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Focus

Roland Berger

The future of steelmaking – How the European steel industry can achieve carbon neutrality

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The future of steelmaking / *How the European steel industry can achieve carbon neutrality*

The European steelmaking industry emits 4% of the EU's total CO_2 emissions. It is under growing public, economic and regulatory pressure to become carbon neutral by 2050, in line with EU targets. About 60% of European steel is produced via the so-called primary route, an efficient but highly carbon-intensive production method. The industry already uses carbon mitigation techniques, but these are insufficient to significantly reduce or eliminate carbon emissions. The development and implementation of new technologies is underway.

With limited investment cycles left until the 2050 deadline, the European steelmaking industry must decide on which new technology to invest in within the next 5-10 years. We assess the most promising emerging technologies in this report. They fall into two main categories: carbon capture, use and/or storage (CCUS), and alternative reduction of iron ore. CCUS processes can be readily integrated into existing steel plants, but cannot alone achieve carbon neutrality. If biomass is used in place of fossil fuels in the steelmaking process, CCUS can result in a negative carbon balance.

Alternative reduction technologies include hydrogen-based direct reduction processes and electrolytic reduction methods. Most are not well developed and require huge amounts of green energy, but they hold the promise of carbon-neutral steelmaking.

One alternative reduction process, H_2-based shaft furnace direct reduction, offers particular promise due to its emissions-reduction potential and state of readiness. It is the technology that we envisage steelmakers will pursue in order to achieve carbon neutrality. H_2-based shaft furnace direct reduction is ready to use and can be introduced step-by-step into brownfield plants. This ensures operational continuity and reduced emissions during the transition from conventional steelmaking methods.

A full transition is only achievable through high CAPEX and a plentiful supply of green electricity. To switch the approximately 30 million tons per annum of steel produced via the primary route in Germany to H_2-based shaft furnace direct reduction would require estimated capital expenditure of about EUR 30 bn at current prices. In addition, electricity production of 120 TWh per annum would be required, a figure roughly equal to half the amount of green electricity Germany produced in 2019. Political support is therefore vital if the European steel industry is to achieve carbon neutrality. Without it, large parts of the steelmaking value chain may move abroad.

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Cover photo sdlgzps/Gettyimages

1 / Feeling the heat

THE CLIMATE CHALLENGE FACING EUROPEAN STEELMAKERS

The European steelmaking industry is under pressure. In November 2018, the European Commission announced a new long-term strategy on climate protection, aimed at fulfilling the targets of the UN's 2015 Paris Agreement. It calls for a climate-neutral Europe by 2050, implying net zero greenhouse gas emissions by that date. This means a 100% reduction of carbon emissions, or the introduction of compensatory carbon-negative processes.

Conventional steel production is one of Europe's biggest sources of CO_2 emissions. The continent's steel industry currently contributes approximately 4% of total European CO_2 emissions, and 22% of industrial CO_2 emissions. Energy- and carbon-hungry upstream operations, such as the production of coke and iron, account for approximately 90% of these. Most emissions come from the 30 or so integrated steel plants that produce almost two-thirds of Europe's steel.

THE STATUS QUO

The majority of European steel (60%) is made via the primary route. It involves processing iron ore to produce iron sinter or pellets, and then melting these in a blast furnace (BF) with coke to make pig iron. This is processed in a basic oxygen furnace (BOF) to create steel. The rest of Europe's steel comes from the secondary route. It produces steel from scrap metal by heating it in an electric arc furnace (EAF). → A

Primary route processes emit mainly direct greenhouse gases. The secondary route emits mainly indirect greenhouse gases, which vary depending on the electricity mix used in the EAF. As the biggest offender, the primary route is the industry's main target to lower emissions. With global production of crude steel set to rise by 30-50% by 2050 according to an OECD long-term study, it has already taken action.

Methods such as coke dry quenching and optimizing pellet ratios, as well as BF equipment like top gas recovery turbines, reduce conventional primary route carbon emissions. Replacing coke with natural gas can also significantly cut CO_2 in primary steelmaking, as can injecting hydrogen or ammonia into the BF to partly replace pulverized coal. However, many of these initiatives are already standard across the industry. And none can ever achieve carbon neutrality because they don't completely remove carbon from the steelmaking process.

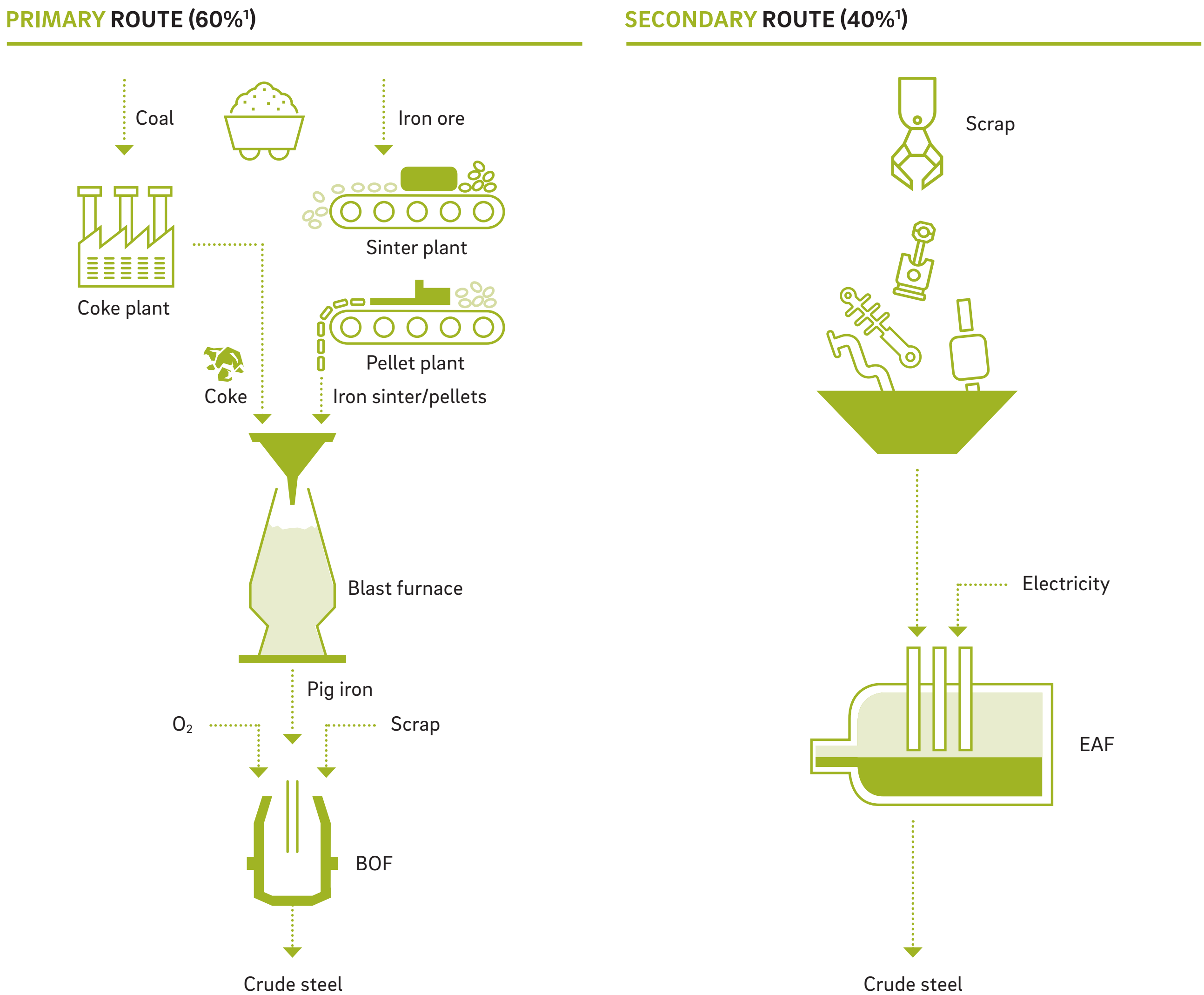
Lower secondary route emissions can be achieved by making savings on the electricity used to power the EAF, or shifting the electricity mix towards renewables. This, in theory, makes carbon neutrality possible. The problem is, the secondary process is limited by the availability of scrap, and cannot produce all steel grades or required quantities.

TIME TO ACT

To meet the European Commission's goals, there is therefore a clear need for a new breed of primary route technologies that can produce carbon-neutral steel. Many of these are already in development, with some in the pilot phase and others technologically ready to go. The challenge for the European steel industry is to identify and support the right one. With only very few investment cycles left before 2050, massive development expenditure and CAPEX expected, and a variety of possible solutions, this is no easy decision. But it has to be made in the next five to ten years.

A: Making steel

The primary and secondary routes account for all European steel production (simplified)



[1] Share of production in Europe

Source: Eurofer, EEA, Roland Berger

2 / Cutting carbon

THE MOST PROMISING NEW TECHNOLOGIES COMPARED

Emerging technological solutions designed to reduce or eliminate carbon emissions from the steelmaking process can be divided into two distinct categories: carbon capture, use and/or storage (CCUS), and alternative reduction of iron ore.

CCUS employs different methods to capture CO_2 emissions and either process them for onward utilization (for example, as fuel) or store them (for example, in geological formations such as exhausted undersea gas reservoirs). Alone, CCUS cannot achieve carbon neutrality. But it could yield a negative CO_2 balance if fossil fuels used in the steelmaking process are replaced by biomass.

The second range of potential technologies involves replacing coke or natural gas with alternative reductants of iron ore. These include hydrogen (H_2) and direct electric current. Their advantage is that they can, in theory, make steel production fully green. However, most will likely require even more time and money to set up than CCUS.

Below, we assess a selection of the most promising of the new CCUS and alternative reduction technologies, including their pros and cons and examples of pilot projects. We also compare each against key criteria, such as industrial production readiness, expected duration until plateau of productivity, development and operating costs, and CAPEX requirements.

In the next chapter, we use this analysis to offer insight on which technology to pursue – H_2-based shaft furnace direct reduction – and give our reasons for it.

2.1 CARBON CAPTURE, USE AND/OR STORAGE

How it works: CO_2 is separated from other gases and captured during heavily emitting processes, such as ironmaking. The captured CO_2 is then either transported via a pipeline or ship to an onshore or offshore storage location (in Europe, old North Sea gas fields have huge potential) or used, for example as fuel or biomass. Processes include post/pre-combustion capture, and compression-transport-store/use. → B

Pros: The main advantage is that CCUS systems can be fairly easily integrated into existing conventional brownfield plants. And as the technology is not specific to steelmaking, other industries can share development and infrastructure costs (for example, around the synthetic fuel market, transportation and storage). Also, future operating costs are largely predictable.

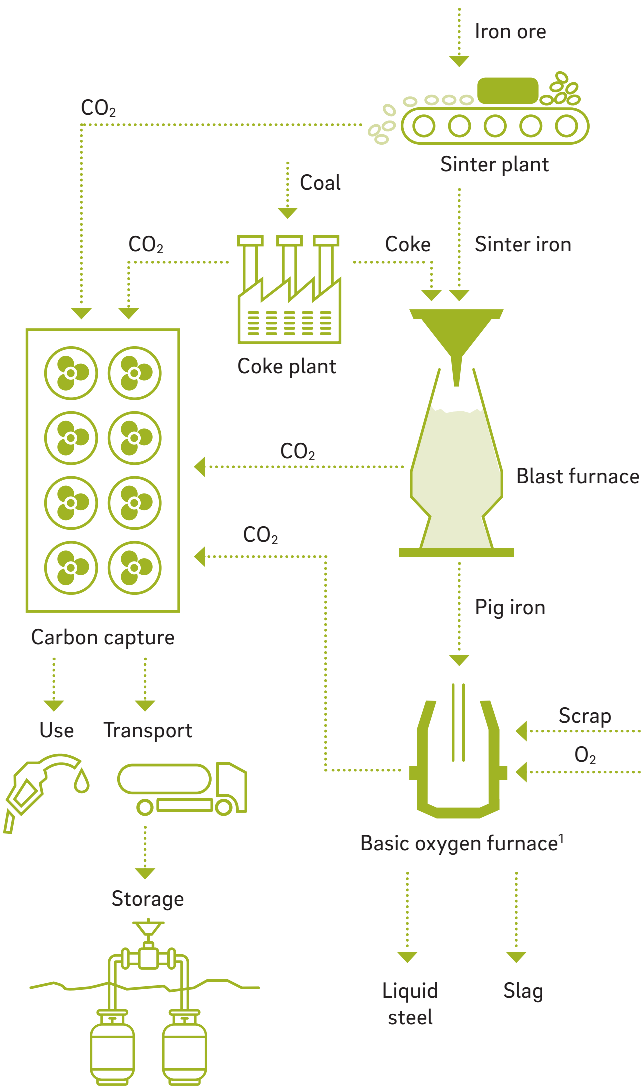
Cons: As well as the fact that CCUS is not fully carbon neutral, as the carbon capture process alone captures only about 90% of CO_2, there are several other challenges. Public acceptance of carbon storage is not guaranteed, disadvantaging first movers. And currently, excepting minor onshore storage locations, the North Sea offers the only suitable large storage location in Europe, necessitating considerable transportation efforts. In addition, utilization of emissions must rule out carbon release at a later stage for the process to be carbon neutral. CCUS equipment also increases maintenance burdens and shutdown times with a significant impact on operating costs.

Pilot projects: The Carbon2Chem project, backed by industrial conglomerate thyssenkrupp, is piloting the processing of emissions such as CO_2 to make synthetic fuel. But this is currently not carbon neutral as CO_2 is emitted at a later stage.

2.2 BIOMASS-BASED IRONMAKING WITH CCUS

How it works: The basic idea is that carbon-neutral biomass partially replaces fossil fuels in preprocessing or as an iron ore reductant. For example, carbon-rich 'chars' made from raw biomass (raw algae, grass, wood etc.) are used to produce a substitute coke, or biogas is injected into a shaft furnace instead of natural gas. Processes include pyrolysis and hydrothermal carbonization. CCUS systems mop up any remaining carbon emissions.

B: Carbon capture, use and/or storage
The production route (simplified)



[1] Incl. secondary metallurgy

Source: Roland Berger

Pros: Biomass alone can cut up to 40-60% of CO_2 emissions, and in combination with CCUS can achieve carbon-neutral steelmaking. In the shorter term, biomass is an instant partial replacement for fossil fuels, allowing quick-win emission reductions at existing plants. CO_2 from emissions can also be recycled using CCUS to produce fresh biomass.

Cons: Cultivation of biomass is problematic. Environmentally, it can lead to deforestation, pollution and reduced biodiversity, and socially, increased food prices and agricultural land use. Political and social acceptance therefore has a high risk. In addition, biomass has a lower calorific value than fossil fuels, limiting its use in large blast furnaces or lowering efficiencies. And due to its high water content, it can also be too heavy for use in large blast furnaces.

Pilot projects: A biomass study by the Swedish research group SWEREA at an SSAB steel plant in Luleå identified potential for a 28% reduction in CO_2 emissions.

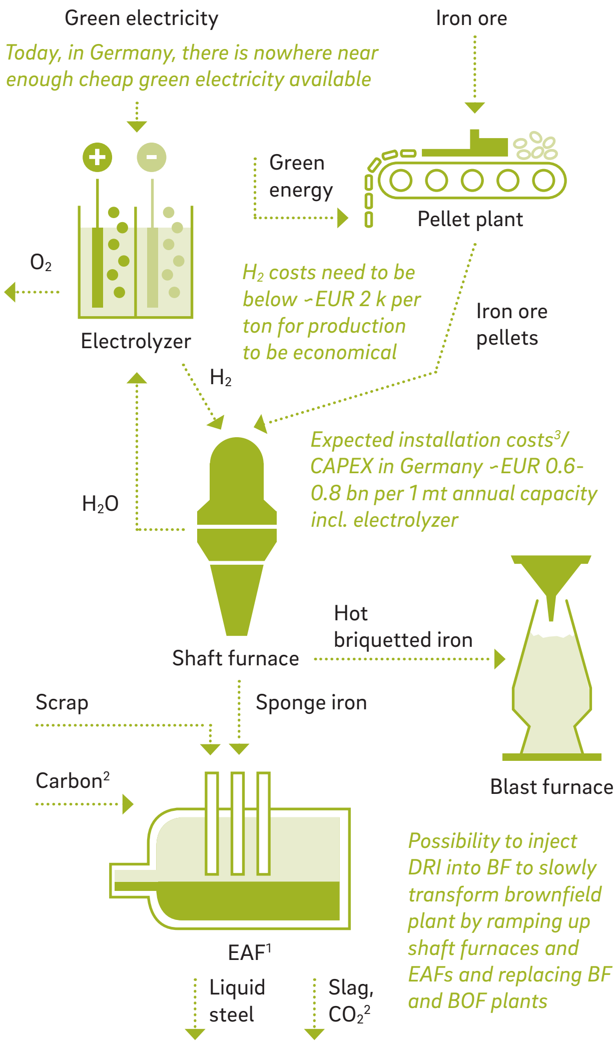
2.3 H_2-BASED DIRECT REDUCED IRON – SHAFT FURNACE

How it works: Instead of a carbon reductant such as coke, H_2 is used to reduce iron ore pellets to "direct reduced iron" (DRI, or sponge iron). The reaction takes place in a shaft furnace, a type of furnace that uses gas reductants to make DRI. The operating temperature can be fairly low, around 800°C. The DRI is then fed into an EAF and turned into steel by further processing it and adding carbon. As an interim technology to pave the way towards carbon-neutral steelmaking, it can also be fed into a blast furnace in the form of "hot briquetted iron" (HBI), a high-quality DRI. This significantly increases the blast furnace efficiency and reduces coke usage. The most common processes are the MIDREX method and Tenova's HYL. → C

Pros: If powered solely by green electricity, the process makes the whole primary steelmaking route carbon neutral and fossil fuel-free. Other benefits include high

C: H_2-based direct reduced iron – Shaft furnace

The production route (simplified)



[1] Incl. secondary metallurgy
[2] Adjust desired carbon content between 0.002% and 2.14%
[3] In today's monetary value

Source: Roland Berger

production flexibility: the process is easy to start and stop, and the ability to use smaller units enables greater scalability. In addition, the ability to feed DRI as HBI into a BF-BOF system means existing conventional brownfield plants can be used while shaft furnace/EAF production is ramped up.

Cons: The process still requires iron ore pellets, and producing them can cause significant emissions depending on the heat source of the pellet plant. Supplying the necessary amount of H_2 is also a problem and efficient large-scale electrolyzers need to be developed. In addition, as the process relies on vast amounts of cheap green energy, steel producing countries like Germany must import H_2 or pre-processed iron, hurting their value chains, if they fail to significantly ramp up their own green energy production. There is also uncertainty around future operating costs, for example relating to H_2 and electricity prices.

Pilot projects: The EU-funded Project GrInHy 2.0, which involves several firms including Tenova, Salzgitter and Paul Wurth, aims to develop the world's largest H_2-producing steam electrolyzer for use in MIDREX and HYL.

2.4 H_2-BASED DIRECT REDUCED IRON – FLUIDIZED BED

How it works: As with the shaft furnace version, this method uses H_2 to reduce iron ore and produce DRI to feed into an EAF. The differences are that reduction occurs in a fluidized bed rather than a furnace, and finely processed iron ore powders (fines) are used instead of pellets. Fluidized beds are reactor chambers that can continuously mix solid feedstocks with a gas to produce a solid. There are several possible processes, including FINEX and Circored. → D

Pros: The use of fines over iron pellets has the advantage of removing the need to pelletize, cutting costs and the high CO_2 emissions involved in the process. In addition, fluidized bed reactors have fewer internal sticking problems than shaft furnaces, achieving higher metallization (approx. 95% to 90%).

Cons: The process shares the same H_2 supply, electrolyzer and operating cost problems as the shaft furnace method. Its electricity supply must also be 100% green to achieve carbon neutrality. In addition, the use of fluidized bed reactors in steelmaking is less developed than shaft furnaces, requiring higher investment.

Pilot projects: Outokumpu, the Finland-based stainless-steel producer, began production of an H_2-DRI plant using the Circored process in Trinidad and Tobago in 1999 (today, it is owned by ArcelorMittal and has been idle since 2015). It can produce up to 65 tons per hour of hot briquetted iron.

2.5 SUSPENSION IRONMAKING

How it works: The process begins with the ultrafine grinding of low-grade iron ore to produce iron ore concentrate. This is then reduced using hydrogen in a high-temperature "flash" reactor for just a few seconds, directly producing steel once carbon is added. The iron ore concentrate can also be pre-reduced at a lower temperature in a separate reactor before being added to the flash reactor. → E

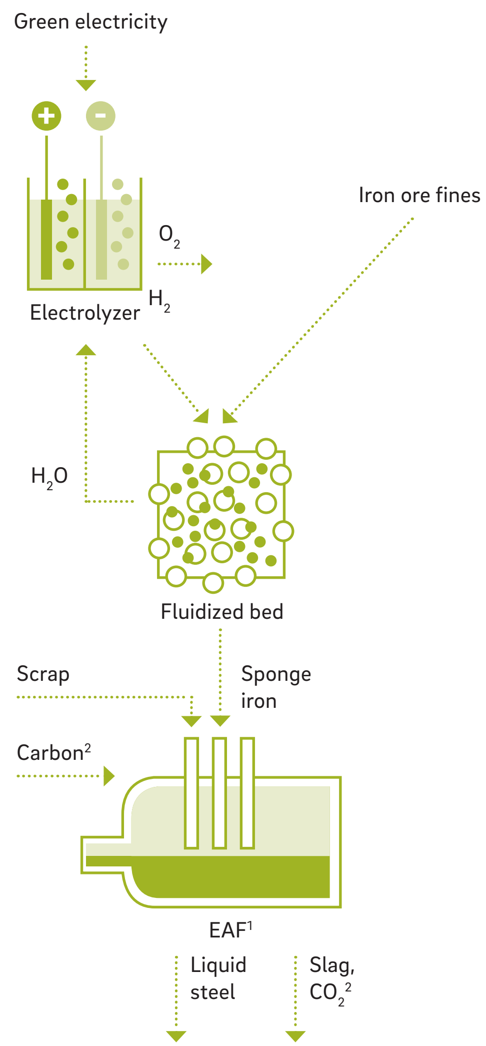
Pros: The direct reduction of iron ore to steel in one reactor, removing the need for ironmaking, sintering or pelletization, has significant cost and emission benefits. It also produces "cleaner" steel as the high temperatures and fast reaction times ensure fewer impurities.

Cons: The technology is not well developed and is still at an experimental stage, with no large-scale reactor tests yet conducted. As a result, the process is a long way from commercialization and will require significant investment. From a practical point of view, the iron ore must be ground to particles of <100 micrometers in diameter, requiring high energy intensity and increased plant maintenance.

Pilot projects: The University of Utah in the USA has

D: H_2-based direct reduced iron – Fluidized bed

The production route

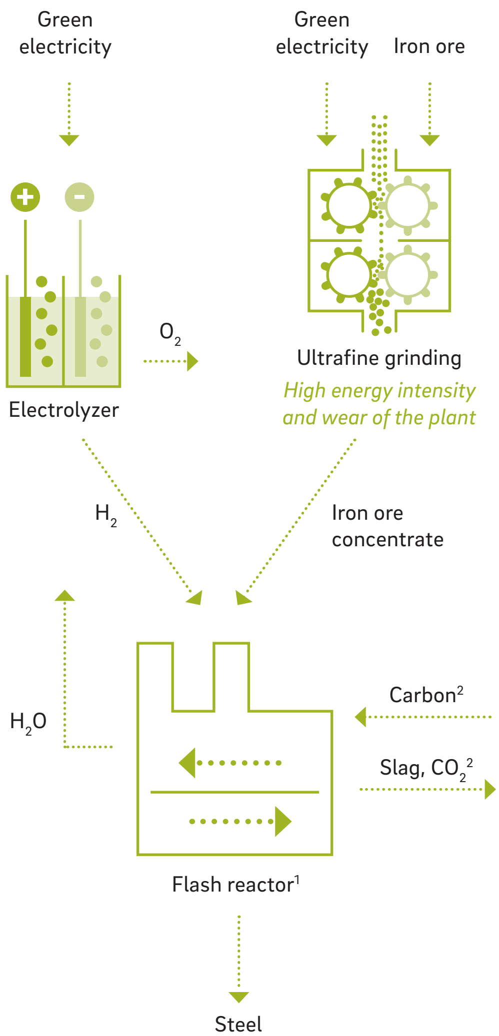


[1] Incl. secondary metallurgy

[2] Adjust desired carbon content between 0.002% and 2.14%

Source: Roland Berger

E: Suspension ironmaking
The production route (simplified)



[1] Incl. secondary metallurgy
[2] Adjust desired carbon content between 0.002% and 2.14%

Source: University of Utah, Roland Berger

conducted proof-of-concept tests in laboratory reactors and is developing the process and reactor design for industrial use.

2.6 PLASMA DIRECT STEEL PRODUCTION

How it works: Iron ore, raw or in the form of fines or pellets, is reduced using hydrogen plasma in a plasma steelmaking reactor. At the same time, carbon is added to the reactor to produce steel. Hydrogen plasma is H_2 gas that has been heated or electrically charged to separate, or ionize, it into its constituent particles. The process may use either thermal plasma (produced by directly heating H_2) or non-thermal plasma (produced by passing a direct current or microwaves through H_2). → F

Pros: The process removes the need for preprocessing of iron ore and allows for lower reactor temperatures. It is also highly integrated, with some methods (for example, hydrogen plasma smelting reduction) requiring only a single step. This makes it commercially attractive: if the technology was ready to use today, it would have the potential to reduce costs significantly, as well as offering higher product quality and better production flexibility.

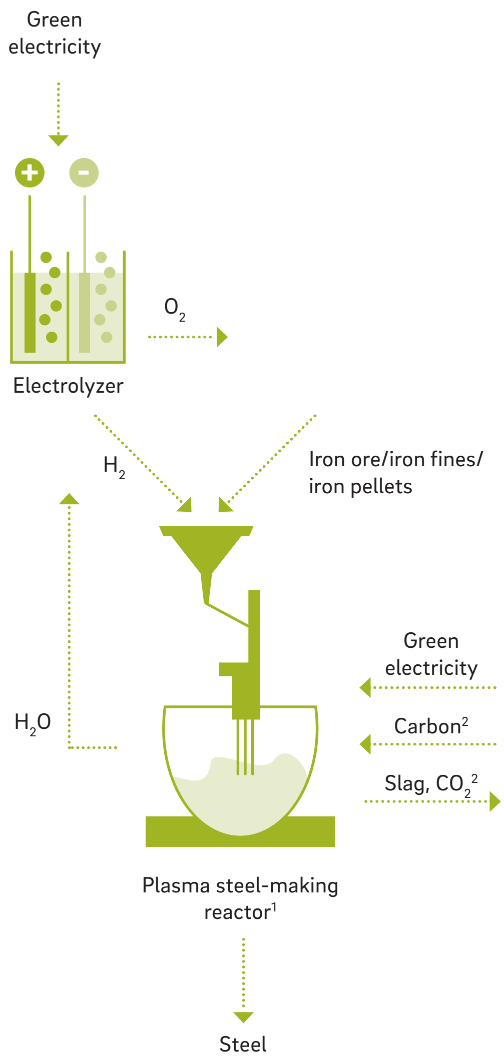
Cons: The technology is at a very early stage of development, with an optimal process and full reactor design yet to be developed. Its commercial feasibility is also still to be proven.

Pilot projects: As part of its Sustainable Steel (SuSteel) project, the Austrian steelmaker voestalpine has built a small pilot hydrogen plasma reduction reactor at its Donawitz site.

2.7 ELECTROLYTIC PROCESSES

How it works: There are two types: electrolysis and electrowinning. Electrolysis transforms iron ore at approx. 1550°C into liquid steel using electricity as a reductant. In electrowinning, iron ore is ground into an ultrafine concentrate, leached and then reduced in an electrolyzer at around 110°C. The resultant iron plates

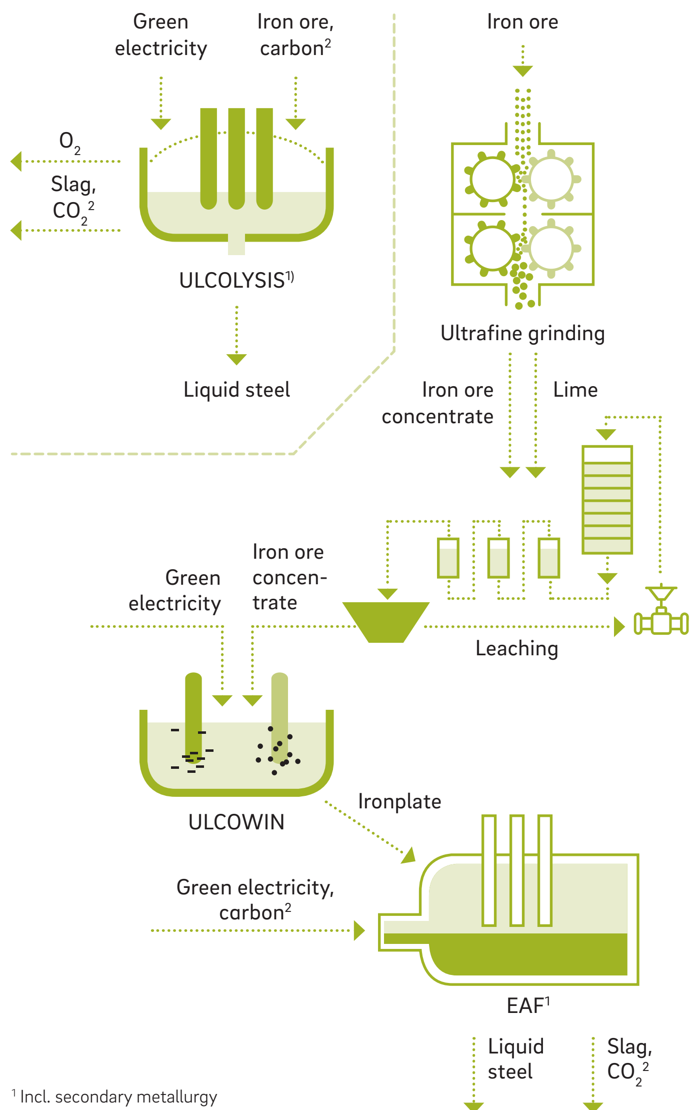
F: Plasma direct steel production
The production route (simplified)



[1] Incl. secondary metallurgy
[2] Adjust desired carbon content between 0.002% and 2.14%

Source: Roland Berger

G: Electrolytic processes
The production route (simplified)



[1] Incl. secondary metallurgy
[2] Adjust desired carbon content between 0.002% and 2.14%

Source: ULCOS, EU Commission IERO, Roland Berger

are fed into an EAF, which turns it into steel. ULCOLYSIS is the main electrolysis method, ULCOWIN the main electrowinning one. → **G**
Pros: Because they skip the upstream stages required in other production routes, such as producing coke or H_2 as reductants, electrolytic processes have the potential to become the most energy-efficient steelmaking methods, especially electrolysis. They also promise to significantly lower CAPEX as, in the case of electrolysis, only very few aggregates are needed.
Cons: The technology, especially electrolysis of iron ore, is still being tested in laboratories, suggesting a long and costly development phase. The process is also relatively inflexible compared to H_2 direct reduced iron methods as it cannot be stopped easily. Lastly, while green electricity remains expensive and storage possibilities few, profitability will be low as the process needs a constant source of electricity and therefore cannot take advantage of excess cheap green energy.
Pilot projects: The EU's ULCOS project, which involved many European steelmakers including ArcelorMittal, led the development of ULCOLYSIS and ULCOWIN. It demonstrated laboratory-scale high-temperature electrolysis for direct production of liquid steel. → **H**

H: Technologies compared

How the seven processes perform against key criteria for future steelmaking

		Technology readiness	Years until plateau of productivity	Development costs[1]	CAPEX requirements[2]	Operating costs[3]	Public acceptance	Possibility to transform brownfield plant
CCUS	Carbon capture, use and/or storage	◕	5-10	◑	◔	◕	◔	●
CCUS	Carbon capture, use and/or storage with biomass	◑	5-10	◕	◑	◔	○	◕
Alternative reductant agent	H_2-based direct reduced iron – Shaft furnace	●	0-3	◔	◔	◔	◕	◕
Alternative reductant agent	H_2-based direct reduced iron – Fluidized bed	◕	5-15	◔	◔	◔	◕	◕
Alternative reductant agent	Suspension ironmaking technology	◔	17-22	◕	◔	◔	◕	◔
Alternative reductant agent	Plasma direct steel production	◔	20-25	●	◔	◔	◕	◔
Alternative reductant agent	Electrolytic processes	◔	20-30	◕	◔	◔	◕	◔

● High ○ Low

[1] Compared to the other presented carbon neutral technologies [2] Compared to CAPEX of BF-BOF greenfield plant in 2040-2050
[3] Compared to BF-BOF plant in 2040-2050 (incl. carbon tax)

Source: Roland Berger

3 / A solid solution

RECOMMENDATIONS

With a decision looming for steelmakers on which technology to pursue, we believe clear, evidence-based insight is helpful.

It's apparent from our analysis above that CCUS is unlikely to be sufficient to ensure carbon-neutral steelmaking by 2050. Nor is the public likely to accept it within that timescale. This leaves the alternative reduction technologies.

These also remain problematic. All five of our considered methods require massive amounts of affordable green electricity – for iron ore preprocessing, H_2 electrolyzers, furnaces and electrolysis – to meet the carbon neutrality goal. But such energy sources are far from meeting the required price points compared to coke (excl. carbon tax) and will take time to develop.

I: The carbon-neutral future

How to transform a brownfield steel plant into an H_2-based DRI shaft furnace plant

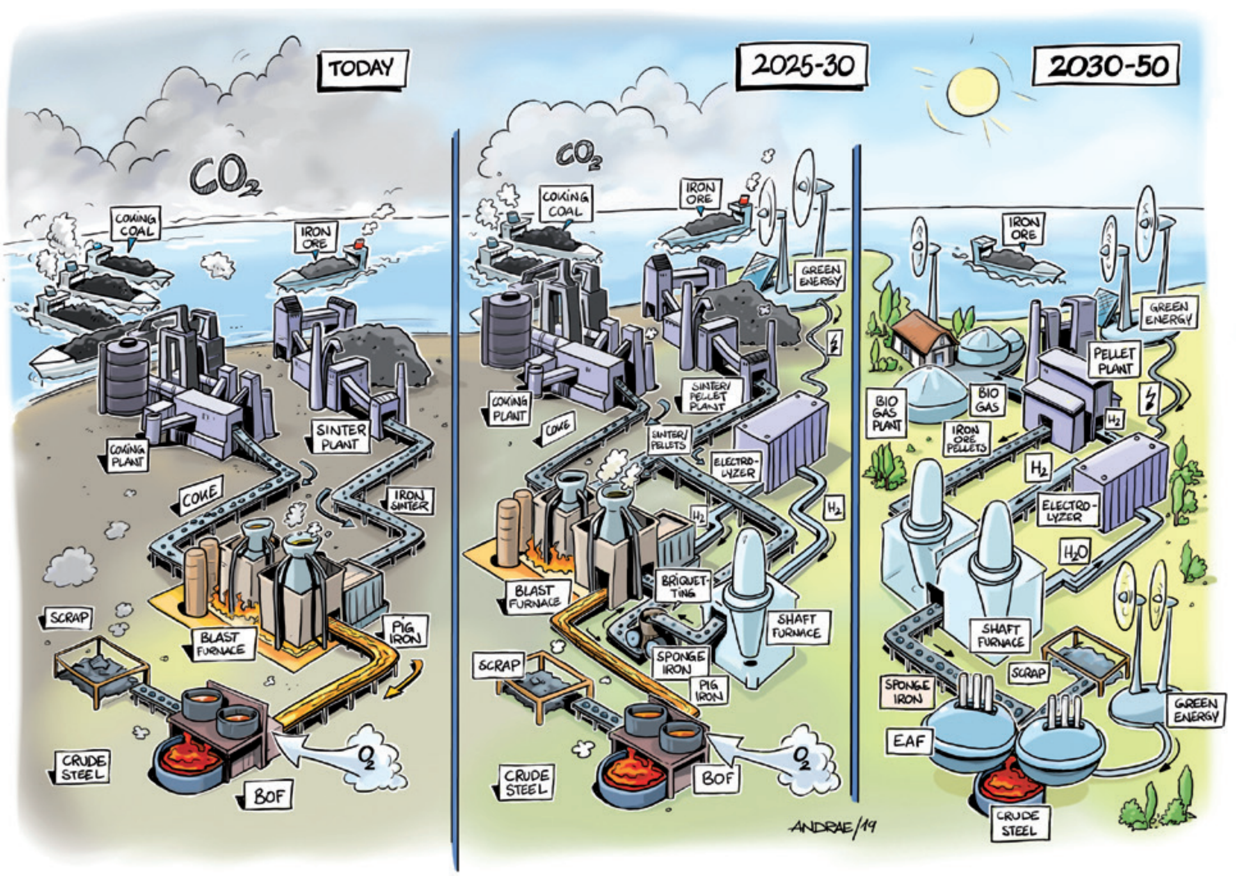


Illustration Thomas Andrae

In addition, three of the five – suspension ironmaking, plasma direct steel production and electrolytic processing – are at an early stage of development themselves. Their technical and economic viability in large-scale production is yet to be tested, leaving a degree of uncertainty over their industrial deployment.

The H_2-based reduction technologies are more developed and lower risk, but not without challenges. As yet, for example, there is no sufficiently large-scale H_2 electrolyzer, a prerequisite to produce sufficient H_2 for the reduction process. For example, the world's largest H_2 electrolyzer, with 100 MW performance, is planned in Hamburg. Neglecting any degree of efficiency or possible shutdowns, this would result in only < 1 TWh H_2 produced per annum. This compares to the ~70 TWh of H_2 required to shift the 30 million tons of crude steel produced in Germany via the blast furnace route to H_2 direct reduction in a shaft furnace. Total energy consumption sums up to ~120 TWh of required green electricity to run the pelletizing plant, shaft furnace preheater, EAF and to account for conversion losses in the electrolyzer in addition to the required ~70 TWh H_2.

Despite this, we see H_2-based direct reduced iron either in a shaft furnace or a fluidized bed as the dominant future technology to produce carbon-neutral steel. We expect steelmakers to support the shaft furnace DRI process.

As well as the promise of future carbon neutrality, it offers short-term, transitional benefits as it is ready to use. DRI can be fed into existing brownfield blast furnaces in the form of hot briquetted iron to make them instantly more CO_2 efficient. This also creates operational breathing space to ramp up the replacement of blast furnaces with shaft furnaces. In a second transitional step, BOFs can be maintained alongside new electric arc furnaces until sufficient capacity is built up to fully switch to the H_2-based DRI shaft furnace method. Then, just add green electricity. → I

Conclusion

Making a prediction is one thing, executing it is another. As well as the specific problems with the technologies assessed in this report, including our favored method, Europe's steelmaking industry faces wider challenges in its shift to a greener future.

As outlined above, CAPEX requirements for carbon-neutral steel production are high and operation is only sustainable and economically viable if cheap green energy is available. For example, as a rule of thumb, the CAPEX of every million tons of H_2-DRI-EAF production capacity is EUR 1 billion at today's prices. This results in an EU-wide CAPEX requirement of up to EUR 100 bn to make the approximately 100 million tons of crude steel produced in the bloc today via the integrated blast furnace route carbon neutral. This means European steelmakers are dependent on political support to meet the EU's carbon emissions targets. Only governments can offer the necessary tax breaks, levies, subsidies, financing etc. to ensure cheaper green electricity and help with the high CAPEX requirements.

The EU itself must also step up. It needs to ensure that imported steel and steel products are also carbon neutral, or taxed accordingly if they are not (via a carbon tax). In addition, the bloc must ensure its long-term rules and targets are set in stone to safeguard the huge amount of investment required to meet them. It should also seek agreements with other countries and trading blocs to align these rules and targets. This will level the playing field when it comes to exporting carbon-neutral steel, and make the process easier.

Without such support, there is a high risk that large parts of the steelmaking value chain will be moved out of Europe to countries with cheap access to energy, and fewer regulations. This would damage not just the European steel industry, but also the chances of a global carbon-neutral future.

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