
Gas and carbon capture-based DRI	IEA	+35%
Hydrogen-based DRI	University of Cambridge Institute for Sustainability	+10-27%*
	IEA	+72%
	ArcelorMittal	+60%
	Voestalpine	+80%
Carbon capture-based smelting reduction	University of Cambridge Institute for Sustainability	+15%
	IEA	+10%

** depending on electricity prices*

DRI-based steel production is 20–30% more expensive compared to the traditional BF-BOF route. This technology however provides CO_2 emissions reduction till 1.0 ton per ton of steel only. According to a survey by the IEA, **equipping DRI furnaces with capture units will add another 11% to the primary cost.** DRI-based carbon-free production can be achieved alternatively **through the use of hydrogen as a reducing agent. Steel production based on this technology will cost another 27% more** than the capture-based production. The use of hydrogen will however be justified in the regions with cheap electricity, without possibility of CO_2 storage, and high costs associated with CO_2 transportation.

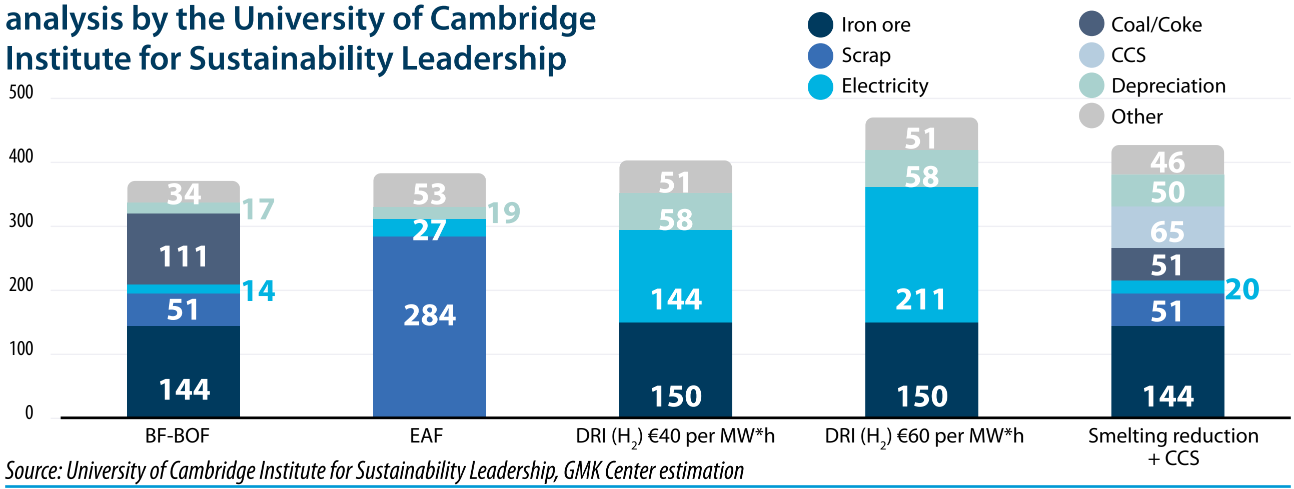
Costs of steel production by technologies, $ per ton, in terms of liquid steel, IEA analysis



Source: IEA, GMK Center estimations

An analysis by the University of Cambridge Institute for Sustainability Leadership shows how the structure of steel production costs will change with the transition to carbon-free technologies. In traditional technologies, raw materials accounted for a lion's share in the primary cost, whereas in DRI-based production technologies, electricity costs are on the top. They will account for 35–45% of the total cost of DRI-based production. Electricity will be the most sensitive cost factor. Specifically, an increase in prices from €40 to €60 per MWh will prompt a 17% increase in the cost of steel. The main competitiveness factor will be access to cheap electricity sources, not to raw materials. As a result, market volatility will increase, because factors such as weather changes may affect prices. Also, this situation will change the alignment of forces and the extent of influence of raw material suppliers on steel producers, which in turn will affect the situation on raw materials markets.

Costs of steel production by technologies, $ per ton, in terms of liquid steel, analysis by the University of Cambridge Institute for Sustainability Leadership



Source: University of Cambridge Institute for Sustainability Leadership, GMK Center estimation

The differences in the amounts of costs in different surveys are due to different assumptions for raw materials prices, and in particular for electricity and hydrogen, which are the subject of the greatest uncertainty. Understanding the risks of price fluctuations and a possible shortage of hydrogen supplies, the companies most actively engaged in R&D have announced the implementation of their own projects or partnerships geared towards generating electricity from renewable sources and producing hydrogen.

It is important to note that both surveys have shown that in terms of expenses, smelting reduction based on CO_2 capture units will be the most cost-efficient technology for zero emission steel production. Its application can be associated with 10–15% higher costs compared to the traditional BF-BOF technology. In terms of the cost structure, smelting reduction is similar to the traditional technology. It implies lower costs for raw materials, in particular for coke, because gasified coal is used in the production process. At the same time, a hike in costs is due to carbon capture and storage costs ($23–65 according to various estimations). Smelting reduction will cost just 6% more than the traditional technology, without taking into account the difference in the amount of depreciation deductions. ►►

Steelmaking companies

CO_2 NEUTRAL

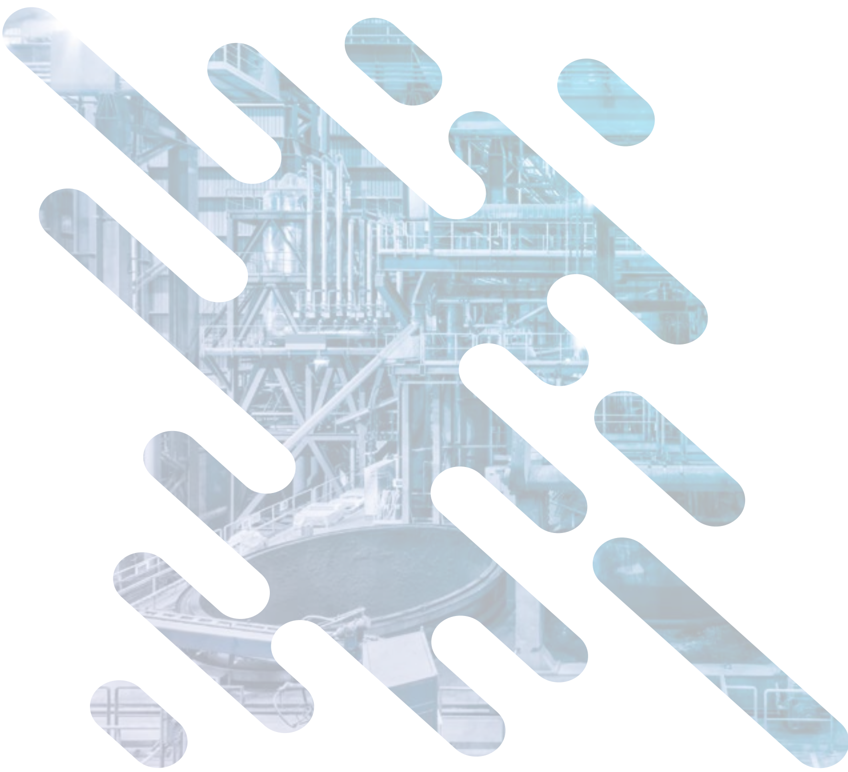
Carbon neutrality

SMELTING REDUCTION

- HISARNA — TATA STEEL

CARBON CAPTURE AND USE

- Carbon2Chem — thyssenkrupp
- Steelanol — ArcelorMittal
- Carbon2Value — ArcelorMittal
- Everest — ArcelorMittal, TATA STEEL
- INITIATE — ArcelorMittal, SSAB
- i³upgrade — voestalpine



Source: Eurofer, media, companies' websites

are actively investing in R&D

technologies

HYDROGEN-BASED DRI

- HYBRIT — LKAB, SSAB
- SuSteel — voestalpine
- H_2 Hamburg — ArcelorMittal
- SALCOS — SALZGITTER AG Stahl und Technologie
- GISH
- HYFOR — voestalpine

ELECTROLYSIS

- Siderwin — ArcelorMittal
- Boston Metal — BOSTON METAL

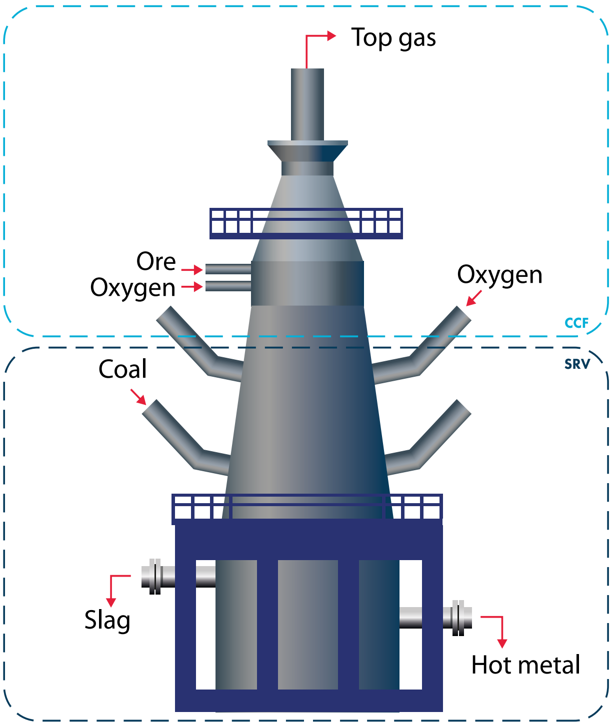
The above is a list of on-going projects. This list does not include research projects that have already been finished. These are STEPWISE (CO_2 capture from blast-furnace gases and follow-up hydrogen production), FreSMe (production of methanol based on a CO_2 mixture obtained from blast-furnace gas and H_2 obtained either from blast-furnace gas or by electrolysis), Carbon4Pur (production of polyols, the main components of polyurethane insulation materials and coatings, based on exhaust gases emitted by the steel industry), BOF2Urea (CO_2 capture-based carbamide production).

Smelting reduction

HISARNA

HISARNA is a Tata Steel's project based on smelting reduction technology. The project is being developed in conjunction with Rio Tinto metals and mining corporation. Tata Steel, Rio Tinto, ArcelorMittal, ThyssenKrupp, Voestalpine and Paul Wurth are currently testing and further developing the technology.

How HISARNA works



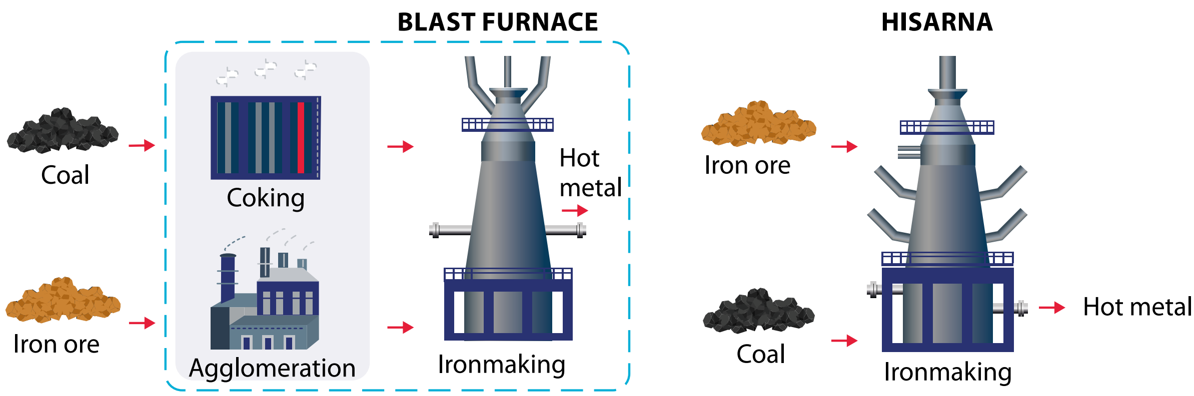
HISARNA combines two process units, the Cyclone Converter Furnace (CCF) and a Smelting Reduction Vessel (HIsmeltTM Smelt Reduction Vessel, SRV). CCF was developed by Tata Steel, SRV was initially developed by Rio Tinto and later bought by Tata Steel.

The production process is as follows:

- crushed iron ore is injected into this cyclone together with oxygen making in the long run partly reduced iron that drips down (to the SRV);
- molten iron from the cyclone falls into the molten slag;
- powder coal is injected into the slag layer;
- dissolved in metal, carbon reduces iron from the slag to pig iron and slag;
- carbon with coal particles goes up and is partly burnt by oxygen, generating heat;
- part of the heat is returned to the bath with metal;
- residual heat is used to smelt and reduce iron in the CCF.

As a result, production is simpler than the blast furnace process.

Comparison of the HISARNA process and the blast furnace process



Emissions reduction in the HIsarna technology compared to the blast furnace process

Scenarios	Emissions reduction		
	CO_2	NO_x	SO_x
HISARNA without Carbon Capture and Storage	20%	70%	60%
HISARNA with Carbon Capture and Storage	80%	90%	85%

Source: Tata Steel

The HISARNA installation emits almost pure carbon dioxide, which is easy to capture. Besides, HISARNA allows to reduce CO_2 emissions:

- by 20% without changing the baseline technology;
- by 50% with the use of biomass and scrap;
- by 80% with the use of CCS technologies.

As coking and sinter plants are not part of the production process, HIsarna also allows reducing emissions of other gases.

HIsarna pilot plant was built in 2010 at Tata Steel Ijmuiden, the Netherlands, as part of ULCOS (Ultra-Low Carbon Dioxide Steelmaking) project. The plant's capacity is 65 thousand tons of pig iron per annum. The amount of construction investment is **€20 million.**

Since 2011, experiments have been carried out at the pilot plant using various raw materials (thermal coal, low-quality iron ore, scrap, and charcoal). The HIsarna project was funded by partner companies, EU programs (EU FP6, Research Fund for Coal and Steel, Horizon 2020) and the Dutch government (Demonstratie Energie Innovatie).

In 2010–2017, **a total of over €60 million was invested in the project.** The latest significant engineering modifications took place in 2015–2017 (investment — €25 million).

€300–350 million are to be invested in the construction of a demonstration plant (0.5–1.0 million tons per annum), excluding the carbon capture unit. **The carbon capture unit costs at least €20–25 million.**

If developers manage to make the technology ready for full-scale commercial operation, **its commercialization will take 10 years**. Later, the technology could be used in the construction of new plants.

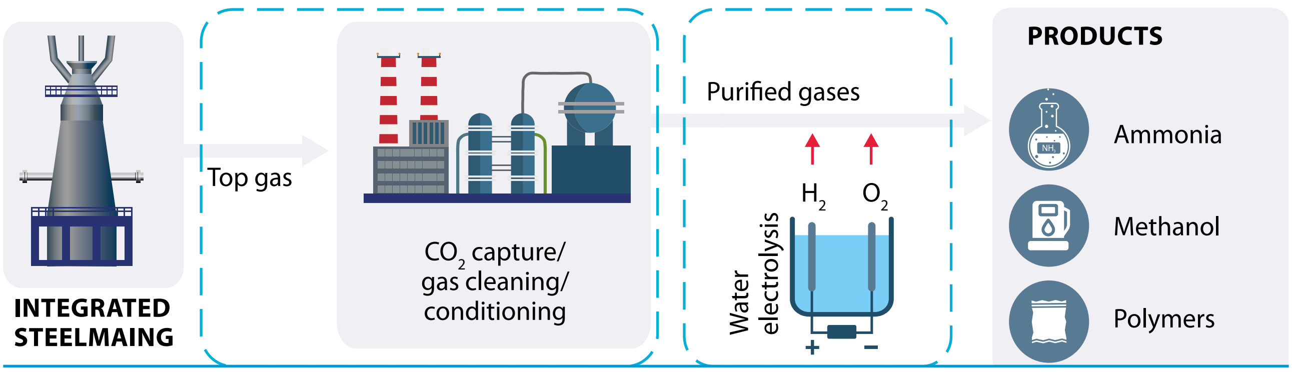
Carbon capture and use

Carbon2Chem

Carbon2Chem is a joint project of Thysenkrupp and 17 other partners. The project proposes the following **production scheme:**

1. Exhaust gases emitted during steel production (coke, blast furnace, converter ones) are cleaned of unnecessary impurities.
2. Cleaned gases are mixed with hydrogen and oxygen made by electrolysis from water with the use of alternative sources of energy.
3. Chemical products — ammonia, methanol, polymers or higher alcohols — are produced from the gas mixture. ►►

Carbon2Chem process scheme



€120 million were spent for research. €500 million are needed for the demonstration phase. The objective of scaling up the technology will cost around €1 billion.

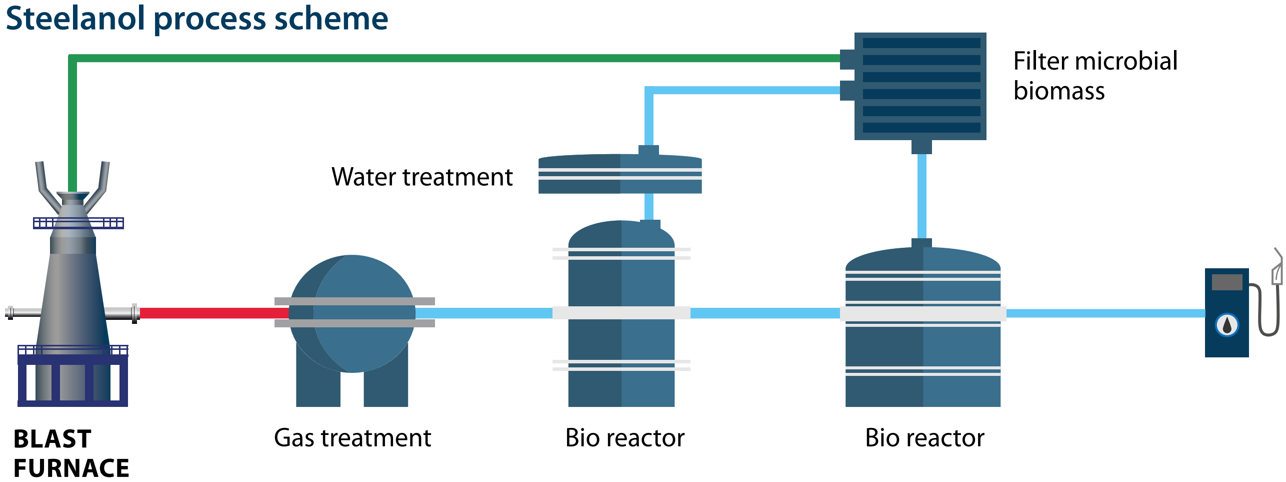
On 20 September 2018, a pilot plant officially commenced methanol production. The Federal Ministry of Education and Research supported the construction with €60 million, while Thysenkrupp invested €34 million. Thysenkrupp received €75 million for the second stage of work from the German Ministry of Education until 2024.

The project is expected to be ready for industrial commercialization by 2030. Carbon2Chem has potential of reducing carbon emissions in Germany's steel sector by 20 million tons per annum.

Steelanol

Steelanol is ArcelorMittal's project aimed at producing bioethanol using exhaust gases. The project is based on producing bioethanol through an innovative gas fermentation process using exhaust gases emitted by the steel industry. It is expected to receive 50 kg of bioethanol per ton of steel produced.

Steelanol process scheme



A pilot plant for bioethanol production will be mounted at ArcelorMittal Belgium (**investment in construction — €120 million**). The EU funded the project in the amount of €10 million.

The launch of bioethanol production is scheduled for 2020. The plant will capture 15% of exhaust gases emitted by the plant and convert them into 80 million liters of ethanol per annum.

The complete processing of exhaust gases through the Steelanol technology by all EU basic oxygen steelmakers (28 companies) will cut CO_2 emissions by 33.3 million tons per annum.

Carbon2Value

Carbon2Value is a joint project of ArcelorMittal and 5 partners (research organizations and technology providers). It involves the capture of gases emitted by the steel industry and their separation into CO and CO_2. CO will be used to produce ethanol as a component of transport fuel (Steelanol is a subsidiary of Carbon2Value) and synthetic hydrocarbons. It is planned to use CO2 in the future.

The objective is to prove the possibility of reducing CO_2 emissions in the steel industry by 30–45% through the proposed capture and use technology.

On 18 March 2019, a Carbon2Value pilot plant was launched at ArcelorMittal Gent. The commissioned plant separates CO_2 and CO from exhaust gases emitted by the steel industry. The project budget is €10.5 million, of which €4.4 million were allocated under EU Interreg 2 Seas.

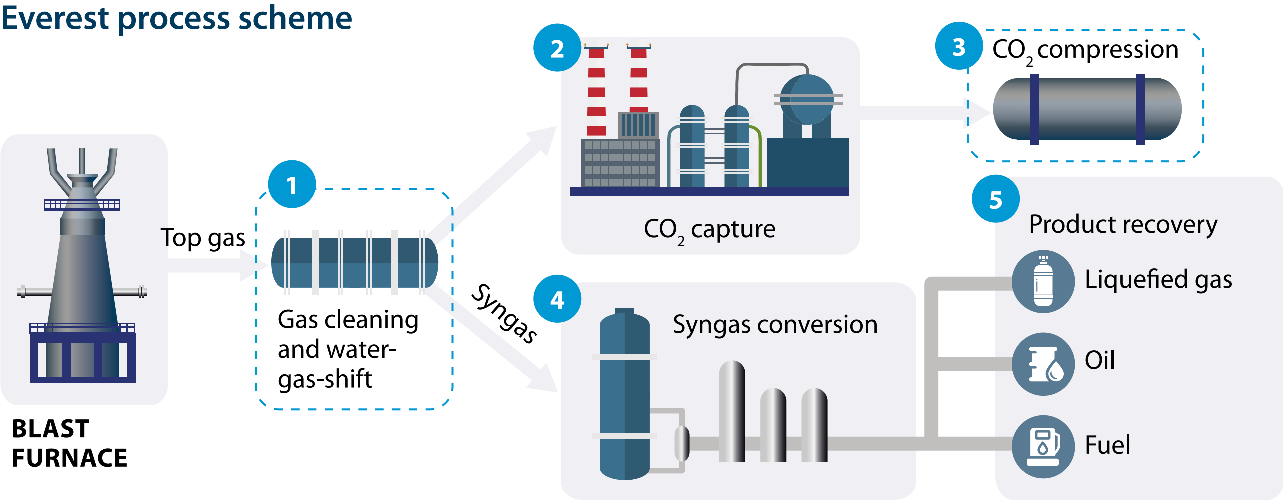
Another pilot plant on the CO_2 capture is under way at ArcelorMittal Dunkirk. **The project costs total €20 million.**

Everest

Everest (Enhancing Value by Emissions Re-use & Emissions Storage) is a project of Tata Steel, Dow Chemical, Arcelor Mittal, ISPT, University of Gent, ECN. The primary target of Everest is to reduce Tata Steel's CO2 emissions by 4 million tons per annum.

The project is based on the idea of converting carbon-containing gases into ligroin (naphtha) — liquid fuel. Potential products of conversion are methanol, acetic acid, kerosene, ammonia and methane.

Everest process scheme



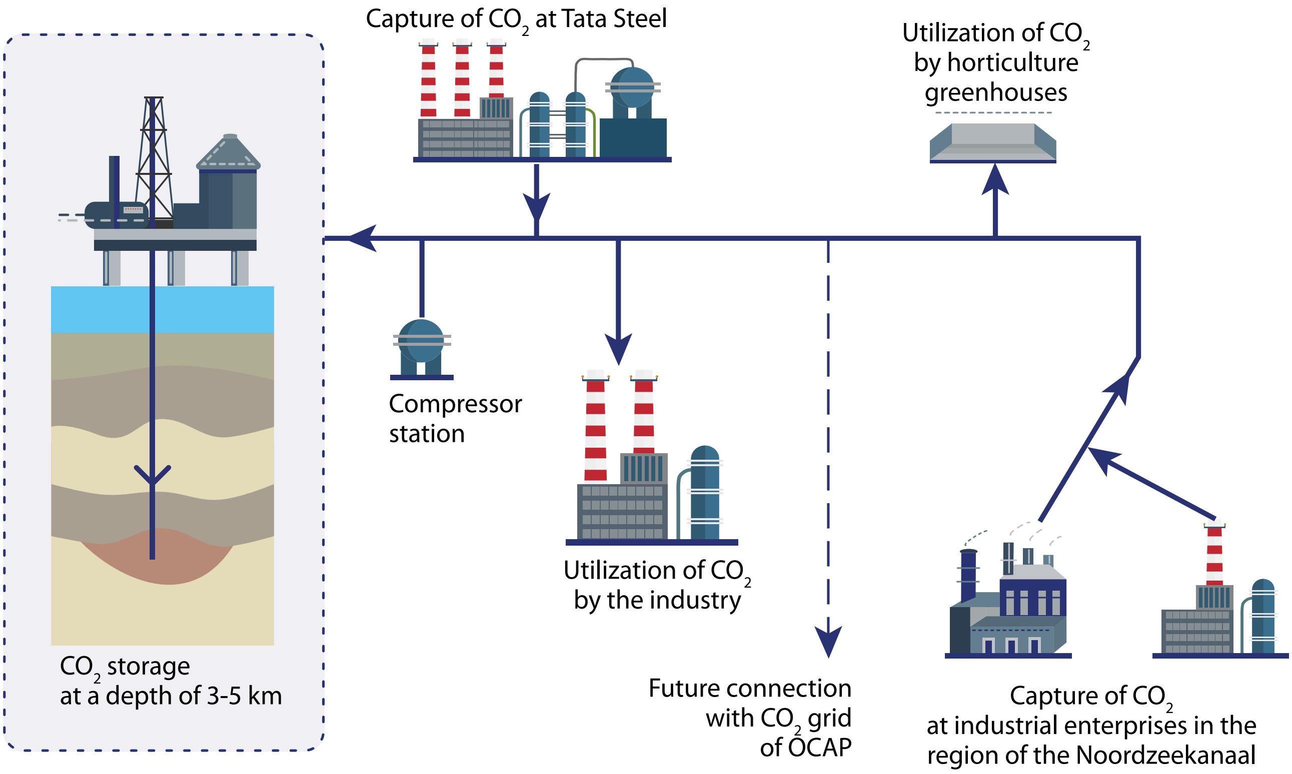
The production route is as follows:

1. Removal of nitrogen and sulfur compounds from the blast-furnace gas is followed by the water-gas shift. Function: to adjust the CO:H_2 ratio in the blast-furnace gas to make it suitable for syngas conversion (in the case of naphtha, 2.1:1).
2. CO_2 capture.
3. CO_2 compression function: to pressurize CO_2 to the required pressure at the point of custody transfer with **Athos** project (*see **the Scheme** on p.* ***30***);
4. Syngas conversion into chemicals. Naphtha is produced through the Fischer-Tropsch reaction.
5. Hydrocarbon post-processing (e.g. drying) and separation of the gaseous phase from the liquid phase.

Pilot plant design works to capture CO_2 were launched in Q2 2019. A pilot installation at ArcelorMittal Gent, Belgium, is scheduled to be put into operation in Q2 2020 and at Tata Steel IJmuiden, the Netherlands, in Q4 2021. The plant engineering for the Fischer-Tropsch reaction will start in Q3 2021. Everest is expected to be commercialized in Q2 2027.

Everest is linked to the Athos project, which aims to develop a CO_2 transport and storage network in the North Sea Canal area (running from the port of Amsterdam to the North Sea at IJmuiden). Athos is implemented by a consortium of TATA Steel, Port of Amsterdam, Gasunie and EBN. ►►

Athos.
CO_2 capture, transport, utilization and storage under the North Sea



The network will comprise onshore CO_2 transport pipelines, offshore storage facilities, and exit- and feed-in points for companies directly connected to the network. The project is at the stage of assessing the interest in connecting to such network (questionnaires of companies that are potential network participants were collected until 31 December 2019).

INITIATE

INITIATE is a research project carried out by a TNO-led consortium of participants. Steel industry representatives include ArcelorMittal Belgium and SSAB. The project aims to develop a technology for production of carbamide from exhaust gases emitted by iron and steel works. The project participants intend to draw up a roadmap for technology commercialization following the completion of the research stage.

The project outcomes will include a reduction of primary energy intensity by 30%, CO_2 emissions by 95%, raw material intensity by 40%, and waste generation by 90%.

The project time frame is 01.11.2020 to 30.04.2025. **The budget is €23.1 million**, of which €21.3 million is funded by the EU.

i³upgrade

i³upgrade (Integrated and intelligent upgrade of carbon sources through hydrogen addition for the steel industry) is a joint project of Friedrich-Alexander-Universität Erlangen-Nürnberg and eight other partners, including Voestalpine and Primetals. The project develops a technology for synthesizing methane and methanol by using renewable hydrogen and process gases that are produced during the steel manufacturing process.

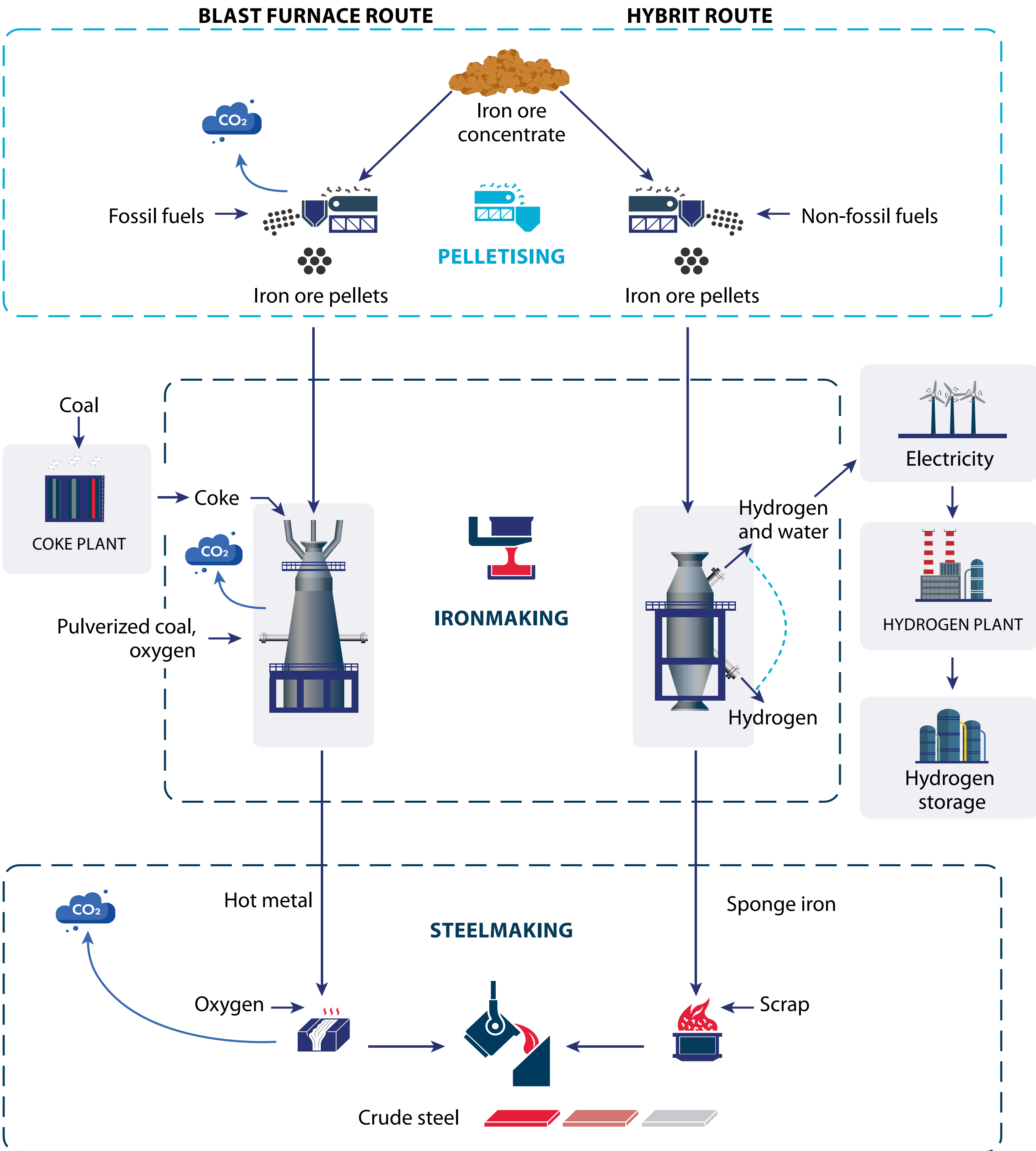
The project was started in June 2018 and is scheduled for completion in November 2021. **It is being funded at a total of €3.3 million.** Funding is received from the Research Fund for Coal and Steel (RFCS).

Hydrogen-based DRI

HYBRIT

HYBRIT (Hydrogen Breakthrough Ironmaking Technology) is a joint project of three Swedish companies, SSAB, LKAB and Vattenfall. The project is aimed at hydrogen-based direct reduction of iron ore. Hydrogen is to be produced through water electrolysis with the use of renewables. ►►

Comparison of the HYBRIT process and the blast furnace process



A pre-feasibility study conducted in 2016–2017 concluded that transition to hydrogen-based direct reduction of iron will reduce CO_2 emissions per ton of steel by 98.4%, from 1,600 kg (BF–BOF route in Sweden) to 25 kg (HYBRIT technology). The fossil-free steel will be 20–30% more expensive.

In the summer of 2018, the construction of a HYBRIT pilot plant at SSAB in Lulea, Sweden, was launched. A site for fossil free steel production was provided at SSAB in Lulea, Sweden.

The pilot phase costs are estimated at SEK 1.4 billion ($154 million). The Swedish Energy Agency has committed to contribute SEK 55 million. The project participants, SSAB, LKAB and Vattenfall, contributed the remaining costs in equal shares. Earlier, the Swedish Energy Agency allocated SEK 60 million ($6.6 million) for research and feasibility study.

The pilot phase is expected to end in 2024. In 2026, a pilot plant for the production of 'green' direct reduced iron is scheduled to be put into operation. Its initial capacity will be 1.3 million tons of sponge iron per annum and may reach 2.7 million tons by 2030.

SuSteel

SuSteel (Sustainable Steelmaking) is a research project of Voestalpine and partners (K1-MET, Primetals, MUL) for carbon-free production of crude steel. The project is being implemented at Voestalpine's steel production site in Donawitz, Austria.

It implies direct reduction of iron ore using hydrogen plasma. Hydrogen is used as a reduction agent for iron ore, while its plasma state offers thermal energy for melting.

Through the SuSteel technology, steel will be directly reduced from iron ore fines in special electric-arc furnaces.

The project budget is €2.6 million. 60% of funds is received from the Austrian Research Promotion Agency (FFG).

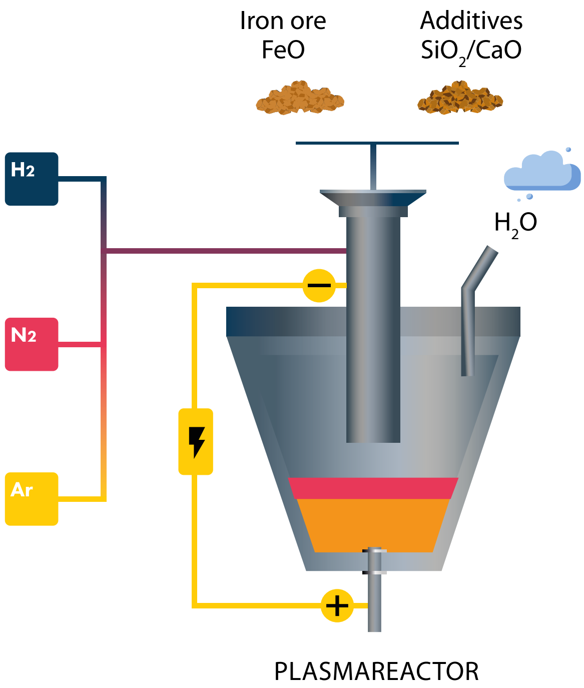
The project is at the pilot plant scaling-up phase.

H2Future is parallel to SuSteel. It is a joint project of Voestalpine and partners (Siemens, VERBUND, Austrian Power Grid (APG), K1-MET, ECN). The project is targeted at commercial production of 'green' hydrogen. It is based on water electrolysis technology. Excess renewable electricity in power grids will serve as a source of power.

The project was launched on 1 January 2017 and will last for 4.5 years. The project budget is EUR 18 million, of which €12 million was allocated under the EU Horizon 2020.

On 11 November 2019, a pilot plant for the CO2-neutral production of hydrogen commenced operation at the Voestalpine site in Linz, Austria. With a capacity of 6 MW, the plant can generate 1,200 cubic meters of 'green' hydrogen per hour.

Susteel process scheme



Hydrogen is currently supplied to the plant's internal gas networks and then used as part of tests at various stages of steel production.

Voestalpine is exploring the possibilities of bridging between the existing coke-based blast furnace route and electric-arc furnaces powered with 'green' electricity partly generated using 'green' hydrogen.

H_2 Hamburg

H_2 Hamburg is ArcelorMittal's project for hydrogen-based direct reduction of iron. The project is to be implemented at a plant in Hamburg. The plant manufactures direct reduced iron using natural gas. The use of hydrogen will be tested in a new furnace with an annual capacity of 100 thousand tons.

The project budget is €65 million.

Hydrogen (of at least 95% purity) produced through the separation of exhaust gases of the existing plant will be used at the initial phase. Afterwards, the plant will switch to 'green' hydrogen.

In July 2020, ArcelorMittal Bremen signed an agreement with a German energy company, EWE, and its subsidiary wb (Stadtwerke Bremen) to establish a 'green' hydrogen production facility. At the first stage, a hydrogen electrolysis unit, with a capacity of up to 24 MW, will be installed at the plant's site. Hydrogen is to be supplied to ArcelorMittal plants.

SALCOS

SALCOS (Salzgitter Low CO_2 Steelmaking) is a joint project of Salzgitter and other companies (Sunfire, Paul Wurth, Tenova, Avacon, Linde, Fraunhover). The project is targeted at producing direct reduced iron using hydrogen.

Its objective is to produce hydrogen in Salzgitter (GrinHy project) by means of PEM electrolysis using electricity generated by wind power (WindH_2 project).

Salzgitter's plants currently emit around 8 million tons of CO_2 per annum. In the first phase of SALCOS, CO_2 emissions could fall by up to 25% by around 2025 (costs total €1.2 billion).

In January 2020, Salzgitter announced its intention to carry out a feasibility study with partners (Rhenus and Uniper) for the construction of a hydrogen-based DRI plant in the coastal area. If research produces positive results, the partners will start the project. The goal is to launch production of direct reduced iron of 2 million tons per annum.

In December 2020, the German Ministry of the Environment approved funding for Salzgitter's DRI project (according to media reports, the amount of government funding is €5.3 million). At the first phase, DRI will be used in blast furnaces to save coal used in pulverized coal injection plants and in an electric-arc furnace at Peine plant.

GrInHy (Green Industrial Hydrogen via reversible high-temperature electrolysis), a joint project of Salzgitter and partners for the production of 'green' hydrogen, is designed to provide SALCOS with hydrogen. The advantage of the GrInHy technology based on high-temperature electrolysis is the use of waste heat from steel production. The electrolysis plant proved to consume less electricity.

An electrolysis plant prototype, with a hydrogen production capacity of around 40 normal cubic meters per hour, is built and tested under the first phase of the project. The test results met expectations. The first phase lasted from 1 March 2016 to 28 February 2019. Its budget totaled €4.5 million (100% EU-funded).

The second phase, GrInHy 2.0, was launched on 1 January 2019. A five-fold increase in the electrolysis plant's power is set as a target. In June 2020, Salzgitter started testing a hydrogen production plant.

The budget of GrInHy 2.0 totals €5.5 million. The GrInHy 2.0 plant is expected to produce 100 tons of hydrogen for steel production until the end of 2022.

In May 2020, construction of 7 turbines comprising the Windpark Salzgitter, started. They will supply electricity for 'green' hydrogen production. The total turbine capacity is 30 MW. Investment in the project, including the construction of turbines, a hydrogen plant and related infrastructure, will amount to $56 million. ►►

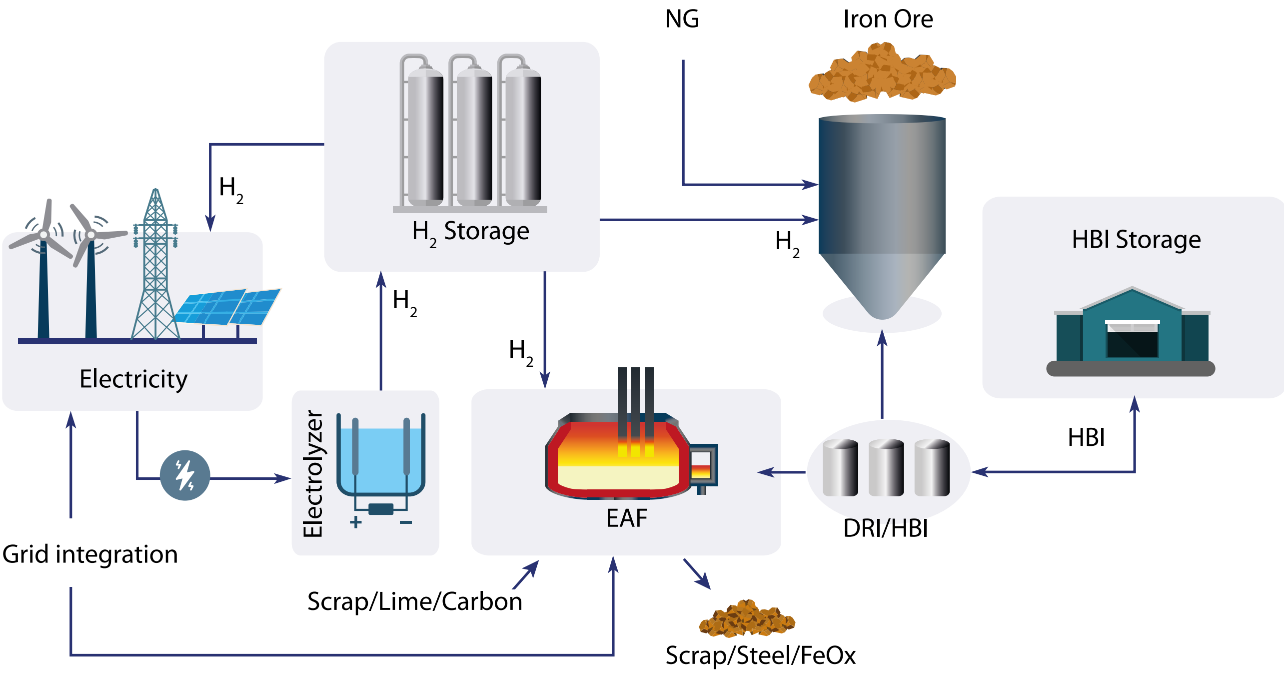
GISH

GISH (Grid Interactive Steelmaking with H2) is a project of Missouri University of Science and Technology and the University of Arizona. Among the partners are Voestalpine, Nucor, Gerdau.

GISH demonstrates a steelmaking system that combines DRI technology, electric-arc steelmaking, and 'green' hydrogen production.

The project has been approved for funding from the U.S. Department of Energy in the amount of $4 million.

GISH process scheme



HYFOR

HYFOR (Hydrogen-based Fine-Ore Reduction) is a research project pioneered by Primetals Technologies, voestalpine Stahl Donawitz GmbH, Montan University Leoben and K1-MET. It is the direct-reduction process for iron-ore concentrates based on hydrogen. The technology enables to work with particles less than 0.15 mm in size, which does not require any preprocessing of the material after beneficiation.

It is planned to build a pilot plant in Donawitz. The plant will consist of three parts:

- preheating unit (iron ore concentrate will be heated to 900°C and then transferred to a recovery unit);
- hydrogen preparation unit;
- recovery unit (for hydrogen supply to reduce iron from concentrate; the waste-heat recovery system, which uses the heat of exhaust gases, will ensure optimal energy use, and the dry dust cleaning system will reduce dust emissions during production).

DRI comes out of a reduction unit with a temperature of about 600°C and can be fed to an electric-arc furnace or used for hot briquetted iron production.

Electrolysis

SIDERWIN

SIDERWIN (formerly ULCOWIN) is a project led by ArcelorMittal Maizieres Research SA, France. SIDERWIN proposes to develop a breakthrough innovation process to transform iron oxide into steel plates by means of electrolysis. When iron ore is placed in the electrolytic cell (a cell with two electrodes through which electric current is passed), iron is accumulated on one electrode, and oxygen on the other.

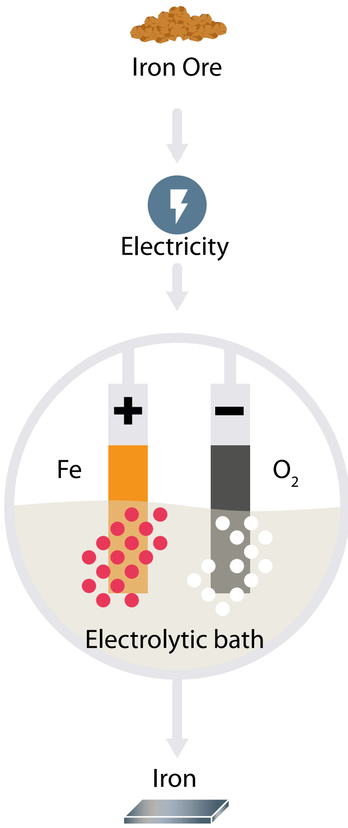
Positive impacts of the SIDERWIN technology:

- **reduction of the direct CO_2 emissions by 87%;**
- reduction of the direct energy use by 31%;
- ability to produce steel from by-products rich in iron oxides from non-ferrous metallurgy residues;
- increased integration with renewables with a more flexible process.

ArcelorMittal has been working on the iron electrolysis technology for 12 years. Over this period, 5 pilot projects have been implemented in this area. The tests showed that electrolysis of iron has significantly higher energy efficiency than electrolysis of hydrogen from water.

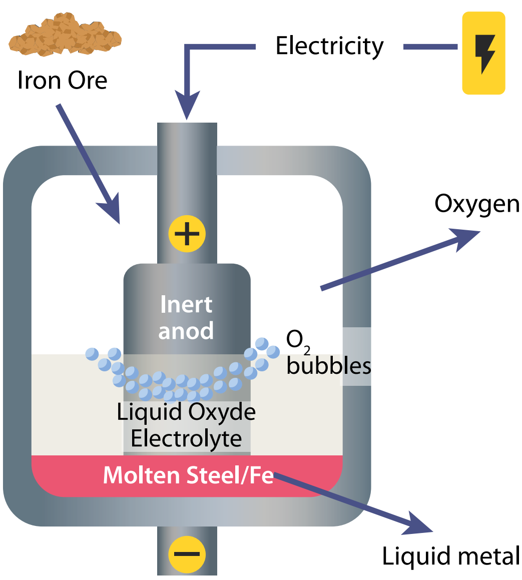
ArcelorMittal is currently working with 11 partners to build a new 3-meter pilot plant. The EU invested **€6.8 million** in the implementation of the current stage of the SIDERWIN project (1 October 2017 to 30 September 2022).

SIDERWIN process scheme



Boston Metal

Boston Metal process scheme



Boston Metal is developing electricity-based molten oxide electrolysis (MOE) technology. **The proposed technological scheme:**

1. Raw materials in solid state (iron ore, iron ore concentrate or other oxide) containing iron oxide are placed in a special chamber.
2. Iron oxide is mixed with other, more stable oxides to form a molten electrolyte.
3. Electricity is passed through the chamber to melt oxides and reduce iron.
4. Iron accumulates at the chamber's bottom and can be mixed with other metal substances before being discharged from the chamber.
5. Oxygen, released during iron reduction from oxide, is emitted into the atmosphere.

In 2020, the project was through a series of tests. Pilot testing is scheduled for 2021–2022. **The construction of the first industrial-scale plant is planned for 2024.**

The startup is actively raising venture investment. **In 2019, the company raised its first $20 million round of funding** (Breakthrough Energy Ventures affiliated with Bill Gates was among the investors). In 2021, **Boston Metal raised $50 million as part of the second round** (among the investors were Piva Capital, BHP Ventures, Devonshire Investors). In March 2021, the startup has been reported to receive funding from BMW venture fund. ►►

Other decarbonization initiatives of steel and iron ore producers

Company	Plans/intention
Liberty Steel	Liberty Steel has signed a memorandum of understanding with Paul Wurth and Stahl-Holding-Saar for the construction of a hydrogen-based steelmaking plant in Dunkirk. The project provides for the construction of a DRI plant with an annual capacity of 2 million tons of DRI and an integrated 1 GW hydrogen electrolysis unit. The DRI plant will initially use a mixture of hydrogen and natural gas, and then it will switch to hydrogen only. Direct reduced iron/hot briquetted iron will initially be used in electric-arc furnaces at Ascoval plant in France. An excess of DRI will be shipped to Liberty's plants in Ostrava and Galati, as well as to Stahl-Holding-Saar's plants in Germany
ArcelorMittal	ArcelorMittal and Vow ASA signed a memorandum of understanding to build a biogas plant. The plant is about to be built at a site of ArcelorMittal Rodange plant in Luxembourg. The two companies aim to have the biogas plant operational in 2023. Biogas will be made using Vow's patented 'Biogreen' pyrolysis technology, which involves heating sustainable biomass at high temperatures. Gases emitted during this process are then captured and processed into biogas, which will directly replace the use of natural gas in the Rodange plant's rolling mill reheating furnace. Biocoal will also be created during the process and re-used within ArcelorMittal
ArcelorMittal	AArcelorMittal will partner with Dastur Energy and MN Dastur & Co to do research on an industrial-scale solution for BFG capture. The work will focus on designing a carbon capture system capable of capturing 50–70% of CO_2 emissions from blast-furnace gas. The project will be conducted at ArcelorMittal's Burns Harbor plant in Indiana. The project budget is $1.9 million, of which $1.5 million will be funded by the U.S. Energy Ministry
Ovako	In April 2020, the company conducted a series of tests, in which billets were heated using hydrogen before rolling. LPG was replaced with hydrogen. Ovako expects this technique to cut CO_2 emissions by 20 thousand tons annually
Nippon Steel	The company announced its intention to commission a large electric-arc furnace for 'green' steel production in 2030. Nippon Steel intends to use it for partial replacement of its blast furnace capacities. Scrap and direct reduced iron will be used as raw materials for the electric-arc furnace. The EAF is expected to run on 'green' electricity
H_2 Green Steel	The company is planning to invest €2.5 billion in the construction of a fossil fuel-free steel plant in Sweden's Norrbotten region. Production is reportedly scheduled for 2024. The plant plans to have an annual production capacity of 5 million tons by 2030
BHP and JFE Steel	The company will partner with a Japanese steelmaker, JFE Steel, to explore CO_2 reduction technologies. They will study the properties of Australian raw materials, how they can help reduce emissions and improve efficiency of the BF route. BHP's investment in the project will amount to $15 million throughout five years
Mitsubishi Heavy Industries	The company is planning to build a 'green' steel plant at a site of Voestalpine in Austria. The basic technology is hydrogen-based reduction of iron ores. The plant's production capacity will be set at 250 thousand tons of steel per annum. Plans are under way to launch test operations in 2021
Rio Tinto, Nippon Steel	The companies have signed a memorandum of understanding to partner for decarbonization. The main goal is to cut CO_2 emissions along the entire steel value chain
POSCO, Fortescue	The companies have agreed to jointly produce 'green' hydrogen from renewable energy sources
Liberty Steel	The company is planning to replace four tandem furnaces with two hybrid ones by 2023 at its Ostrava plant (the Czech Republic). Environmental modernization will help reduce CO_2 emissions by 50%
BHP, Baowu	As part of a five-year partnership, the companies will develop low-carbon technologies and opportunities to reduce the intensity of greenhouse gas emissions from steel production. Specifically, BHP and Baowu will explore the opportunities of using technology for carbon capture, use and storage at a Chinese plant. The companies will also cooperate to find low-carbon fuel sources, including hydrogen, for the BF route of steelmaking. BHP's investment in the project will amount to $35 million
Dillinger and Saarstahl (SHS Group)	The companies have started to inject hydrogen, either in the form of pure hydrogen or as hydrogen rich gases such as coke oven gas, into blast furnaces. Dillinger and Saarstahl invested €14 million in the project

Steelmakers set ambitious emission reduction targets

With the help of governments, steelmakers set ambitious goals to curb CO_2 emissions. The year 2050 has become a kind of benchmark for achieving carbon neutrality. ■

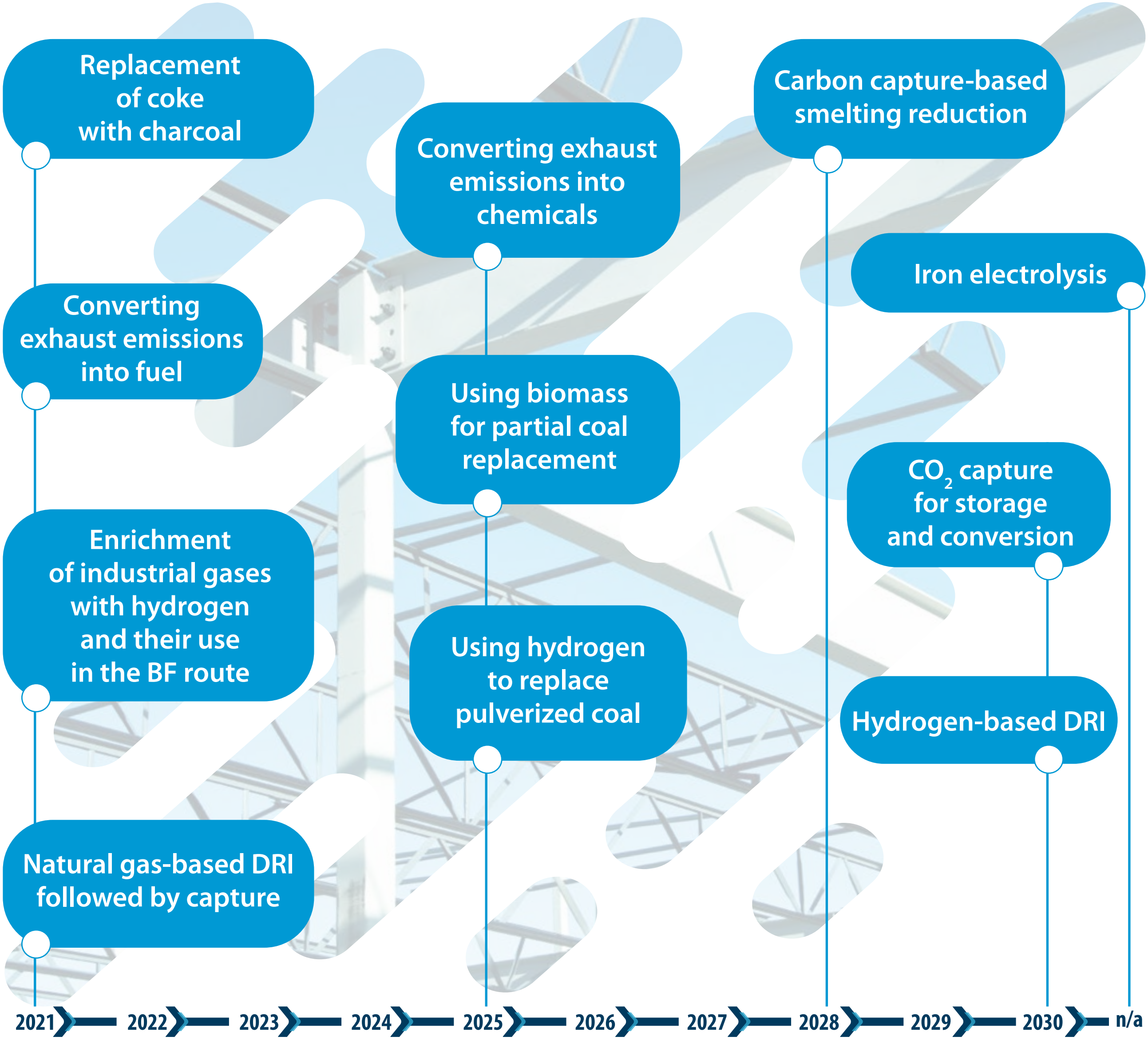
Steelmakers' plans to cut CO_2 emissions

Source: companies' data

The steel industry will radically change in 2050–2070

According to the IEA, the most important technologies for reducing greenhouse gas emissions will be commercially available not before 2030. The targets to cut GHG emissions by 2030 could therefore be achieved only through more intensive use of scrap and energy efficiency improvement measures.

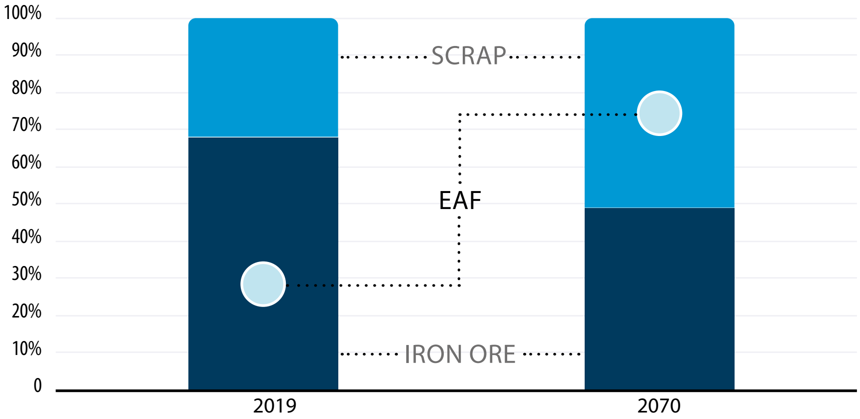
Time frames for the development of decarbonization technologies



Source: IEA

To date, a more intensive use of scrap is deemed to be the most affordable way to reduce GHG emissions. There are favorable preconditions for developing the EAF steel production process in a number of regions, as scrap availability is expected to surge.

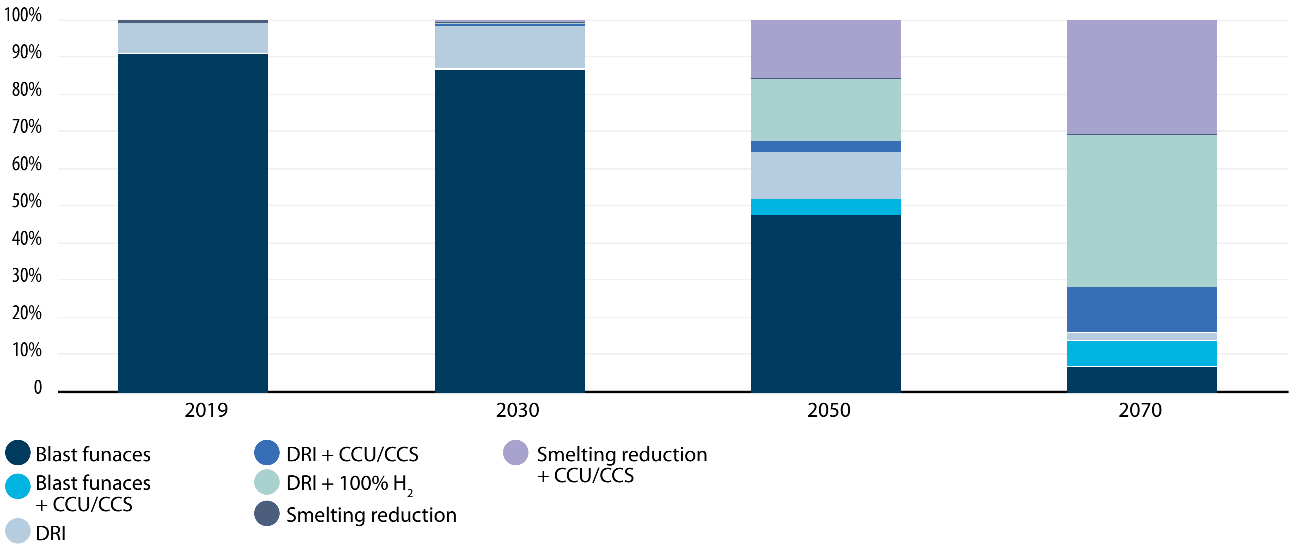
Structure of global steel production by raw material types, %



Source: IEA, Sustainable Development Scenario

According to the IEA's Sustainable Development Scenario, the share of EAF steel output will increase from 29% in 2019 to 75% by 2070, while the share of scrap steel output will reach just 51%. The gap between the shares of EAF and scrap steelmaking creates a potential for DRI to grow, up to 25% in the total global steel production and over 50% in the total global iron ore-based steel production. In other words, iron ore will continue to play a significant role in the steel industry of the future, with respective production technologies dramatically changed.

Projected structure of iron ore-based steel production, %



Source: IEA, Sustainable Development Scenario

2021–2030. No significant changes in technologies are expected until 2030. Throughout this period, conditions will be created for the accelerated development of DRI production, with an 8% to 12% increase of its share in iron ore-based steel production. Most of the emerging technologies will only enter the stage of commercial testing by 2030. Until 2030, the main ways to reduce emissions will be greater use of scrap and implementation of energy efficient measures.

2031–2050. More radical changes could be anticipated in 2030–2050. By 2050, the share of the traditional BF route will decline to 48%. The DRI technology will be significantly developed, with a 32% share in iron ore-based steel production. Most steel will be produced using hydrogen instead of natural gas. Carbon capture technologies will not play a significant role in DRI production until 2050. Throughout this period, DRI emissions charges are likely to be lower than a hike in carbon capture costs. Capture technologies will not be widely applied in the BF route due to the difficulties associated with a large number of emission sources and, consequently, lower capture efficiency. By 2050, smelting reduction technologies will have a significant share in steel production — 16%, which is associated with lower production costs compared to DRI. ►►

2050–2070. By 2070, the industry will dramatically change. Traditional blast furnaces will virtually cease to exist, their share in iron ore-based steelmaking and in the total steel production will be minimal, 7% and 3.5% respectively. Capture technologies will not be widely used in BF steel production, 7% in the total iron ore-based steel production. Almost all traditional DRI assets will be equipped with capture installations, 12%. The hydrogen-based DRI will be the key technology for iron ore-based steel production, 41%. In total, the share of DRI technologies in iron ore-based steel production will be 55%. In 2050–2070, the output of steel produced by smelting reduction with carbon capture will almost double and exceed 30%. This means that in 2070, steel will be produced either from scrap or iron ore using hydrogen or capture technologies.

Key solutions for decarbonizing the steel industry

Source: IEA, GMK Center estimations

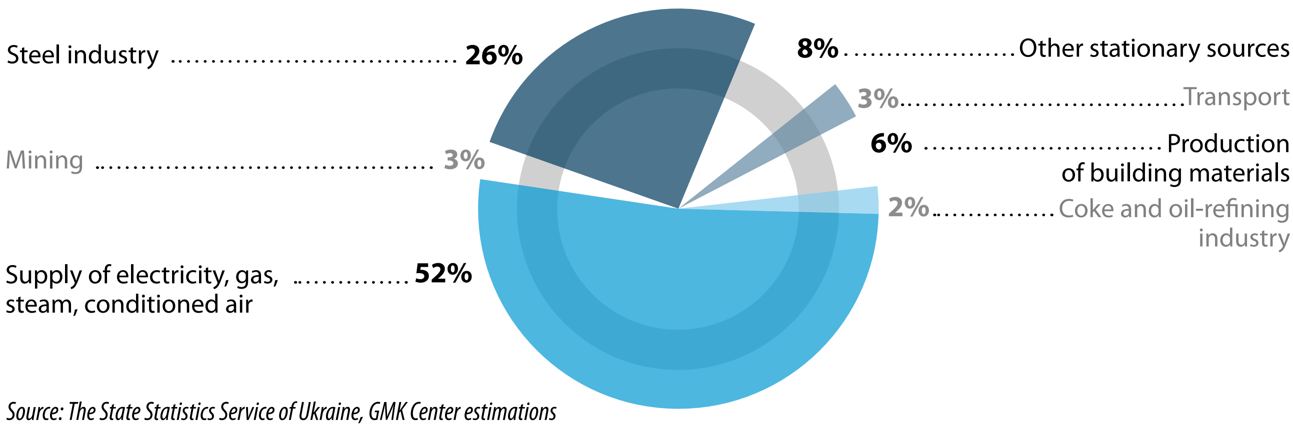
The importance of vertical integration with electricity and hydrogen production will considerably increase and replace integration with raw materials producers in the years to come. Some companies, along with projects to launch low-carbon technologies in steelmaking, are implementing projects or partnerships for hydrogen production and electricity generation from renewable sources. The examples include Thysenkrupp's partnerships with RWE and STEAG for 'green' hydrogen production, ArcelorMittal Bremen's partnership with EWE energy company, construction of Salzgitter's own wind turbine fleet, GrInHy's R&D project, Posco and Fortescue partnership for joint production of hydrogen, ArcelorMittal's 'hydrogen consortium' with 11 global companies, etc.

The IEA forecasts show global carbon-free steel production could be achieved only by 2070. The World Steel Association's representatives share this opinion, voicing doubts that even the EU will be able to switch to carbon-neutral steel production by 2050. The transition time frame will depend on a number of factors independent from the steel industry, in particular on electricity and hydrogen availability and prices. ■

Ukraine is actively contributing to the decarbonization process

Ukraine also intends to follow a decarbonization path, though at a slower pace. In January 2020, Ukraine's Green Energy Transition Concept was presented. Its main goal is to achieve carbon neutrality of the national economy by 2070. At the same time, the Ukrainian and global emission structures differ: **26% against 6% of CO_2 emissions from the steel industry.** Hence, the role of the steel industry in decarbonization of the Ukrainian economy is much higher than the global average.

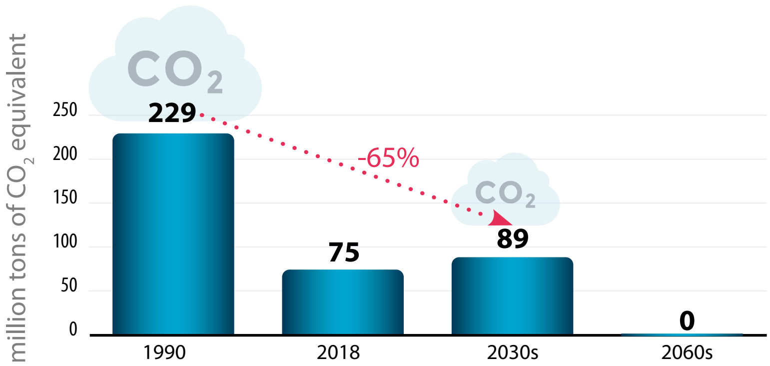
Structure of CO_2 emissions in Ukraine in 2019 by industries



Source: The State Statistics Service of Ukraine, GMK Center estimations

In April 2021, a draft of the Second Nationally Determined Contribution (NDC 2) under the Paris Agreement was presented. According to it, Ukraine is to cut CO_2 emissions by 65% by 2030 compared to 1990, including industrial emissions by 61%. Although a separate target for a cut in carbon dioxide emissions has not been set for the steel industry, the results of simulations made in the process of development of NDC 2 show that steelmaking will account for 88% of the total industrial GHG emissions reduction. Based on the results of the same estimations, **iron and steel works need to invest a total of €7.7–8.3 billion in 2021–2030 in order to achieve this target.**

CO_2 emission reduction targets for Ukraine's industries under NDC 2

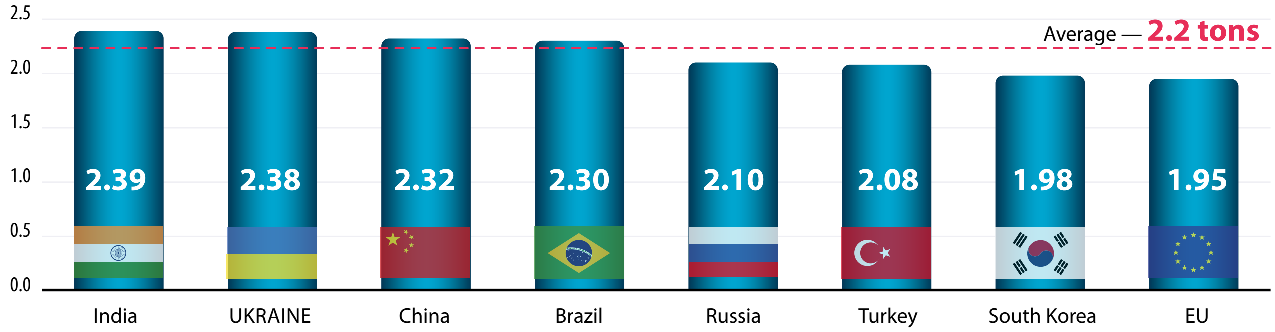


Source: the Ministry of Environmental Protection and Natural Resources of Ukraine, GMK Center estimations

NDC 2 also sets a tougher target to have a carbon-neutral economy than the Green Energy Transition Concept: 2060 against 2070. Consequently, expectations on the rate of reduction of CO_2 emissions by Ukrainian iron and steel works are gradually increasing.

Specific CO_2 emissions of Ukrainian steel producers were 8% higher than the world average as of 2020. To date, this minor difference does not pose risks for the businesses, but evidences a greater potential for curtailing emissions. Maximum emissions in the BF-BOF route are just 22% higher than their minimum rate. ►►

CO_2 emissions in BF-BOF steel production (scope 1 + scope 2), ton per ton of steel



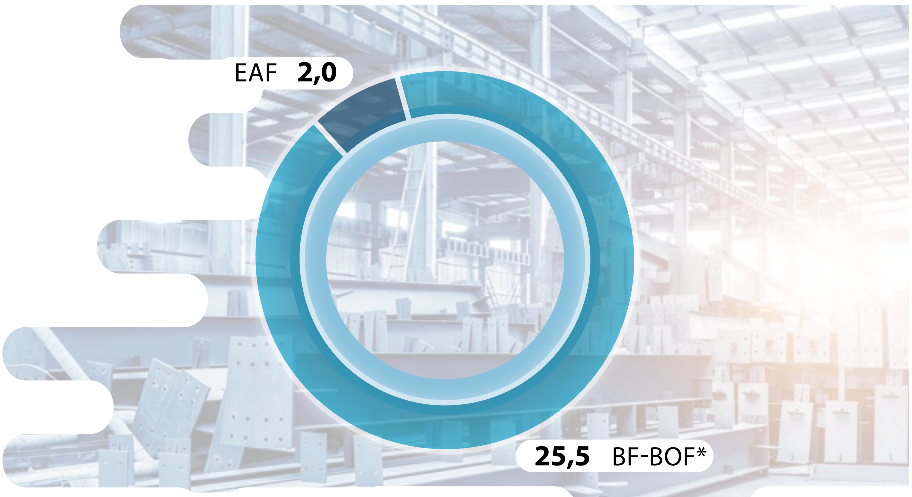
Source: companies' data, media, GMK Center estimations

Though the ambitious plans of global steel companies to achieve carbon neutrality by 2050 put pressure on Ukrainian steelmakers. To successfully compete in foreign markets, Ukrainian producers also need to have CO_2 emission reduction targets and decarbonization strategies.

The imposition of the CBAM (Carbon Border Adjustment Mechanism) in the EU is an additional factor urging Ukrainian companies towards decarbonization to have access to the EU market. If Ukrainian steelmakers fail to cut CO_2 emissions, their products will be non-competitive due to additional carbon border fees.

Based on the above projects and benchmarks, steelmakers will have to pay $1,000 per ton of BOF capacity to go carbon neutral. BOF and OHF capacities in Ukraine totals 25.5 million tons per annum. **Hence, Ukrainian steel producers will need to spend $25 billion in capital investment for decarbonization. The main investment load will fall on 2030–2070.**

Structure of steelmaking capacities in Ukraine, million tons



** including the OHF route*

Source: GMK Center estimations

25.5 million tons

BOF and OHF capacities in Ukraine

$1,000

CAPEX per ton of steelmaking capacity

$25.5 billion

CAPEX to achieve carbon neutrality of the Iron&Steel industry of Ukraine

As a developing economy, Ukraine cannot lead the decarbonization process. For objective reasons, Ukrainian companies cannot develop new steel production technologies on their own. Full decarbonization of Ukraine's steel industry can therefore be launched as soon as carbon-free technologies ready for commercialization are available in the market. In a short-term perspective, Ukrainian companies can reduce CO2 emissions through improving energy efficiency.

Risks and opportunities of decarbonization of Ukraine's steel industry

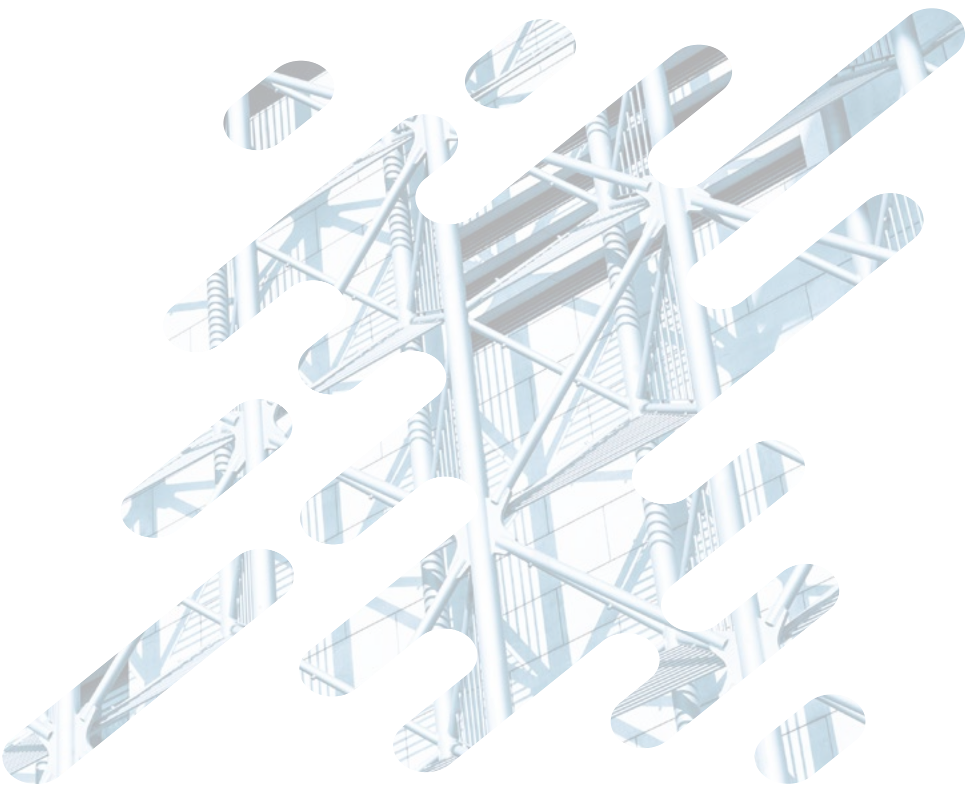
Risks

1. Ukraine's capabilities to develop EAF steelmaking are limited because of insufficient scrap resources due to weak investment processes in the economy
2. Decarbonization of both the steel industry and energy sector is a capital-intensive process. Funding difficulties may negatively affect the sustainability of companies
3. A delay in the development of 'green' energy and 'green' hydrogen production may lower the competitiveness of Ukraine's steel industry, since access to cheap electricity will be a key advantage
4. The success of decarbonization directly depends on a policy pursued by the government. An excessive fiscal burden and lack of incentives will slow down the process of Ukraine's decarbonization

Opportunities

1. Development of DRI-based EAF steelmaking requires investments along the entire route (iron ore production, construction of electric-arc furnaces, hydrogen production)
2. The raising of funding from the EU under the Green Deal, access to funds generated from CBAM fees
3. The active development of low-carbon, cheap electricity and hydrogen production. The stake will be on the use of the smelting reduction technology, although the prospects for its use have not been studied so far.
4. If Ukraine seeks to achieve the same results in the area of decarbonization as the EU, it should use the same tools as the EU

It should be noted that due to competitive advantages (iron ore reserves, skilled workers, logistics advantages), Ukrainian suppliers have successfully integrated into global added value chains in the steel industry; it is therefore important that Ukrainian producers can maintain their market positions throughout the decarbonization process. ■



METINVEST

About the Metinvest Group

Metinvest is an international vertically integrated group of steel & mining companies. The Group controls mining and metallurgical assets in Ukraine, Europe and the U.S., complemented by a global sales network. Metinvest manages the entire production chain, from iron ore and coal mining to production of semi-finished and finished steel products. With assets close to key railway lines and ports, Metinvest can supply raw materials and steel products anywhere in the world.

Metinvest in figures, 2020

No. 45
World's largest steel producers

No. 11
World's largest iron ore producers

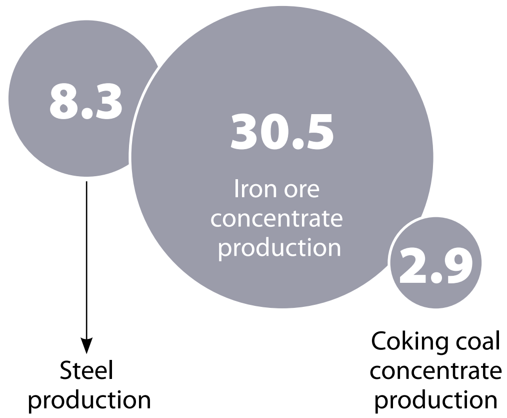
92,000
Number of employees*

22
Operational and repair assets

45
Sales offices and service centers

10,000
Consumers

Operational highlights, 2020 (million tons)



Social responsibility

For the Metinvest Group, social responsibility means being responsible for our actions and assessing their impacts on local communities. We adhere to the principles of sustainable development in all areas of our work.

$204 million
Environmental CAPEX in 2020

+31.6%
Growth of environmental CAPEX y-o-y

30.8%
Contribution of environmental CAPEX to total CAPEX in 2020

₴22.1 billion
Taxes paid in 2020*

$106 million
Investments in labor protection in 2020

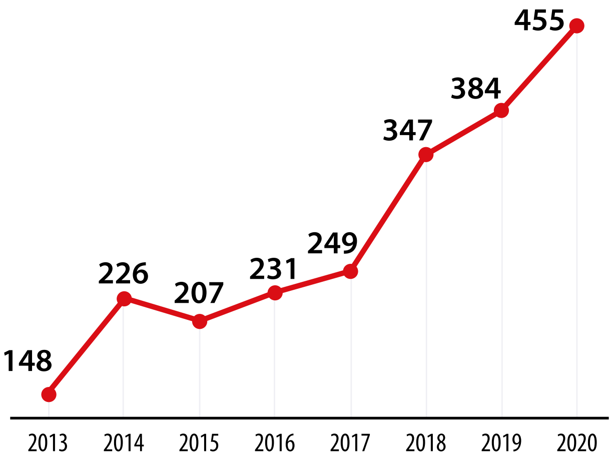
$15.4 million
Social investments in the development of areas of presence in 2020

** including joint ventures and associates*

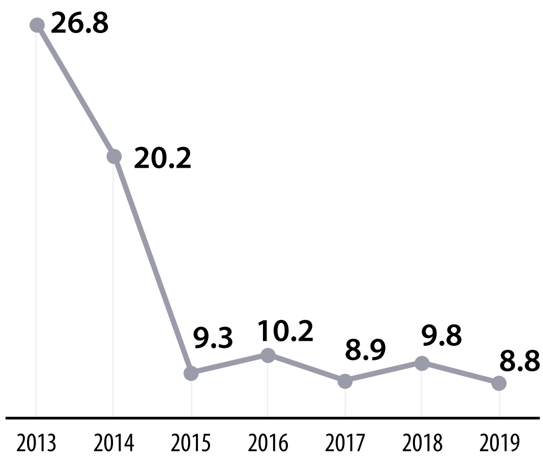
Key strategic CAPEX projects in 2020

Ilyich Iron and Steel Works	Reconstruction of the gas cleaning system at the sinter plant	90% reduction in dust emissions 46% reduction in SO_x emissions
Azovstal	Reconstruction of the gas cleaning systems for basic oxygen furnaces No. 1 and No. 2	70% reduction in dust emissions
Northern GOK	Replacement of gas cleaning units of Lurgi 552-A roasting machine	40% reduction in dust emissions

Environmental protection costs (CAPEX + OPEX), $ million



GHG emissions in CO_2 equivalent, million tons



ESG rating of Metinvest Group

SUSTAINALYTICS

31.7

In April 2021, Metinvest has improved its ESG risk rating by Sustainalytics from 32.0 to **31.7** on a scale between **0** (lowest risk) and **100** (highest risk).

While the risk of experiencing material financial impacts driven by ESG factors was assessed as high due to the steel industry's significant exposure, Sustainalytics recognized the Group's management of material ESG issues as strong. Sustainalytics noted the high quality of the programs, practices and policies of the Metinvest Group.

The agency added that the Metinvest Group's ESG report is in line with the best practices, which implies a high degree of accountability to all stakeholders.

Metinvest's ESG reports are based on the **Global Reporting Initiative (GRI)** international non-financial reporting standards and the recommendations of the **Sustainability Accounting Standards Board (SASB)**.

Stanislav ZINCHENKO:

"Ukraine should adhere to all the best practices in decarbonization policy"

Stanislav Zinchenko,
Director of GMK Center,
Head of the Committee
on Industrial Ecology and
Sustainable Development of the
European Business Association

Our study shows that decarbonization is not a tribute to fashion. Decarbonization is the process for the coming decades. It will affect not only steelmakers, but also all economic and industrial entities that need to ramp up capital investment to cut CO_2 emissions.

Decarbonization of the steel industry will first and foremost require supply of carbon-neutral energy. **Therefore, the electricity sector will be the first to embark on the path to low-carbon development.** Research organizations will have much to do to develop state-of-the-art low-carbon technologies for steel production. Equipment manufacturers and engineering companies need to find technical solutions to commercialize new technologies. **Consumers should be prepared for a hike in prices for metal products** and understand that additional costs are the price for a new economy, consistent with the principles of sustainable development.

The state as a system of official institutions of power plays a special role in the decarbonization process. **The state is supposed to encourage economic development and improve the environment. All tools of economic policy, ranging from regulatory to fiscal ones, are centered in the hands of the state. Hence, a pace and effectiveness of decarbonization depend on its actions.**

A live discussion is under way in the EU on what public decarbonizing policies should be like. Talking with European steelmakers at international conferences, we hear that they are dissatisfied with the actions of the European Commission and EU governments. Until recently, the EU decarbonization policy has mostly implied restrictive and fiscal measures, with no fundamental changes occurred. An emphasis shifted at the end of the 2019 — the European Commission developed a large-scale investment plan seeking carbon-neutral status of economies of Member States thus offering cautious optimism.

Ukraine makes efforts to follow European trends. It is very important on this path not to repeat the others' mistakes and adopt only the best and most effective methods and techniques. Although the European Union is ahead of Ukraine in terms of decarbonization, this enables our country to have the best unique European experience.

Ukraine is an industrial country. We hope it will remain in this status. To this end, the decarbonization process must be constructive, not destructive. **As a matter of fact, decarbonization can create conditions for the emergence and development of new companies, sectors and jobs.** At the same time, decarbonization can result in the closure of entire industries if Ukraine follows a path of restrictions and bans that actually offer advantages to our competitors.

We hope that our study will help all climate change stakeholders understand decarbonization and turn it into a creative process. Decarbonization shapes the steel industry of the future. This future depends on our joint effort. ■

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