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AGENCE DE LA TRANSITION ÉCOLOGIQUE

SECTORAL TRANSITION PLAN FOR THE FRENCH STEEL INDUSTRY

Survey of the industry, decarbonisation modelling and courses of action

FINAL REPORT

July 2024

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1. Introduction and Method

1.1. Overall context and aims

The National Low-Carbon Strategy (SNBC) sets out the path France intends to take to achieve carbon neutrality by 2050[1], a commitment it made following the 21st Conference of the Parties (COP 21) convened under the United Nations Framework Convention on Climate Change (UNFCCC). For industry, this trajectory translates into an 81% reduction in emissions in 2050 compared to 2015. An intermediate target of a 35% reduction in emissions has also been set for 2030. While a number of guidelines have been put forward (e.g. providing a framework to encourage management of the demand for energy and materials, giving priority to decarbonised energies and the circular economy, etc.), their content and costs at the operational level have not been detailed, giving rise to a problematic lack of visibility for manufacturers, whose commitment to making investments makes medium-term projection necessary. Indeed, it is not uncommon, particularly in heavy industry, for industrial plant to have a lifespan of several decades: it is therefore likely that the investment decisions, for plant that will be operating in 30 years' time, will be taken in the coming months. Sectoral Transition Plans are adapted to this time frame and this need for visibility for industrialists. For the public authorities, it is also a question of being able to propose effective policies that encourage decision-making with regard to the investments required in order to achieve carbon neutrality by 2050.

By drawing up these Sectoral Transition Plans (STPs) in consultation with the key actors in the sectors concerned, ADEME aims to provide visibility for both manufacturers and investors, as well as public authorities, in order to achieve the target set in the SNBC of a reduction of 81% for industry. The project is therefore a continuation of the work carried out for the SNBC, breaking down heavy industry into 9 sectors in order to tailor decarbonisation solutions as closely as possible to the industrial issues facing each sector (Figure 1).

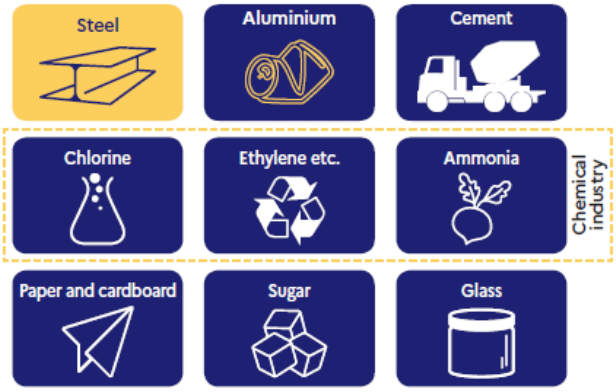


Figure 1: The 9 sectors covered by the Sectoral Transition Plans

The STPs are concentrated in France, despite the fact that the national industrial leaders' business activities extend well beyond the national borders. However, international opportunities are nevertheless envisaged through the sharing of methodological good practices and support for existing international tools, in particular the ACT® (Assessing low Carbon Transition) initiative[2].

1.2. The Sectoral Transition Plan: a 360° view

On the basis of the observation that the vast majority of studies in the national, European and international literature essentially focus on the technological component of the industrial transition, the project adopts a 360° view in order to avoid the neglect of aspects such as the cost and impact of this transition on the market and employment. Part of a European LIFE programme entitled Finance ClimAct[3] (Figure 2), the STPs are based on a cross-cutting analysis of the deployment of decarbonisation technologies, the cost that this represents, in particular in order to anticipate funding requirements and effects on competitiveness, and the impact of changes in the market in terms of demand and competition by the year 2050.

[1] The current revision of the SNBC (3rd edition) will potentially lead to the definition of new sectoral objectives. For further information: https://www.ecologie.gouv.fr/strategie-francaise-lenergie-et-climat-lancement-consultation-publique

[2] Further information is available on the ACT initiative website: https://actinitiative.org/

[3] The LIFE programme is the European funding instrument for the environment and climate action, in place since 1992. Further information is available on the Finance ClimAct website : https://finance-climact.eu/

Figure 2: The Finance ClimACT project

Effects on employment and any changes in the skills generated (retraining, relocation, etc.) in order to adapt to the sector's transition are also discussed within the framework of STPs, in addition to the subject of regional footholds and the degree of regional dependence with regard to the industrial sector studied. Proposals for public policies (e.g. support measures,

taxation, regulations etc.) and moreover potential commitments from the stakeholders in each industry (manufacturers, funding agencies, clients, suppliers, etc.) will be backed up by the different scenarios. Ultimately, this work is designed to result in the formulation of "public-private" courses of action to support the sector in the completion of its transition.

Figure 1: 360° vision of the ADEME Sectoral Transition Plan

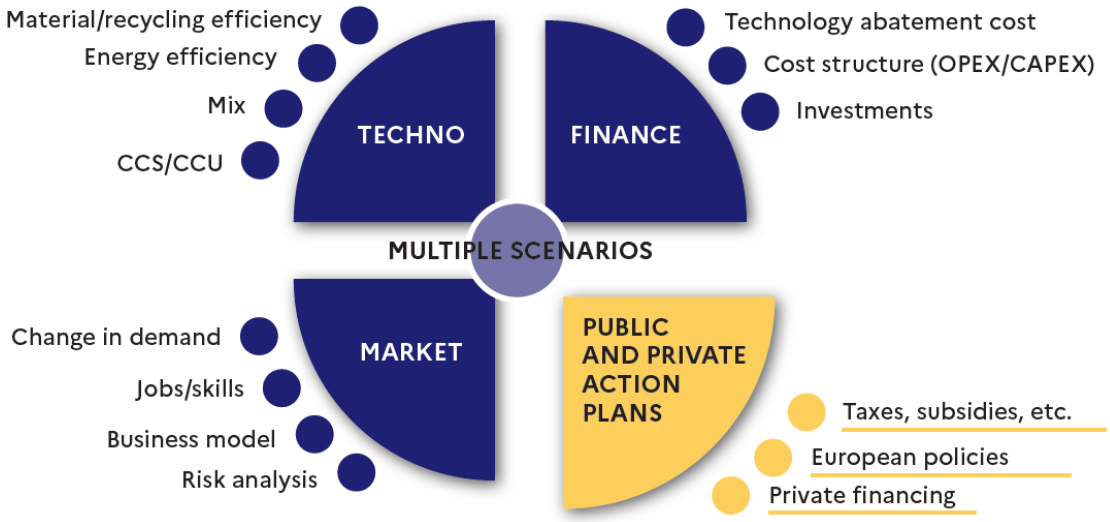


Figure 3: 360° View used in Transition Plans

1.3. The steel industry, the highest-emitting industrial sector and the principal consumer of coal

At the international level, direct CO_2 emissions connected with steel production (2.6 $GtCO_2$/year) represent around 5% of global greenhouse gas (GHG) emissions[4], principally due to high levels of consumption of coal, which represents 74% of energy requirements. In addition to these direct emissions, waste-to-energy recovery of steelmaking gases from processes (e.g. coke oven gas and blast furnace gas) and consumption of other energy sources (steam and electricity) add 1.1 $GtCO_2$/year of annual indirect emissions. Steel production is therefore responsible for a total of 3.7 $GtCO_2$/year, that is to say around 7% of global greenhouse gas emissions and 10% of CO_2 emissions from the energy system[1].

In France, including emissions connected with waste-to-energy recovery of steelmaking gases, steel production represented between 20 and 25 $MtCO_2$ of direct emissions (Figure 4) depending on the year between 2010 and 2017, that is to say 5% of France's annual greenhouse gas (GHG) emissions[5] and a quarter of emissions from French industry.

[4] In 2019, including the LULUCF sector (land use, land-use change and forestry).
[5] In 2019, excluding LULUCF.

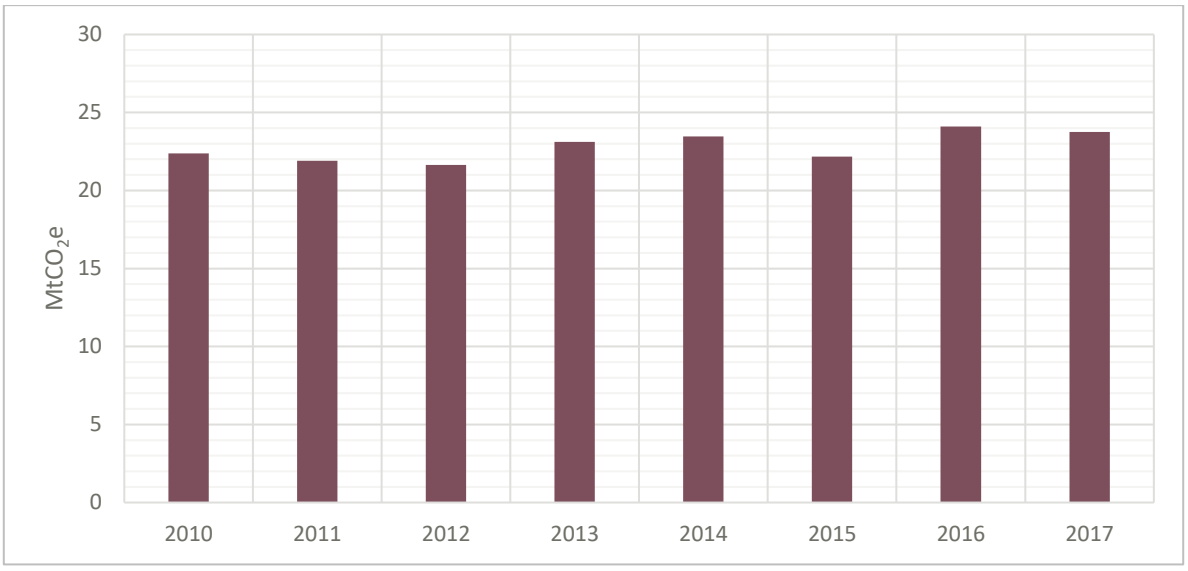


Figure 4: Annual GHG emissions from the steel industry in France [2]

Of all the sectors covered by a Sectoral Transition Plan, the steel sector has by far the highest concentration of GHG emissions (Figure 5).

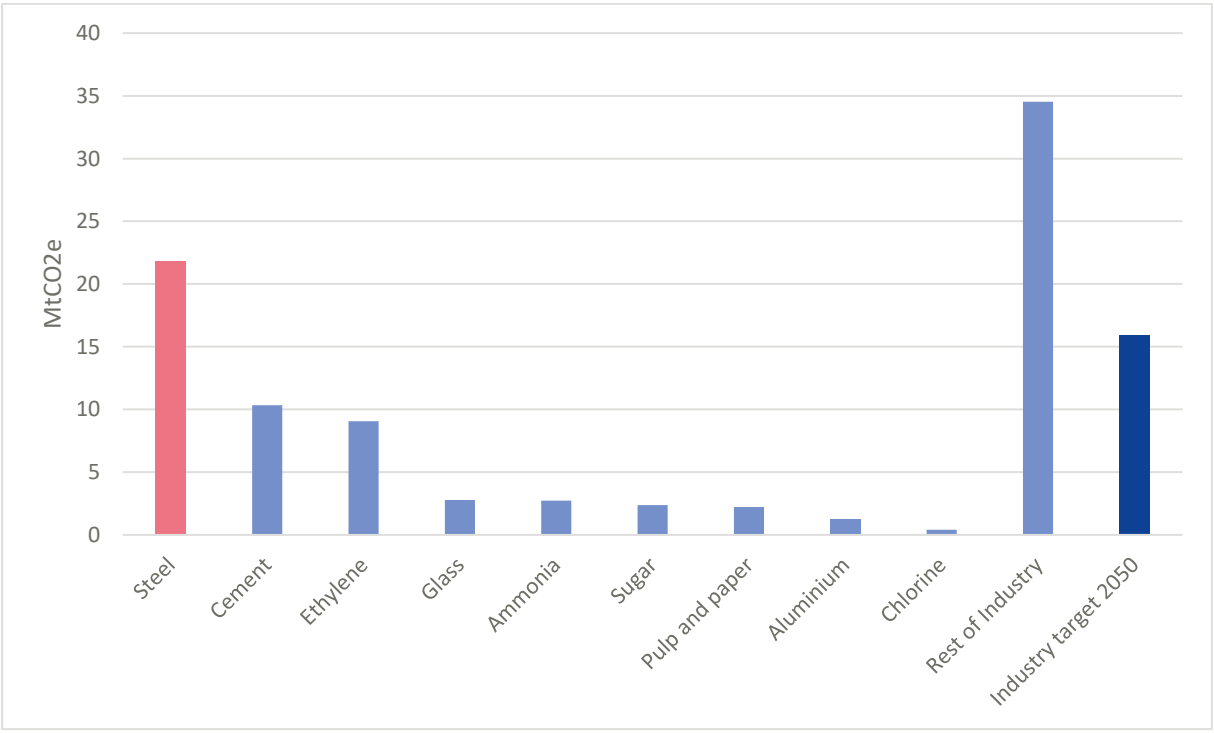


Figure 5: Direct GHG emissions from industry in 2015 according to the principal energy-intensive sectors (source: ADEME calculations on the basis of CITEPA data)

1.4. Main limitations and scope of the study

The whole of the results presented are the outcome of an ambitious modelling exercise concerning decarbonisation trajectories for the steel industry up to 2050, with a methodology that is innovative, but also subject to limitations, in particular in terms of scope and access to data. Readers should view the document through this prism in terms of the conclusions to be drawn from it, taking the following elements in particular into account:

- **A common emissions reduction target for different industrial sectors.** The target from the SNBC 2 of an 81% reduction in greenhouse gas (GHG) emissions from manufacturing industry was applied to the steel industry subsector as an input

constraint to the scenario-building exercise. This choice presents the advantage of defining a common working framework for all of the sectors covered by a Sectoral Transition Plan. However, this assumption closes the door to a more flexible allocation of emission reduction targets between industrial sectors for which abatement potentials and associated decarbonisation efforts may be different. An analysis of all sectors could eventually make it possible to define more appropriate targets.

- **An exercise focused on direct emissions.** In accordance with this target from SNBC 2, only direct emissions from French steel-manufacturing sites are included in the scope (category 1 emissions). Emissions connected with external production of energy (electricity in particular), downstream (e.g. transport of steel) and upstream (e.g. production of ferro-alloys) of steel-manufacturing sites are not covered. For example, emissions connected with electricity consumption from direct reduction plants using hydrogen or iron electrolysis are thus not taken into account, and neither are emissions outsourced abroad due to changes in the value chain.
- **A broad view of the steel sector, which is heavily dependent on external factors.** This exercise is aimed at providing the broadest possible view of the determinants of GHG emissions from the steel industry. It was therefore necessary to make direct or indirect assumptions about parameters outside of the sector, such as demographics and moreover changes in demand for steel from the transport and building sectors.
- **And nonetheless, an approach which could be further enriched by other determinants brought by other economic players.** The steel industry constitutes a link in a complex economy that interacts with entities upstream and downstream, which are themselves evolving. An exhaustive systemic approach to decarbonisation of the sector would make it necessary to adopt a vision going far beyond the boundaries of this sector, and would therefore involve a multiplication of assumptions concerning the other links in the system. In particular, this is the ambition of ADEME's more global foresight project, entitled "Transition(s) 2050"[6], published at the end of 2021.
- **Moreover, as with any foresight exercise, the range of assumptions and combinations thereof is infinite, and each scenario may be called into question by the different players concerned.** Thus, without giving them a predictive character, these scenarios are principally the fruit of ADEME's own work, which has been submitted to the players in the industry for comment. Nevertheless, they reflect technically plausible outcomes, of greater or lesser desirability. The aim of this work is to help the stakeholders take advantage of the exercise for their own use, with the same expectation of transparency regarding the assumptions made and the outcomes envisaged, while acknowledging the limits of the exercise. These analytical elements are based upon extensive bibliographical research, public sources of information and interviews with industry players, with the intention of securing the greatest possible objectivity in view of the authors' cross-referencing of the whole of these sources.

1.5. Method of construction of a Sectoral Transition Plan

A methodological guide was published in January 2024 (English translation March 2024) in order to extend the means of completion of a Sectoral Transition Plan to sectors other than the nine largest consumers of energy. It is available on the ADEME website[7] and comprises the three phases described below.'

1.5.1. Phase I: Survey of the Industry

This first phase is devoted to understanding the challenges of decarbonisation of the sector. It covers different aspects connected with the industry's energy transition:

- Its greenhouse gas (GHG) emissions: emitters, volumes, nature, history;
- Its value chain: players, socio-economic, territorial and regulatory environment;
- Its market: production, foreign trade, consumer sectors;
- Its industrial processes: operation, energy-material inputs, products and waste;
- Its decarbonisation levers: maturity, technical and economic constraints.

The bibliography can be compiled from various reports, studies, scientific publications and databases. It is consolidated and given a more specific focus by interviews with stakeholders in the industry, in particular federations and unions representing manufacturers, their clients and suppliers, and consumer associations.

This phase opens with a meeting with all of the stakeholders in the industry known as a 'kick-off' meeting. Its aim is to communicate the approach to the whole of the industry and to involve the players that want to join the project. Phase I ends

[6] For further information, visit the dedicated website: https://www.ademe.fr/en/futures-in-transition/

[7] Available from the ADEME bookshop website https://librairie.ademe.fr/7014-methodological-guide-to-drafting-a-sectoral-transition-plan-for-the-decarbonisation-of-industry.html

with a meeting with all of the stakeholders called the 'Industry-photo' "*'Photofilière"*) meeting. The aim of the latter is to provide the industry with the whole of the analysis of the literature. It also makes it possible to determine the scope of the STP study, that is to say the whole of the aspects that are to be covered in or excluded from the STP.

1.5.2. Phase II: Construction of Decarbonisation Scenarios

This second phase is devoted to the construction of scenarios for decarbonisation of the industry. It can be divided into 4 sub-phases with more or less concurrent time frames.

1.5.2.1.Modelling the production tool as a reference plant

This first sub-phase consists of modelling the operation of the industrial facilities. "Reference plants are tools for modelling industries. They represent the manufacturing processes most commonly used or which could be developed in the future within the scope of the industrial facilities in question. Each is described in terms of its production, its equipment, its processes, its thermal and electrical energy consumption, its GHG emissions and its production costs" (Figure 6). The reference plant is a fictitious model of the operation of industrial processes, but is representative of the scope defined in phase I. In other words, the reference plant does not represent the operation of a production site, or even the average for these sites, but the typical and realistic operation of the industrial processes covered by the STP.

The construction of reference plants is based on the analysis of the literature on industrial processes in France and the collection of associated data conducted in phase I. A number of indicators are then defined in order to characterise the operation of this reference plant: specific material and energy consumption, specific GHG emissions, annual production cost, etc.

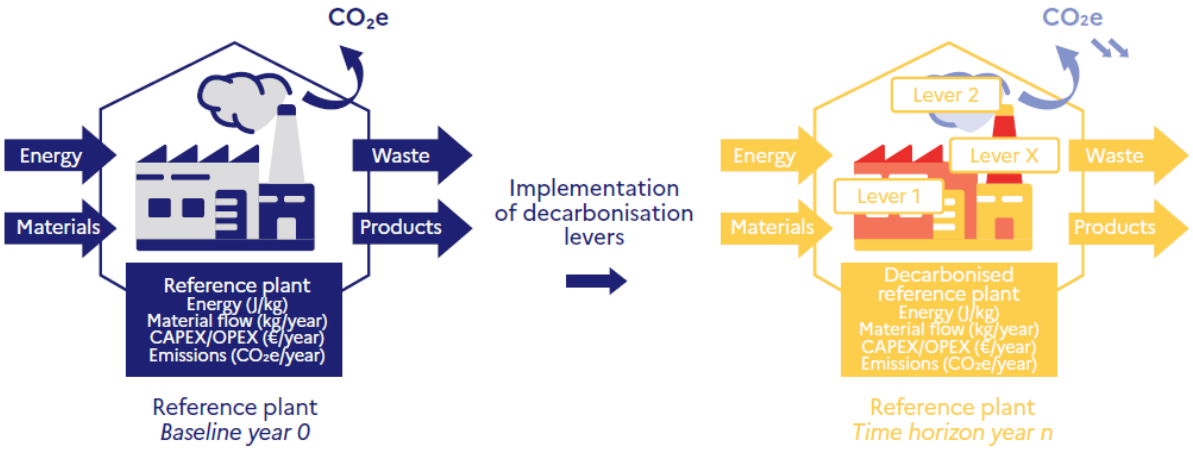


Figure 6: (left) Simplified diagram of a reference plant representative of manufacturing processes in France; (right) Simplified diagram of changes in the operation of the reference plant after implementation of decarbonisation levers.

In case of industrial processes that are are too different, the number of reference plants modelled should be increased in order to provide a better description of the operation of the industrial processes; in case of lack of available data or limits imposed by statistical confidentiality, the number of reference plants modelled should be reduced in order to represent more general industrial processes.

The reference plant or plants are ultimately submitted for validation to the industrial players concerned. These reference plants are the basic building blocks for the modelling of technological pathways. Indeed, implementation of decarbonisation solutions changes its operation: the monitoring of changes in its key indicators thus makes it possible to measure the impact of these different decarbonisation levers.

1.5.2.2. Modelling a reference scenario with the stakeholders in the industry.

This second sub-phase consists of the construction of a scenario moving in the general direction of the precise eventual objective of decarbonisation of the industry. The modelling a scenario consists in defining a transition world and assumptions concerning technological, market and cross-cutting changes (Text Box 1).

The transition world and associated assumptions concerning changes are thus selected in line with a certain continuity of historical dynamics. This scenario makes it possible to illustrate the transition of the industry without making any strong assumptions with regard to market trends in the industry. The technological pathway is thus based on technologies identified as plausible by players in the industry, while the market pathway is based on the continuation of current consumption levels

and stable foreign trade dynamics. These proposals are discussed with the stakeholders in the industry at bilateral meetings. They are compared with pre-existing road maps and industrial decarbonisation strategies. During this period, the assumptions are revised in order to agree on pathways in consultation with the industry stakeholders.

Text Box 1: Glossary of foresight in STPs

Scenario: a coherent set of selected transition worlds in which assumptions have been decided upon with regard to technological change, market trends and cross-cutting change, resulting in technical-financial, economic and social decarbonisation trajectories for the industry studied. Unlike a roadmap, scenarios enable the exploration of possible configurations of an uncertain future.

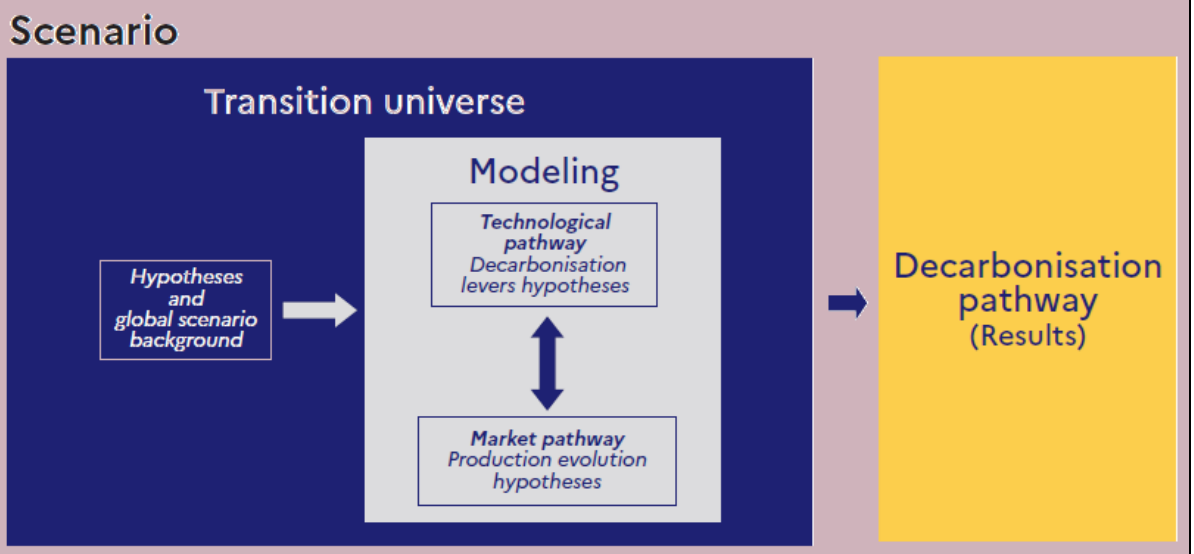


Figure 7: Structure of a scenario in ADEME STPs

Transition world: "exogenous context in which the transition of the sector could take place between now and 2050. Its description is based on quantitative and moreover qualitative elements that could have an impact [...] on the decarbonisation strategies adopted. " A number of transition worlds can be envisaged for however many scenarios. Their construction is based on assumptions concerning changes in structural uncertainty factors..

Structural uncertainty factor: qualitative narrative element associated with a high level of uncertainty and high potential impact on an industry's emissions. These structural uncertainty factors may be "global" (price and availability of materials, changes in the geopolitical context, etc.), "market" (consumption habits, public policies and regulations, etc.) or "technological" (development of disruptive technologies and infrastructures, conditions of operational implementation of decarbonisation solutions, etc.).

Modelling: the digital interface as a whole making it possible (1) to represent the energy-material-emissions-costs operation of the industrial facilities at time t = 0, (2) to transform the whole of the technological assumptions into a technological pathway and (3) the whole of the market assumptions into a market pathway, in a given transition world.

Technological pathway: the outcome of the assumptions concerning technological change, in a world which "defines [the temporal, progressing according to a yearly time scale] deployment of decarbonisation levers in the industrial facilities. "

Market pathway: the outcome of assumptions concerning market trends (consumption levels, changes in foreign trade), which "make it possible to arrive at [annual] production volumes" for the industry.

Decarbonisation trajectory: combination of the technological pathway and the market pathway. It is manifested for example in changes in an industry's GHG emissions, but also includes other results such as changes in energy consumption, technological investment timelines, changes in production costs, and impact on employment, etc.

Alternative scenario: a scenario involving a major paradigm shift, in which the transition world and associated assumptions concerning change are markedly different in order to illustrate the impact of structural uncertainty factors on transition of the industry. It contrasts with the reference scenario, the transition world and tendential assumptions concerning changes.

1.5.2.3. Development and Modelling of Alternative Decarbonisation Scenarios

This third sub-phase is devoted to the exploration of other, more contrasting scenarios than that developed previously in consultation with the industry. These alternative scenarios are intended to illustrate plausible futures based on other prospective visions. They are above all a means of highlighting issues that are often little explored in more conventional road maps.

For this purpose, the choice of transition worlds is based upon the identification of structural uncertainty factors (Text Box 1) for the industry, that is to say decisive assumptions for its transition, such as changes in international competition, access to a resource, the development of a new industry or the advent of a disruptive technology. The selection of these transition worlds consists in fixing these guiding assumptions so as to create a credible backdrop for transition of the industry. In order to cover a wide range of relevant transitions, it may be useful to define contrasting transition worlds, with highly different paradigms but balanced desirability.

Next, assumptions concerning market trends and implementation of technological solutions are selected so as to build market and technological pathways that are consistent with these alternative transition worlds. Indeed, certain assumptions concerning the transition of the industry need to result from prior determination of the guiding assumptions. These alternative scenarios are thus often more constrained, but may also bring out different transition opportunities for the industry.

Within the Cement and Ammonia Sectoral Transition Plans, a baseline scenario and 2 alternative scenarios were thus produced. For all of the other Sectoral Transition Plans studied (Aluminium, Steel, Sugar, Glass, Paper-Cardboard, Chlorine and Ethylene), 2 or 3 alternative scenarios were directly constructed.

1.5.2.4. Comparative socio-economic analysis of scenarios

This final stage enables the socio-economic analysis of the different scenarios to be taken further. In the first place, it enables an analysis of changes in production costs. These results may be backed up with a sensitivity analysis in order to take into account the uncertainty of changes in the prices of the energies, raw materials, infrastructures and technologies required for the transition. These changes in production costs may also be compared with current production costs and with the production costs in a “no action” scenario, and then provide initial elements of analysis concerning the industry’s competitiveness in each scenario. In addition, this analysis may be supplemented by an analysis of the transfer of these additional transition costs down the value chain to the end consumer.

Abatement costs, in €/tCO_2 avoided, may also be calculated in order to determine which technologies and transition scenarios are the most competitive. These results may be modified by other indicators and qualitative elements not taken into account, such as an industry’s resilience and, moreover, the sovereignty and industrial security that it provides. An analysis of the industry’s sensitivity to changes in the decisive CAPEX and OPEX may also be used to broaden the results and include a probabilistic dimension.

Finally, an analysis of employment and regional trends is required in order to take account of the potential social and societal changes brought about by ecological transition of the industry and its value chain. More specifically, changes in direct jobs in each scenario have to be calculated according to the production levels and decarbonisation technologies selected. Changes in indirect jobs upstream and downstream on the value chain can then clarify labour market areas’ requirements in terms of human resources and training.

1.5.3. Phase III: Proposal of courses of action

The third and final phase of the STP is devoted to proposing courses of action to promote acceleration of the sectoral transition and achievement of the SNBC targets. These proposals result from a synthesis of the lessons drawn from phases I and II on the current state of the sector, its decarbonisation challenges and the low-carbon transition scenario construction. They may take the form of recommendations concerning measures to be taken in the short and medium term, or the promotion of good practices, at once by industry, financiers and the public authorities. These proposed courses of action are developed through thematic “action sheets”, of which the drafting process is itself designed as a tool for dialogue between all stakeholders.

2. The Steel Industry Value Chain: Facts and Prospects

2.1. Global production and sectors

As with many materials, global steel production is dominated by China, whose needs have steadily increased since the 2000s, in particular for the construction of infrastructures and in order to cope with growing urbanisation. Between 2010 and 2019, Chinese production increased by 56%, and that of India increased by 63%, while production in the European and global industrialised countries either stabilised or fell (e.g. -9% for Germany and Japan; -6% for France).

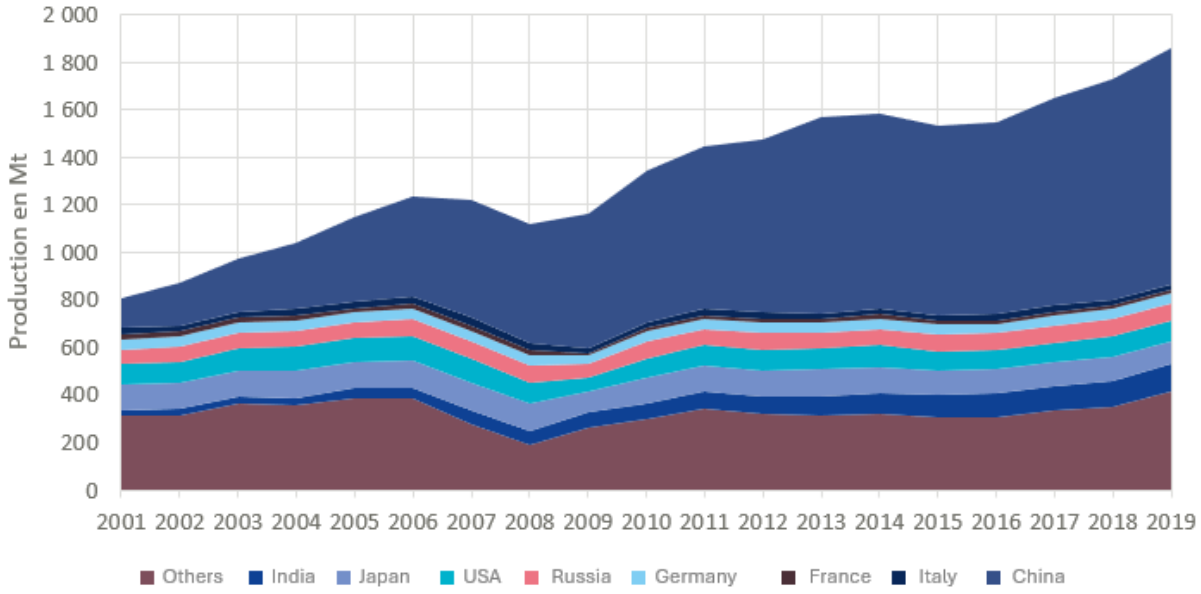


Figure 8 : Global overview of steel production (Source: World Steel Association)

In this context, France's share of global production has fallen steadily from 2.4% in 2001 to 0.8% in 2019. The same is true of Germany, whose share fell from 5.5% to 2.1% over the same period. Within the European Union, Germany remains the principal steel-producing country, with 40 Mt of steel produced in 2019, i.e. 27% of EU production, compared with less than 10% for France.

Projections by the International Energy Agency indicate a global increase in demand for steel between the present and 2050, particularly in India and other emerging countries[1]. The transformation of the Chinese economy more towards goods and services rather than infrastructure-oriented consumption is set to lead to slower growth in demand for basic materials, and therefore to a reduction in China's share of global steel production. According to the IEA scenarios, the industrialised countries (the European Union, the United States, Japan and South Korea) are set to maintain relatively constant production as compared with current levels. These estimates also highlight the potential impact of materials efficiency on final steel demand. On the other hand, this propensity to deploy materials efficiency policies appears to be relatively heterogeneous between regions and between countries.

Beyond estimates of changes in production, it also appears important to take into account differences in the organisation of production between different countries. Generally speaking, a distinction is to be made between the blast furnace (BF or "pig iron sector") sector, which produces steel for the most part from virgin iron ore, and the electrical sector, in which steel is produced by the conversion of scrap in electric arc furnaces (EAF)[8]. The division of the industry between these two sectors varies greatly between different countries. By way of example, according to data from the World Steel Association, in 2022 over 90% of Chinese steel came from the BF sector, as compared with 73% in Japan, 57% in the European Union and 31% in the United States. These production structures condition at once current energy consumption and GHG emissions for the steel industry in each country, and moreover prospects for change in production systems in the future, with a view to their decarbonisation. In France, the steel industry produces around 15 Mt of steel annually. The BF sector represents 67% of production but 96% of the industry's GHG emissions, while the electrical sector represents 33% of production and 4% of the industry's GHG emissions (Figure 9).

[8] More information on the processes in part 3

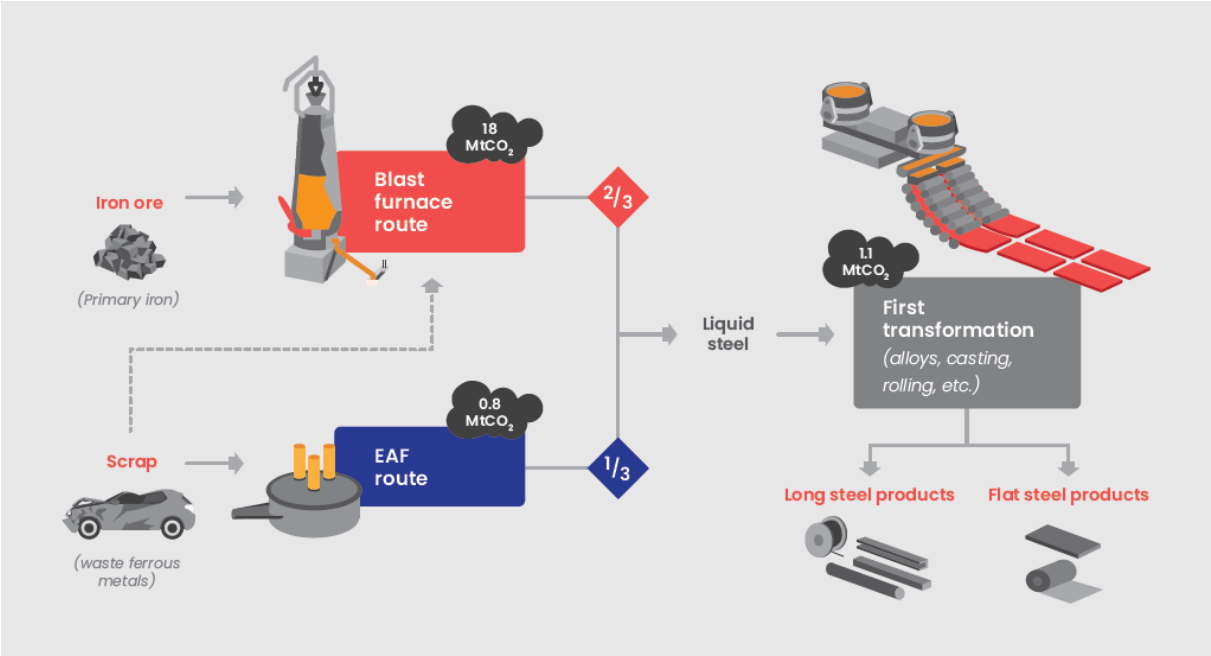


Figure 9: Simplified diagram of the two steel production routes and their emissions in France.

As a result, emissions in France are concentrated on six blast furnaces spread over three sites: three blast furnaces in Dunkirk (which produce around 7 Mt of steel) and two in Fos-sur-Mer (producing around 4 Mt), belonging to ArcelorMittal, and finally one blast furnace at the Saint Gobain site in Pont-à-Mousson, which only produces pig iron.

Conversely, the electrical sector is more localised, it comprises fifteen sites principally located in the eastern half of the country, each producing between 30 kt and 500 kt of steel per year. Its players are historically SMEs and businesses comprising part of a medium-sized international group. Unlike blast furnaces, for which shutdowns cause major damage and restarting is a long and delicate process, production is relatively flexible for sites in the electrical sector, albeit with an impact in terms of energy consumption.

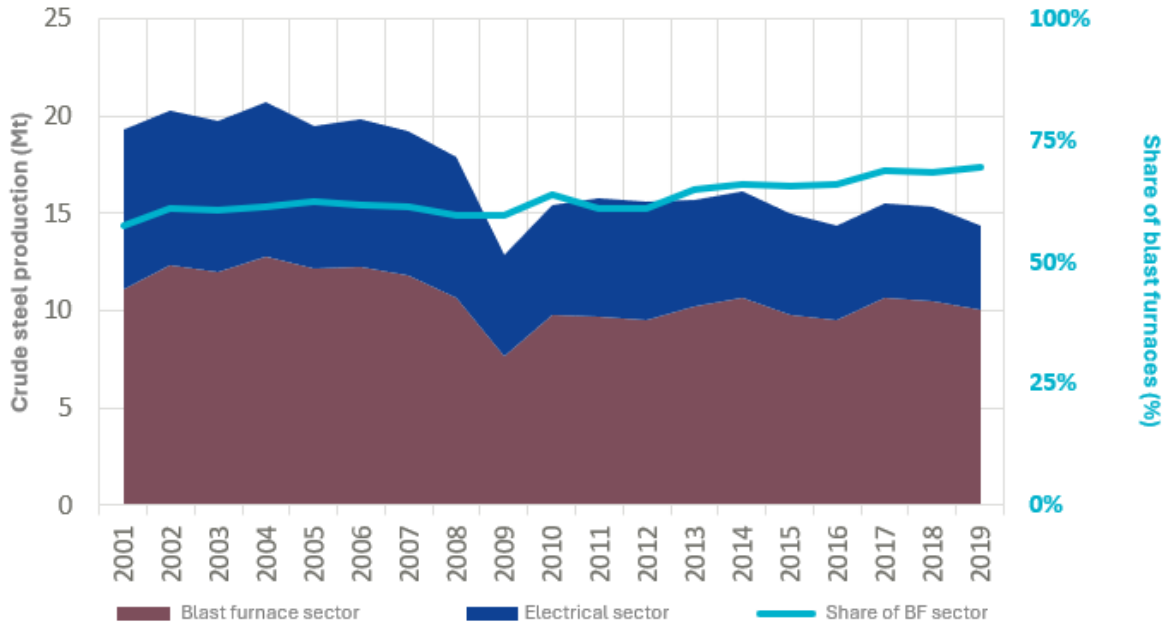


Figure 10: Steel production by sector in France (Source: World Steel Association).

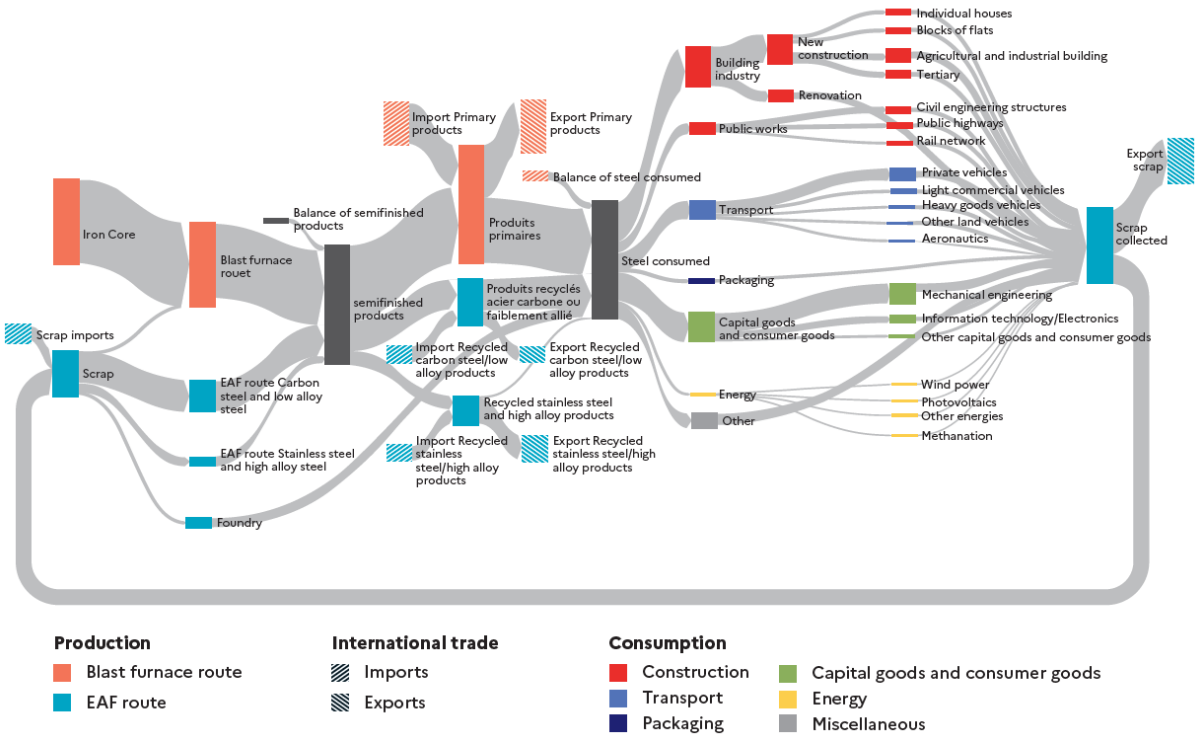
As shown in Figure 10, French steel production was severely affected by the crisis of 2008, particularly as a result of the downturn in the building and civil engineering and motor industries. The economic crisis finally changed taking the shape of a new structural production trend of around 15 Mt, as compared with 20 Mt before 2008.

This period was thus marked by a number of site closures. Among the most emblematic of these was that of the Florange plant in 2012. After several months of industrial dispute, ArcelorMittal's last two blast furnaces in Lorraine were shut down, gradually being replaced over the following years by a number of steel processing lines, supplied by the Dunkirk site. With regard to the electrical sector, there were also capacity closures, such as those at ArcelorMittal in Gandrange in 2009[3], the Akers plant located in Thionville in 2016[4], the Ascometal plants in Allevard in 2015, and Leffrinckoucke in 2017. This restructuring of the industry on a global scale has resulted in a production capacity utilisation rate of less than 80% today.[9].

Between the present and 2030 and 2050, the projected changes in the output of the French steel sites included within the scope of the STP are dependent upon the assumptions concerning changes in demand from the different consumer sectors (sub-section 2.2), as well as the assumptions concerning the shape of international trade and the place of the French steel industry in the medium and long term in this new global configuration (sub-section 2.3).

2.2. Uses of steel focused on the building and civil engineering, capital goods and transport industries

Figure 11 represents the flow of steel from the extraction of iron ore to its end-of-life, including its transformation into a raw material for recycling. Although already complex, this illustration remains simplified since it masks a reality in which many stages of processing coexist, from semi-finished to finished steel products, which are ultimately incorporated as components into final consumer goods. In addition to highlighting the great complexity of the value chain, Figure 11 distinguishes between the two principal steel production routes mentioned in part 3 (that is to say the blast furnace sector and the electrical sector) as well as the "foundry" sector, whose production sites fall outside of the scope of this sectoral transition plan.



Note: On the upstream side of "steel consumed", each node corresponds to a stock in steel equivalent, fed by imports and domestic production, from which one flux goes to external markets and another to the domestic market. The indirect steel balance is an estimate of the tonnage of steel contained in the products consumed by the sectors. It is positive because the steel contained in imports is greater than the steel contained in exports, and therefore adds to the steel footprint of French final consumption, divided between the different uses.

Figure 11: Sankey diagram for the steel industry in France in 2014 (source: ADEME estimates based on data mapping from the MODEIRE tool, see text box on the following page).

[9] Exchanges with industrialists in the sector.

Text Box 2: The MODEIRE tool for the mapping and modelling of material flows

MODEIRE (*MOdélisation DEcarbonation de l'Industrie Ressources-Energie/"*MOdelling of DEcarbonisation of Industry Resources and Energy") is a material-flow mapping and Excel modelling tool developed within the framework of a partnership between the NEGAWATT ASSOCIATION and ADEME. It aims to assess the levels of demand for materials from industry, in particular those produced by the 9 most energy-intensive industrial sectors (steel, aluminium, cement, glass, chlorine, ammonia, ethylene, paper/cardboard and sugar), on the basis of scenarios of change in consumer markets for these materials (mechanics, electricity, textiles, transport, etc.). These scenarios are produced on the basis of assumptions made about a set of more than 600 parameters concerning the period between the present and 2050 (e.g. demographics, recycling rate, per capita consumption of capital goods, and number of kilometres travelled by vehicle). The tool is used within the framework of other Sectoral Transition Plans, enabling estimation of the levels of waste produced each year, and now includes assumptions on the circular economy.

Taking into account the steel content of imported goods and excluding that of exported goods (material footprint), final steel consumption in France is estimated at 16.5 Mt/year. It is divided between 6 macro-sectors, including Building and Civil Engineering (43%), Capital Goods and Consumer Goods (25%) and Transport (15%). A significant quantity of steel (12% of final consumption) is also consumed in a multitude of finished products, for which the traceability of flows is complex. These uses are not linked to a specific macro-sector and the arrows therefore direct them to the "Other" consumption item (Figure 12).

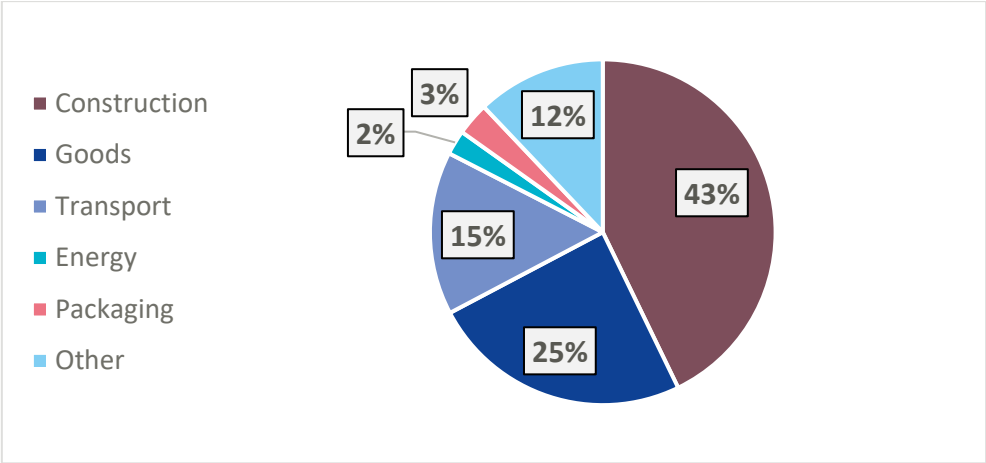


Figure 12: Distribution of final steel consumption in France in 2014 (source: ADEME estimates based on data mapping from the MODEIRE tool)

Moreover, steel exists in a large number of different grades of alloys, each more or less suited to a particular use. For example, so called "carbon" or low alloy steels are more commonly used in the construction sector (beams, concrete reinforcing bars, etc.). Stainless steel, for its part, is prized for its aesthetic qualities, in addition to its properties of durability and corrosion resistance. It is used, for example, in washing machines, saucepans, exhaust pipes and sometimes for the interiors of lifts.

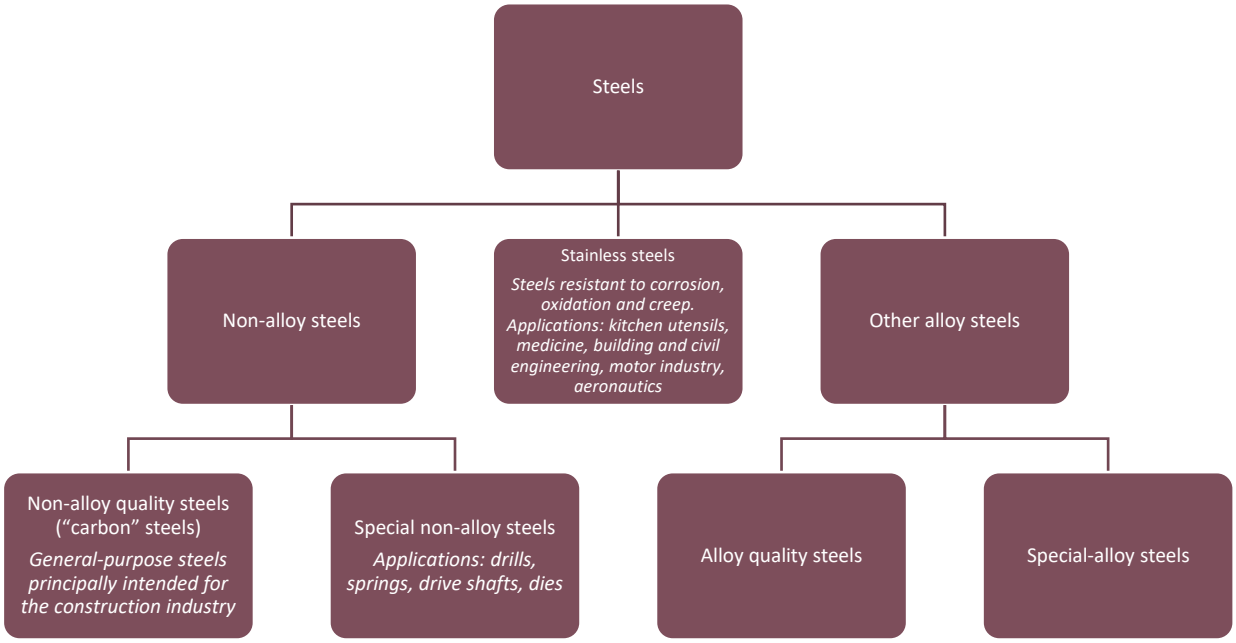


Figure13: Classification of the principal steels in accordance with standard NF EN 10020[10]

The typology of steels according to their alloy level and end use may be supplemented by a distinction according to the form in which semi-finished steel products are manufactured. Thus, "slabs" are parallelepipedal blocks of steel designed to be transformed into flat products, i.e. coils, sheets and plates. Billets and blooms take the form of long products with a square, cylindrical or rectangular cross-section, intended to become steel bars, girders and sections or steel wire.

In France, the blast furnace sector principally produces flat carbon and low-alloy steels, hereinafter referred to as "primary products" or "flat products". The electrical industry produces long carbon or low-alloy steels and stainless and high-alloy steels, which will hereinafter be collectively referred to as "recycled products" or "long products". illustrates the outlets for each of the two sectors and shows that the sites are unequally sensitive to fluctuations in demand: those in the blast furnace sector, with its varied outlets, are less sensitive than those in the electrical sector, whose outlets are more concentrated in specific sectors, particularly the building industry.

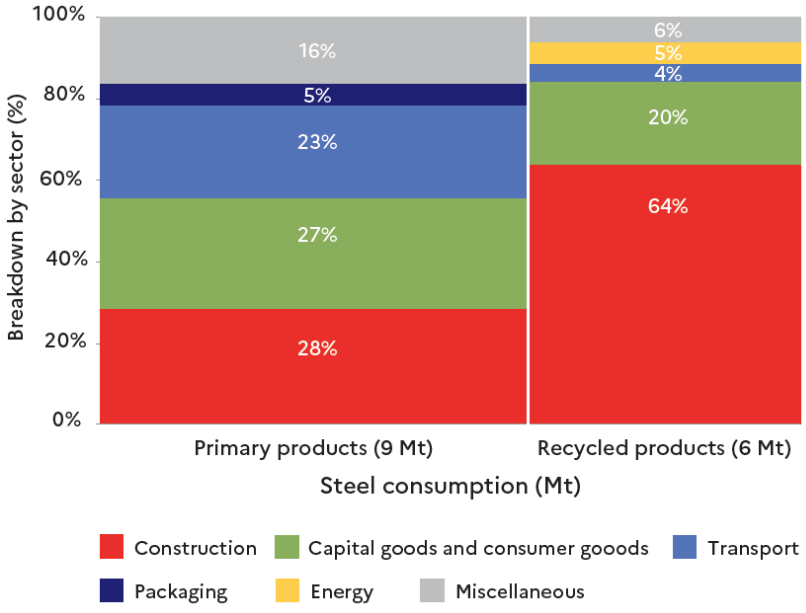


Figure 14. Breakdown of final consumption of primary and recycled products in France (source: ADEME estimates based on data from the négaWatt study conducted on behalf of ADEME and the creation of the MODEIRE tool)

[10] "Non-alloy steels" are also known as "low-alloy steels".

In terms of foresight, assumptions about changes in the uses of goods containing steel make it possible to estimate percentage change in final demand for steel on the French market. By way of example, in building and civil engineering, the current downward trend is set to become more marked in connection with the achievement of the No Net Land Take (NNLT) target, under the 2021 Climate and Resilience Act (*Loi Climat et Résilience*), by 2050. If this trend continues, the long carbon steel products sector will be particularly hard hit, making diversification of its outlets necessary. Competition from bio-based materials as opposed to reinforced concrete in building structures could also have an effect on demand for steel from the building and civil engineering industry. In the energy sector, the deployment of renewable energies should increase the need for steel. However, today, renewable energy production equipment is for the most part produced outside of the European Union. This upward trend would therefore only be able to work in favour of French steelworks – and the rest of the upstream value chain – on the condition of a policy of reindustrialisation. In the transport sector, the trend is more uncertain. Reduced use of cars for commuting – connected with working from home, car sharing and the shift in modes of transport towards rail and bicycle – could limit wear and tear on existing vehicles on the road, and therefore reduce the need for steel for their replacement. Similarly, the use of aluminium and plastics, which are lighter, is tending to replace steel consumption in vehicle design. In addition, European regulations on prohibition of the sale of internal combustion engine-powered vehicles by 2035 are fuelling uncertainty about steel requirements for the motor industry.

2.3. Deterioration in the trade balance for the French steel industry and highly uncertain prospects for change

At every level of its value chain, steel is a material that is highly integrated into international trade. Global import and export flows have grown continuously, spurred on by the needs of developing countries and the lowering of trade barriers. In France, the dynamics are nevertheless specific to each type of steel:

- For primary flat steels, around 70% of French consumption and production is traded internationally, principally to and from EU countries[11].
- For certain stainless and high alloy steels, French sites target niche markets, resulting in an output that is almost entirely exported to destinations throughout the world.
- For long carbon steel products, in particular those used in the building industry, trade is less extensive and takes place on a regional scale.

Between 2014 and 2019, France's steel trade balance[12] deteriorated across all sectors (Figure 15). The flat steel balance went from a surplus to a deficit, while the deficit in the long carbon products balance increased sharply.

[11] However, this trade with the European Union masks more global trade.. Indeed, Belgium and the Netherlands host the ports of Antwerp and Rotterdam, which are major hubs for international trade.

[12] Trade balance in volume (i.e. the difference between the mass of steel exported and the mass of steel imported).

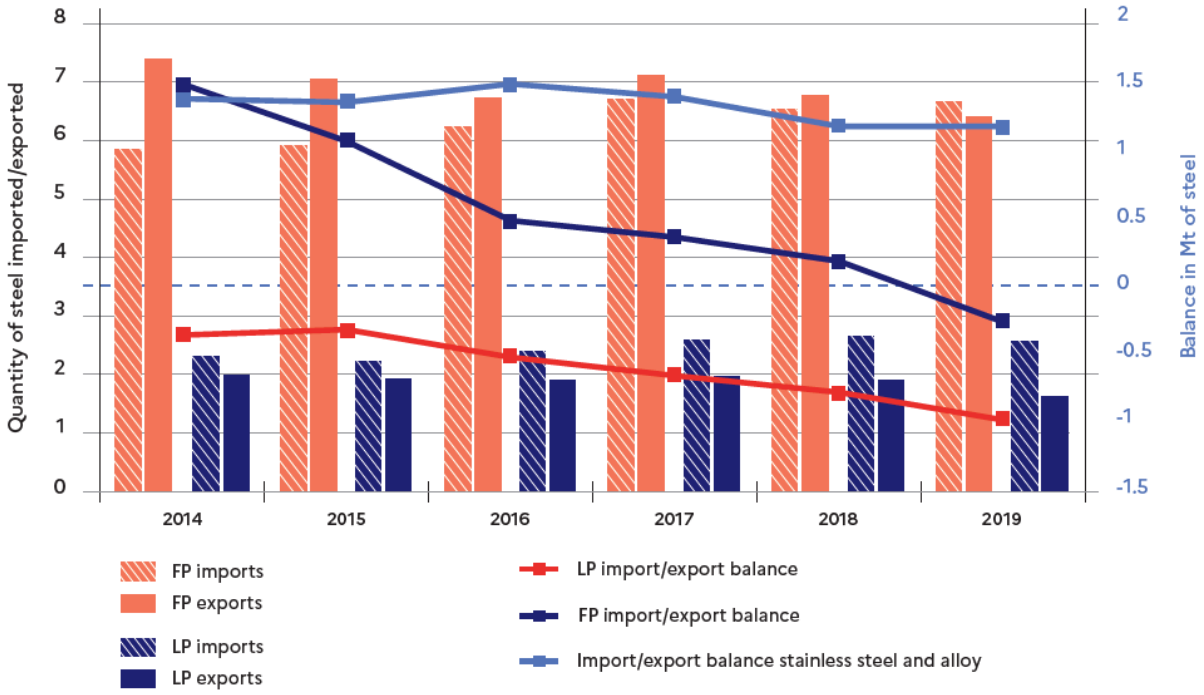


Figure 15. Changes in steel imports and exports from 2014 to 2019, by type of product (source: ADEME on the basis of UN Comtrade data)

While these figures reflect the fact of a probable loss of competitiveness of French manufacturers as compared with their competitors, in-depth studies would make it possible to shed light on the reasons for this in a more effective manner. By way of example, observed production overcapacity worldwide is fuelling the discrepancy between supply and demand (*e.g.* in 2017, the capacity utilisation rate was estimated at 75%), driving prices down and intensifying competition[5]. In this situation, companies in which economies of scale are harder to achieve, and/or that are positioned in the most competitive market segments, encounter difficulties. In certain cases, companies are integrated into larger groups, and sites are either closed or restructured. As mentioned above, the industry's production capacity was progressively reduced after 2010. As a result, France has tended to export less and, at the same time, to become more dependent on imports. In order to provide a more in-depth explanation of the deterioration of this balance and identify possible courses of action to reverse the trend, it is necessary to distinguish between the different markets in which French players are positioned, the factors of competitiveness in these markets, and the positioning both of the principal current competitors, and potential future competitors between the present and 2030, or even 2050.

By way of simplification, the foresight assumptions connected with trends in international trade used in the modelling only distinguish between the three types of steel mentioned above: flat carbon steel, long carbon steel and stainless/high-alloy steel (section 4.2.2). As with changes on the domestic market, this simplificatory typology makes it possible to reflect probable differentiation in trends between these three segments, though it probably masks specific features of the outlets, in France and on foreign markets, for each "sub-segment".

2.4. Focus on Material Inputs

2.4.1. Iron ore

Iron ore is a resource that is unevenly distributed on a world scale, and its mining is highly concentrated geographically. Five countries between them account for almost 80% of global production: Australia, Brazil, China, India and Russia. With the addition of Canada, South Africa, Ukraine, the United States and Sweden, almost 95% of world production is divided between ten countries[6]. Between 1998 and 2017, global production increased by a factor of 2.5 before beginning to reach a plateau (Figure 16).

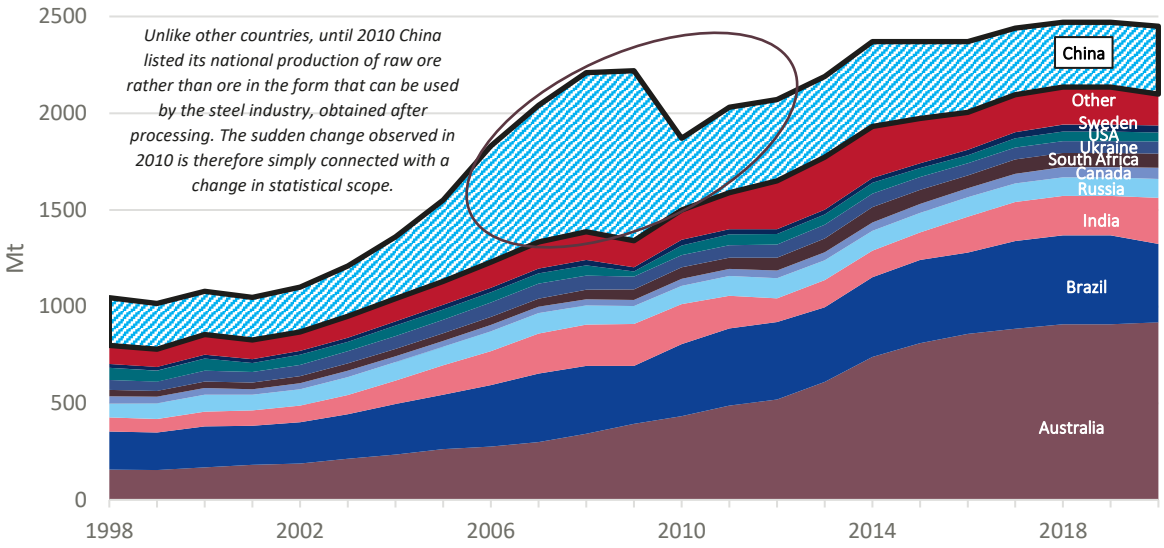


Figure 16: Changes in global iron ore production by country (source: USGS)

Since France no longer produces iron ore, it now imports it, principally from Canada and Brazil, which together represented around 75% of imports in 2021 (Figure 17). The structure of French imports has changed fundamentally over the last twenty years. The total volume of iron ore imported has structurally fallen by around 5 Mt since the financial crisis, as a direct result of the fall in French primary steel production and the closure of certain capacities. Furthermore, Canada, which only accounted for a small proportion of imports in the early 2000s, has now become France's leading supplier. At the same time, imports from Australia and Mauritania have virtually disappeared, while Brazil's share has decreased. Average import prices have also changed significantly over the last 20 years. Before 2005, the price of iron ore was not the result of the interaction of supply and demand, but the outcome of direct negotiations between the world's leading steelmakers and mining companies. The impact of demand for steel from China led to a rise in the price of iron ore, as did a change in the system for setting this price after 2008, which has directly resulted in greater volatility. Ultimately, the price of iron ore today is the result of interaction between demand, principally from China, and supply, which is for the most part controlled by a few big mining groups[7].

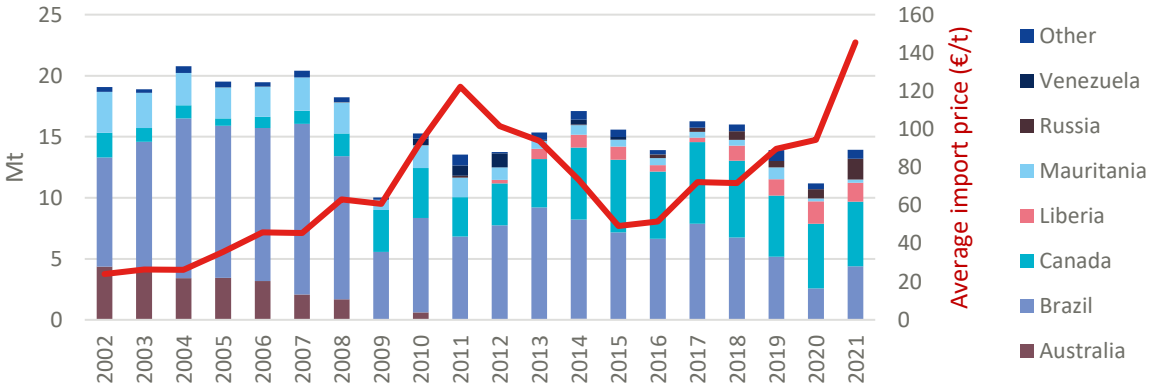


Figure 17: Iron ore imports into France by origin (source: ADEME on the basis of UN Comtrade data[13])

2.4.2. Additional metals

Today, several thousand different steel alloys exist, produced by adding additional metals enabling the improvement of certain properties. The sharp increase in the number of steel grades is relatively recent: around 40% of the alloys produced to date were developed over the last 50 years. [5]. A very high proportion of the composition of certain special steels may consist of alloy metals, such as nickel, which can represent up to 40% of the alloy[8]. Table 1 provides a few examples of alloy metals, the characteristics they can provide to steel, and some of the applications for which they are used. The price of alloy elements fluctuates sharply, driving steelmakers to try to reduce the proportion of these elements in the end products they provide to clients. For example, there is a tendency for the reduction of nickel and copper content[9]. These metals, which

[13] Customs code: 2601 - Iron ores and concentrates, incl. roasted iron pyrites [pyrite ash]

have a major influence on the properties of the steel, are added at the secondary steelmaking stage, in general in the form of ferro-alloys. Ferro-alloys are metal compounds containing iron and other metals, marketed as "ingredients" for steelmaking.

Alloy element	Impact on steel properties	Applications
Chrome (Cr)	• Mechanical resistance when hot • Resistance to oxidation • Resistance to corrosion • Increases hardenability and tensile strength	• Stainless steel: high chromium content. Other components can be used to improve certain properties (nickel, molybdenum, titanium). • Chromoly steel: chromium-molybdenum steel used for high-resistance and high-temperature applications • Nuclear power industry
Manganese (Mn)	• Deoxidising element • Improves machinability through the formation of sulphides • Good resistance to wear • Increases hardenability • Increases tensile strength	• Manufacture of rails
Molybdenum (Mo)	• Resistance to high temperatures • Resistance to wear	• Stainless steel: high chromium content. Other components can be used to improve certain properties (nickel, molybdenum, titanium). • Chromoly steel: chromium-molybdenum steel used for high-resistance and high-temperature applications
Titanium (Ti)	Reduces risk of oxidation of stainless steels	
Vanadium (V)	• Increases hardenability • Raises superheat temperature • Resistance to wear and deformation	

Table 1: Examples of alloy metals, their characteristics and potential applications [10], [11], [12], [13]

In France, the volumes of ferro-alloys involved are relatively small (several kt) compared with the volumes of steel produced (several Mt), but they are absolutely essential elements for the steel industry, without which it would not be possible to endow the various alloys with the necessary properties.

As shown in Figure 18, trade in ferro-alloys is relatively balanced. The principal types of ferro-alloys exchanged are ferrosilicomanganese (FeSiMn), ferromanganese (FeMn), ferrochrome (FeCr), ferronickel (FeNi) and ferrosilicon (FeSi). Other types of ferro-alloy include, for example, ferrotungsten (FeW), ferromolybdenum (FeMo), ferrovanadium (FeV) and ferroniobium (FeNb).

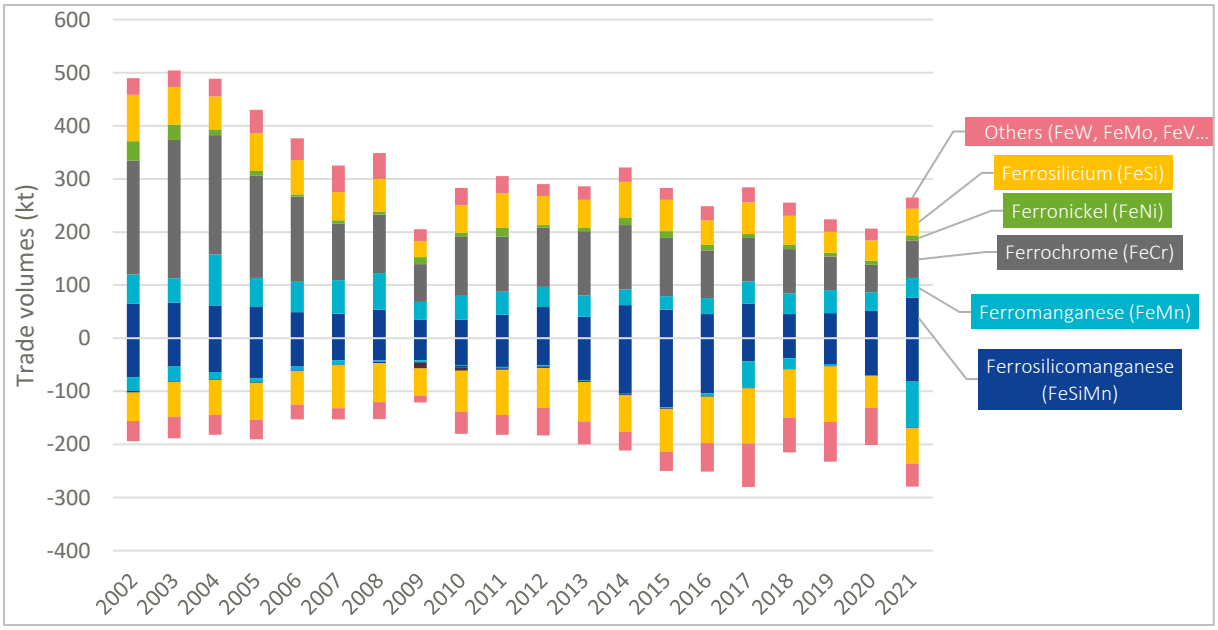


Figure 18: Imports (+)/Exports (-) of ferro-alloys in France by type (source: customs data)[14]).

[14]Customs codes: [720230] for the "Ferrosilicomanganese" category; [720211] and [720219] for the "Ferromanganese" category; [720241] and [720249] for the "Ferrochrome" category; [720260] for the "Ferronickel" category; [720221] and [720229] for the "Ferrosilicon" category; [720250], [720270], [720280], [720291], [720292], [720293] and [720299] for the "Other (FeW, FeMo, FeV etc.)" category.)"..

Text Box 3: Focus on stainless steels

As defined under standard NF EN 10020, stainless steels are steels containing a minimum of 10.5% chromium and a maximum of 1.2% carbon. They are then subdivided into two sub-categories according to whether their nickel content is less than or greater than 2.5%. These steels present three principal characteristics: resistance to corrosion, resistance to scaling and resistance to creep (a phenomenon that causes irreversible deformation of a material placed under stress). Like many commodities, the market is dominated by China, which accounts for 58% of global stainless steel production, as compared with 12% for Europe[14].

Of all the existing grades, 304 stainless steel from the 300 series is the most widespread. In Europe, it represented 51.6% of stainless steel production in 2021. It is widely used in kitchen appliances, in the food-processing industry and in heat exchangers[14]. It is an austenitic steel with a nickel content of 8-10.5% and a chromium content of 18-20%.

There are several possible material input mixes for stainless steel production, which mainly depend on economic trade-offs and the availability of raw materials in different geographical areas. R. Gyllenram & W. Wei (2022) [14] conducted a carbon footprint study of 304 grade stainless steelmaking for three different regions: Europe, China and Indonesia (which represents 9% of world production).. In order calculate this footprint, the average material mixes used to produce 304 grade stainless steel were modelled (Figure 19). For China, three different material mixes (corresponding to letters A, B and C) representing three commonly-used major production strategies were taken into account. The 'average' for China is based on a weight average of 80% mix A, 15% mix B and 5% mix C. While European (and to be specific French) producers mainly use stainless steel scrap as a material input, Chinese and Indonesian producers use a significant proportion of nickel pig iron (NPI). Nickel pig iron (1-15% Ni) was initially developed in China as an inexpensive alternative to other nickel sources such as ferronickel (20-30%) and pure nickel. Since the export ban on nickel ore introduced in Indonesia in 2014, NPI capacity in the country has boomed, with production in the country finally overtaking that of China in 2020, thus making Indonesia the world's leading producer of NPI[14].

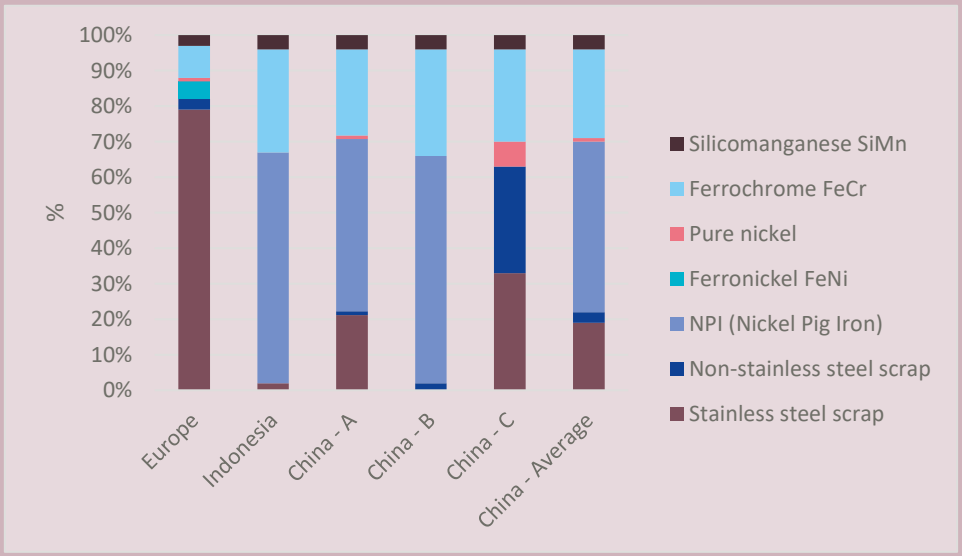


Figure 19: Material input mix for the production of one tonne of 304 grade stainless steel in Europe, Indonesia and China[14].

The choice of materials mix and the carbon content of the electricity grid mix used to produce the inputs are the two principal determinants of the carbon footprint for stainless steel. Figure 20 shows the results of the carbon footprint calculation for 304 grade stainless steel[14]. While Scope 1 emissions (which are alone taken into account within the scope of the STP) represent in the order of 0.1 to 0.3 $tCO2e/t_{steel}$, taking Scope 3 emissions into account results in an increase in the carbon footprint to almost 2 $tCO2e/t_{steel}$ in the case of Europe and to more than 10 $tCO2e/t_{steel}$ in the case of Indonesia.

Figure 19 and Figure 20 illustrate the fact that the principal environmental issue associated with stainless steel production resides in the carbon content of the inputs (more specifically the alloy elements) and not in direct emissions. The methodological framework for Sectoral Transition Plans does not make it possible to deal with these indirect emissions in a quantitative manner, even though, in the case of stainless steel at least, it would be highly worthwhile to take them into account in a future foresight exercise.

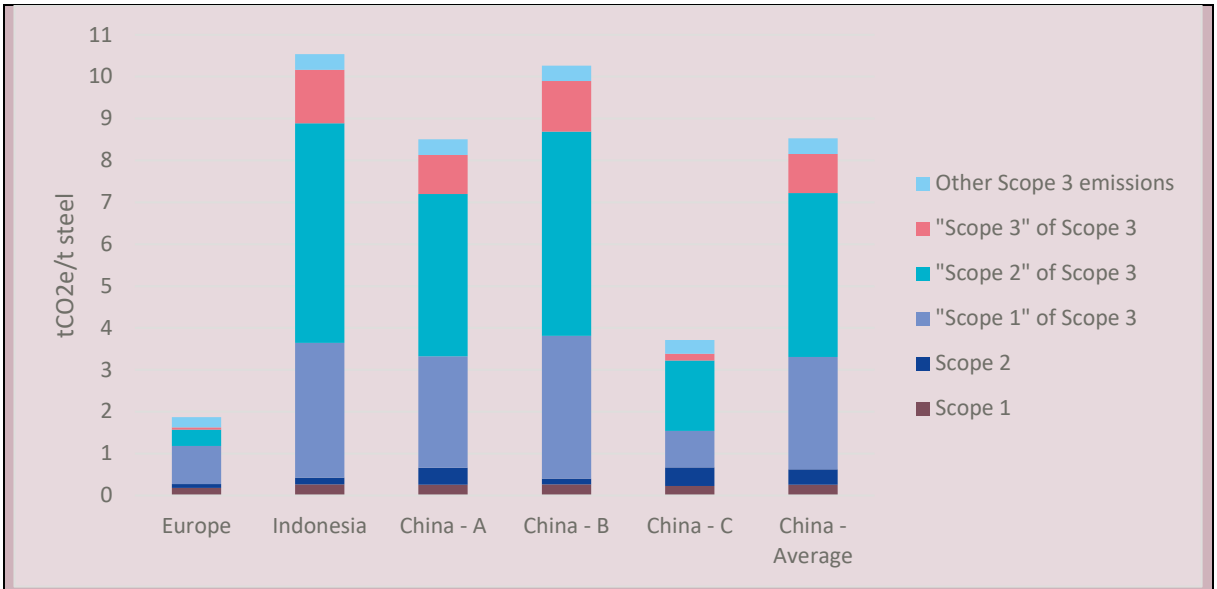


Figure 20: Carbon footprint of one tonne of 304 grade stainless steel in Europe, Indonesia and China [15].

2.4.3. Scrap

2.4.3.1. Quantitative issues

As mentioned above, the electrical sector depends exclusively on an adequate supply of scrap for its output. This supply may at once come from industrial production scrap, which in this case offers the advantage of better knowledge of its composition, as well as above all from end-of-life products containing steel, which is then referred to as external scrap. Figure 21 summaries the end-of-life possibilities for products containing steel[15].

[15] Note: The EPR (Extended Producer Responsibility) channels appear on the diagram at the level of collection for recycling, but play a more global role in the management of end-of-life of products and even upstream, in waste prevention and eco-design. Further information available here: https://expertises.ademe.fr/economie-circulaire/filieres-a-responsabilite-elargie-producteurs-rep/fonctionnement-filiere-rep

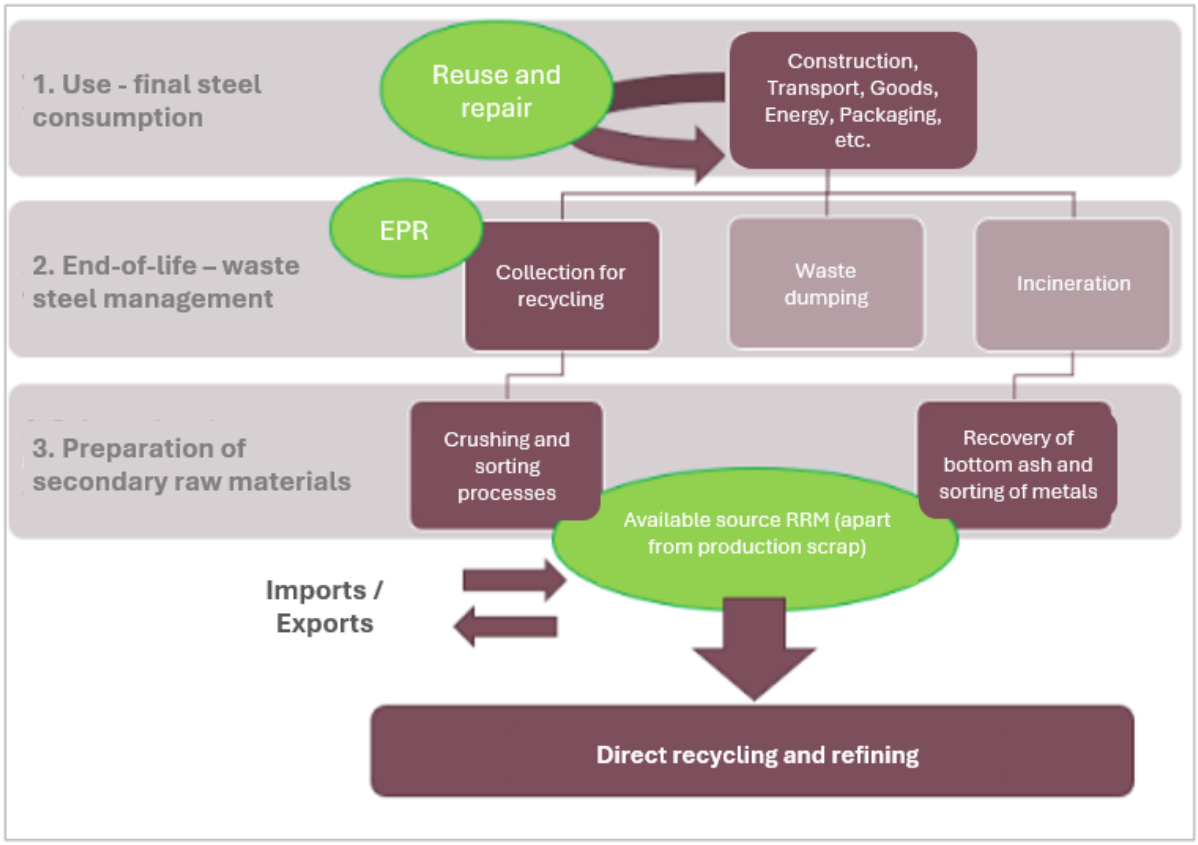


Figure 21: Simplified diagram of the construction of scrap metal reserves

Before they are considered to be "waste", used products may benefit from extension of their lifespan through reuse and repair policies[16]. These activities, some of which are connected with the social and solidarity economy, improve material efficiency and, all other things being equal, reduce demand for final goods. They thus make it possible to save resources and automatically reduce the CO_2 emissions associated with production systems. On the other hand, they have the disadvantage of limiting the amount of waste potentially available for manufacturers. Once a product has reached its end-of-life, there are three main streams: collection for recycling, waste dumping or incineration. Steel can therefore therefore end up in one or other of these streams depending on the type of product in which it is incorporated, and on the sorting process. Although quantities of steel scrap can be recovered after the incineration stage (in clinker), the main stream promoting the availability of this scrap for industry is collection for recycling, principally in the electrical sector and foundries, but also, to some extent, in the blast furnace sector as a supplement to the recovery of production scrap.[17]. This collection process is nevertheless particularly complex due to the dispersion of steel products according to their multiple uses. Although traceability is complex and national scrap reserves are not known with certainty, work has been conducted to reconnect flow circuits within the framework of the MODEIRE modelling tool (Text Box 2, sub-section 2.2) and on the basis of the ADEME French National Recycling Report (*Bilan National du Recyclage*) database[18]. Building and civil engineering thus appears to be the sector in which the highest volume of scrap is collected. These estimates do not reflect the efficiency of collection in each sector, but nevertheless provide an indication of the resources that can be mobilised in the future and the quality of these resources.

[16] Further information available here: https://expertises.ademe.fr/economie-circulaire/dechets/passer-a-laction/eviter-production-dechets/reemploi-reutilisation

[17] So called "internal scrap": pre-consumer scrap steel.

[18] Further information available here: https://librairie.ademe.fr/dechets-economie-circulaire/6959-bilan-national-du-recyclage-bnr-2012-2021.html

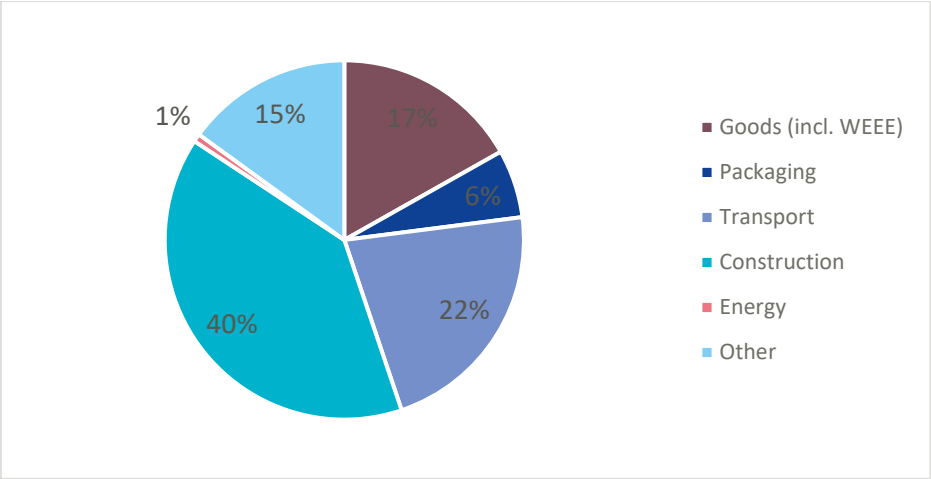


Figure 22: Sectors of origin of scrap in France in 2014 (source: ADEME on the basis of data from the négaWatt study on behalf of ADEME)

Moreover, like many consumer goods, scrap metal is traded internationally. In Europe, this market is highly regionalised, with most trade taking place between European countries. France is a net exporter of scrap, principally to its neighbouring countries (Belgium, Spain and Italy).

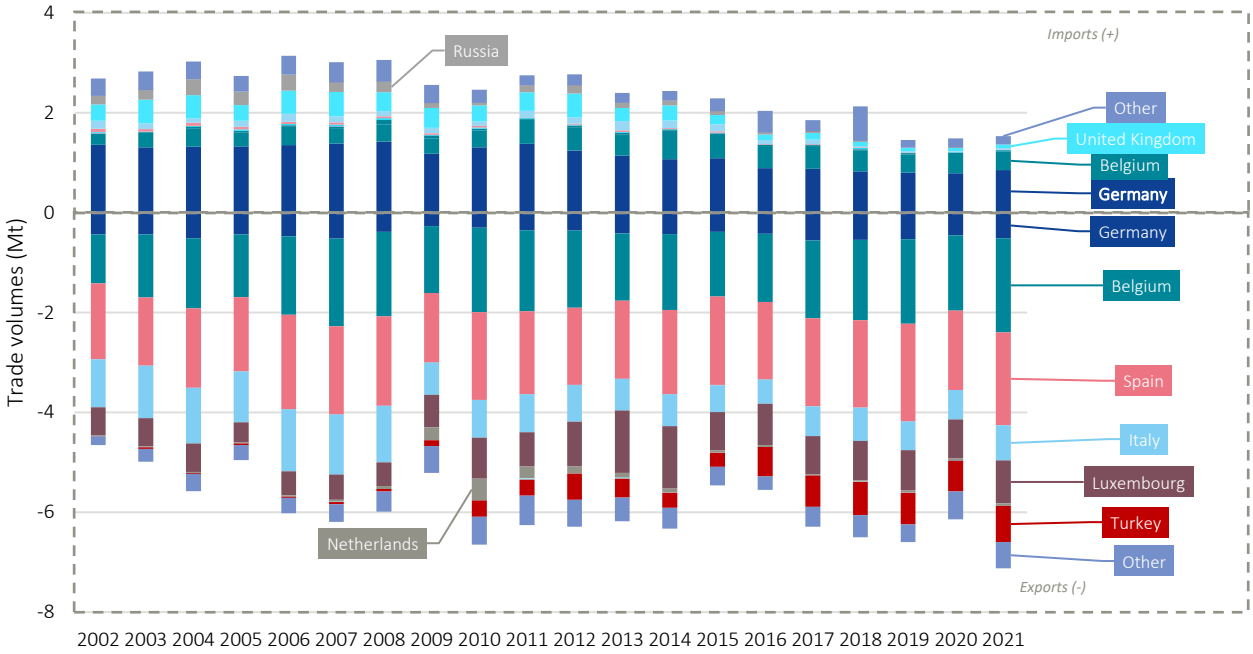


Figure 23: Imports (+) and exports (-) of waste in France by country of origin/destination (source : UN Comtrade[19]).

An in-depth study on the recycling of the most important metals, including steel, was published in March 2024. It is aimed at gaining a better understanding of and quantifying the resources available for recycling in France, and at identifying possible solutions enabling improvement of the recycling rate for these metals. Among these possible solutions, the study suggests the introduction of an incentive for the incorporation of recycled raw materials into finished products, via a "recycled content label". An estimate of consumption trends between now and 2030 and their impact on the circularity of metals is also put forward in this study [20].

2.4.3.2. Scrap quality

[19] Customs code 7204 - Waste and scrap pig iron, iron and steel [scrap ferrous metals].

[20] ADEME, Pierrick DRAPEAU, Louis OLLION, Guillaume BOUYER. 2023. *Étude du potentiel de recyclage de l'acier, de l'aluminium et du cuivre en France* ["Study of the potential for recycling steel, aluminium and copper in France"]. 206 pages. Further information available here: https://librairie.ademe.fr/dechets-economie-circulaire/6958-etude-du-potentiel-d-amelioration-du-recyclage-des-metaux-en-france.html

There are several qualities of scrap, not all of which can be used to produce the same types of steel. The two principal parameters used to establish the quality of scrap metal are the presence of the residual elements it contains (principally copper, tin, chromium, nickel and molybdenum, the sum of which can be used as a proxy for scrap metal quality), and the presence of non-metallic residues on its surface (remains of concrete, paint, organic matter, etc.). Copper is particularly problematic since it is often mixed with steel at the stage of recovery and preparation of certain scrap metals, due to the residual presence of electrical cables in cars destined for recycling. Unlike certain elements, copper is very difficult to separate from steel and contributes to reducing the strength of the material [15]. S. Dworak & J. Fellner (2021) [16] studied changes in the generation and composition of steel scrap in the European Union between 1946 and 2017. The article shows that the average quality of scrap generated in Europe (characterised by the concentration of trace elements such as copper and tin) has declined in recent decades. In particular, a surplus of low-grade scrap has been recorded since the 1990s, which, as illustrated in Figure24, strongly coincides with the upward trend in net scrap exports to destinations outside of the European Union. The study thus suggests that lower quality scrap generated in Europe is now exported outside of the EU, while good quality scrap is recycled within EU countries, in both cases presumably for economic reasons.

Figure24: Estimated surplus of Q3 and Q4 quality scrap and net exports of scrap from the European Union [16]

2.5. Co-products: steelmaking slag

Steelmaking slag is a by-product of the steel industry. Mastery of the chemistry of slag is essential to steel production, so much so that an old expression that has currency in the steel-making world pays tribute to it: “Make the slag and the steel will make itself” [17].

Raw materials, principally iron ore, coal and scrap, are always sources of impurities that need to be removed. They include sulphur, silica, phosphorus and various types of oxides such as alumina [17]. In order to form the slag and eliminate a part of these impurities, lime is added at different stages of the process. Since these elements are acidic, lime is used to maintain the basicity of the slag. It reacts with the elements with the following reactions:

Silica	$SiO_2 + 3\ CaO \rightarrow (Ca_2SiO_4) + (Ca_3SiO_5)$
Alumina	$9\ Al_2O_3 + 16\ CaO \rightarrow (CaAl_2O_4) + (Ca_3Al_2O_6) + (Ca_{12}Al_{14}O_{33})$
Sulphur	$2\ S + 2\ CaO \rightarrow 2\ CaS + O_2$
Phosphorus	$2\ P + 3\ CaO + 5\ FeO \leftrightarrow 3\ CaOP_2O_5 + 5\ Fe$

However, iron can be lost in the slag in the form of FeO, and for this reason the presence of impurities tends to reduce the ferric yield and therefore productivity [18]. Generally speaking, steel-making slag is recycled in the construction sector. Blast furnace slag is thus used in the composition of certain cements [21], while slag from electrical steelworks is often used as a road base because of its geotechnical properties. Slag from stainless steel production is more difficult to recover since it has a high chromium content, sometimes as much as 30%. There are several principal types of steelmaking slag, summarised in Table 2 below [19], [20].

[21] Further information is available in the report “Sectoral Transition Plan for the French cement industry” available here:https://librairie.ademe.fr/energies/5185-sectoral-transition-plan-for-the-french-cement-industry.html

Type of slag	Description	Unit production	Composition	Use
Crystallised blast furnace slag	Obtained by slow cooling, which converts the slag into an artificial, chemically stable hard rock. Its physical and mechanical characteristics are comparable to those of natural materials.	~250 – 300 kg/$t_{pig\ iron}$	CaO 40 % SiO_2 35 % Al_2O_3 11 % MgO 8 %	Civil engineering: aggregates for concretes, tarmacs and ballast. This material has high mechanical resistance and low thermal conductivity, concretes made from crystallised slag aggregates are therefore a much better insulating material than conventional concretes.
Vitrified blast furnace slag	This material is obtained by sudden cooling, in general by means of water, giving it a vitreous structure producing properties similar to those of cement. It is usually produced in the form of granulated slag due to its physico-chemical characteristics.	~250 – 300 kg/$t_{pig\ iron}$	CaO 40 % SiO_2 35 % Al_2O_3 11 % MgO 8 %	Civil engineering: principally used in cement production as a substitute for clinker, in particular for making concrete in aggressive environments (alkaline and maritime environments). Also used as an additive in ground form in concrete as a partial replacement for cement, and for making hydraulic gravel bases for roads. Industry: used in the glass industry as a source of alumina and silica.
Oxygen converter steelworks slag	Slag from the oxygen converter is first cooled gradually with air and then suddenly through spraying with water.	~100 kg/t_{steel}	CaO 50 % Fe 15 % SiO_2 12 % MgO 5 %	Agriculture: mixed fertiliser, amendment-fertiliser on crops, pasture, either directly or mixed with phosphate and potassium fertilisers. Civil engineering: backfill material, subgrades, reinforcement of hydraulic structures, tarmacs, etc.
Slag from carbon steel production in the electrical sector	Furnace slag refers to slag produced from the melting of raw materials in an electric arc furnace. Ladle slag ("white slag") refers to slag produced from the refining of steel in a ladle furnace by the addition of alloying elements and deoxidation.	Furnace slag: ~100 kg/t_{steel}		Furnace slag: road base, foundation base, backfill, tarmac, treatment of waste water Ladle slag: agriculture, cement industry
Slag from stainless steel production	Slag is produced at three main stages in the process. Furnace slag refers to slag produced from the melting of raw materials in an electric arc furnace. Ferrosilicon is added to limit oxidation of the chromium, thus producing silica which needs to be removed. Lime is thus added to form a liquid lime silicate which forms the slag.	Furnace slag: ~70 kg/t_{steel} AOD slag: ~90 kg/t_{steel} Ladle slag: ~10 kg/t_{steel}	CaO 45 - 55 % SiO_2 25 - 35 % MgO 2 - 7 %	Civil engineering: construction of tracks and countryside paths, materials for backfill and roadway layers, under surface layer Construction industry: concrete aggregates, hydraulic binding agent for manufacture of bricks

Table 2: Summary of the principal slags produced by the steel industry

3. How is Steel Produced? Past, Present, and Future.

Production of primary steel consists in enriching iron with carbon, starting with iron ore, which is naturally in the form of oxides. This operation requires a chemical reaction (reduction), which in France today is completed in blast furnaces with coke (almost pure carbon) as the reducing agent, at a high temperature (1,250°C). In the course of this process, the carbon undergoes combustion, on the one hand, and captures the oxygen bound to the iron, on the other, resulting in the emission of CO_2.

In order to reduce the emissions from the primary steel production sector, two approaches can be distinguished. The first consists in developing blast furnaces to a higher standard, although these improvements do not enable complete decarbonisation. The alternative is to replace blast furnaces with other, less mature, reduction processes that do not generate CO_2 emissions.

It is also possible to develop the secondary steel sector, which generates far lower CO_2 emissions. However, it is difficult to base steel production solely on this route, since products made solely from scrap are of lower quality, and production capacity is limited by availability of sources of scrap. Moreover, although the secondary sector already produces relatively low emissions, there is still considerable scope for further emission reductions.

3.1. History of steel production processes

The oldest traces of the use and working of iron date to around 2,500 B.C. in Anatolia (now Turkey). Metallurgical techniques such as bloomeries and tempering developed from this period onwards. Because of its greater hardness and resistance, iron gradually replaced bronze in the manufacture of weapons, thus the Bronze Age finally gave way to the Iron Age around 800 B.C. in Western Europe. At that time, blacksmiths worked metal by hand at relatively low temperatures. The blast furnace first appeared in China around 1,000 B.C. The increase in the flow of hot air made it possible to reach higher temperatures, indirectly leading to the discovery of pig iron. The distinction between iron and steel was made in Antiquity, and the blast furnace gradually spread across Europe during the Middle Ages.

Until the 19th century, steel remained expensive and was produced in small quantities. It was reserved for small items such as knives and swords, while large metal structures were made from cast or wrought iron. In 1856, the English engineer Harry Bessemer invented the first oxygen conversion process, which improved the stage of refining molten pig iron (“hot metal”) into steel and sharply reduced production costs. Moreover, Britain was the birthplace of the modern steel industry, representing almost 50% of global pig iron production in 1875, with exports mainly going to the United States. At the end of the 19th century, the United States had become the world’s leading producer and Germany was on the point of catching up with Great Britain. The industrialisation of steel production led, inter alia, to the rapid expansion of rail transport, shipbuilding, toolmaking and heat engines. In combination with coal mining, steel eventually provided the basis for the Industrial Revolution. For its part, the electric arc furnace process still used today was developed by the French physicist Paul Héroult in 1887 (who also invented the aluminium electrolysis process). However, the electric arc furnace was initially reserved for the production of special high alloy steels and ferro-alloys such as vanadium and ferrochromium.

In the aftermath of the Second World War, the steel industry was restructured and gradually entered the era of globalisation: while steel production sites were historically located near mining areas and coal fields, new factories were built in the 1950s on large flat plots of land close to port areas, to facilitate taking delivery of raw materials and exporting of products. It was also in this period that the first modern basic oxygen converter to produce steel was built in 1952 in the city of Linz, in Austria, while the second converter of this type was built in Donawitz, another Austrian town. For this reason the oxygen converter process as used today was named the Linz-Donawitz steelmaking process. The electrical sector also greatly expanded after the Second World War, taking advantage of the large quantities of scrap from the ruins and the fighting. The oxygen converter and the electric arc furnace have gradually replaced less efficient methods such as the Thomas process or the Siemens-Martin process, the last furnace using this process in Europe being closed in 1993, despite the fact that such furnaces accounted for 80% of global production in 1950 [21].

There are a number of different steelmaking processes in the world, as shown in the following diagram:

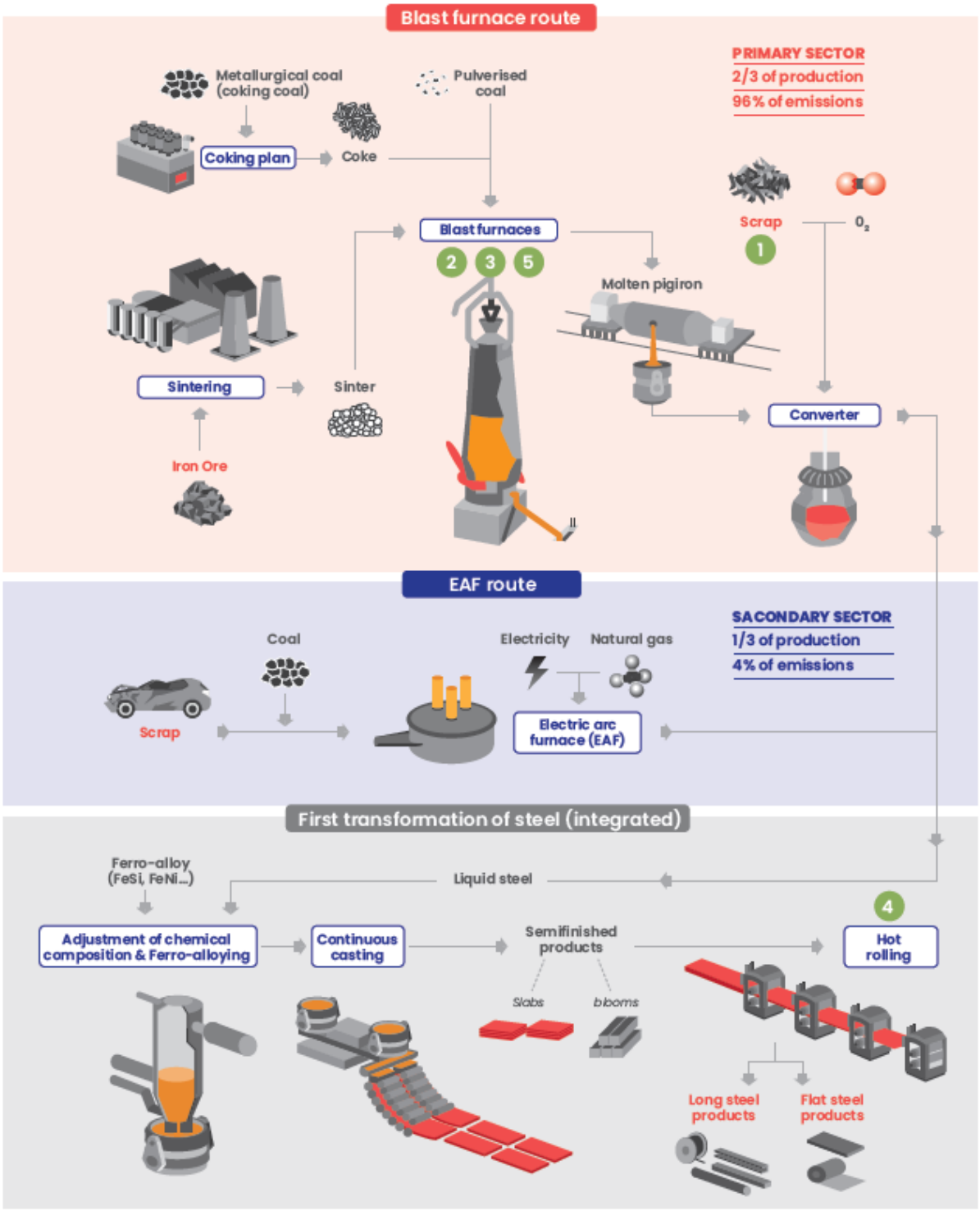


Figure 25: Principal steel production methods in the world (adapted from various sources by Wang et al. (2020)[22]).

3.2. Blast Furnace Sector

3.2.1. Blast furnace sector processes

The blast furnace sector produces what is referred to as "primary" steel, since it comes from the extraction of iron ore[22]. Pre-graded (size) and prepared iron ore is reduced by means of metallurgical (coking) coal in a blast furnace, producing hot metal at a temperature of around 1,250°C. In a second stage, the hot metal is converted into steel in an oxygen converter, in which scrap metal may be incorporated. The oxygen injected into the converter burns off the excess carbon in the pig iron, forming

[22] As opposed to the secondary sector, which uses scrap, i.e. ferrous waste.

liquid steel. All the facilities, including the sinter plant, coking plant, blast furnaces, converters and hot and cold rollers, form an integrated site. A blast furnace can produce several million tonnes of pig iron a year. According to the World Steel Association, the international federation of steel producers, the blast furnace sector represented 72% of the world's steel-making plant in 2022.

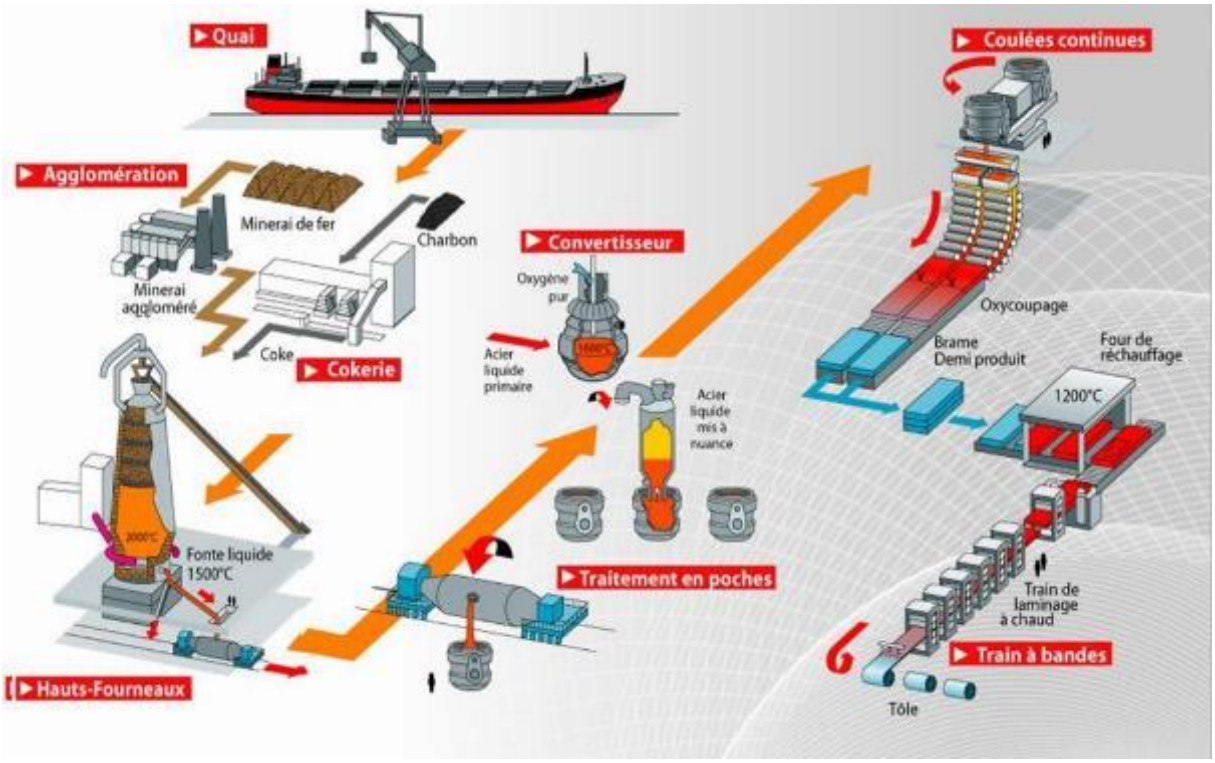


Figure 26: Diagram of an integrated blast furnace site (source: ArcelorMittal [23])

3.2.1.1. Sintering

In order to be usable in a blast furnace, iron ore has to be converted into an intermediate product by sintering. The purpose of this stage is to modify the physical, chemical and mineralogical properties of the raw materials in order to improve the quality of the pig iron and increase the productivity of the blast furnace. In particular, it enables the drying and dehydration of the raw materials, and the elimination of volatile matter [24].

There are two main methods: grate sintering, which results in a product known simply as 'sinter', and pelletising. Grate sintering is the oldest and still the most widely-used process in the world, but pelletising is expanding significantly.

Sintering only concerns iron ore fines, which is one of the two forms of ore delivered to steelmakers. The other form, known as "lumps", is coarser and can be fed into the blast furnace after simple crushing and separation by screening of the fines it contains, which are incorporated into other fines for sintering. Grate sintering uses medium-sized fines, while pelletisation requires smaller fines (see Table 3 below from[25]).

As a result of the depletion of geological resources worldwide, iron ore producers, seeking to meet particularly strong demand from Asia, have observed a decline in the average iron content and quality of the deposits mined in recent years. Thus, lump ore with a high iron content is tending to become scarcer, with increased production of fines, which are more suitable for pelletising rather than sintering [26].

Product	Size	Application
"Lump" ore	6.3-31.7 mm	Can be used directly in blast furnaces and direct reduction furnaces
Fines for grate sintering	0.15-6.3 mm	Sinter for use in blast furnaces
Fines for pelletisation	<0.15 mm	Pellets for use in blast furnaces and direct reduction furnaces

Table 3: Classification of iron ore by-products for steel production[25].

3.2.1.1.1. Grate Sintering

Once homogenised, the fines are mixed with a solid fuel, in general of an inexpensive kind, such as coal or coke waste ("dust"), a flux (a product used to lower the melting temperature of the ore, such as limestone), lime and sources of iron recycled in the process, such as return fines and steelworks sludge. Sintering consists of agglomerating or coalescing the mixture by combustion at a controlled temperature on a travelling grate[21], [27], [28], [29].

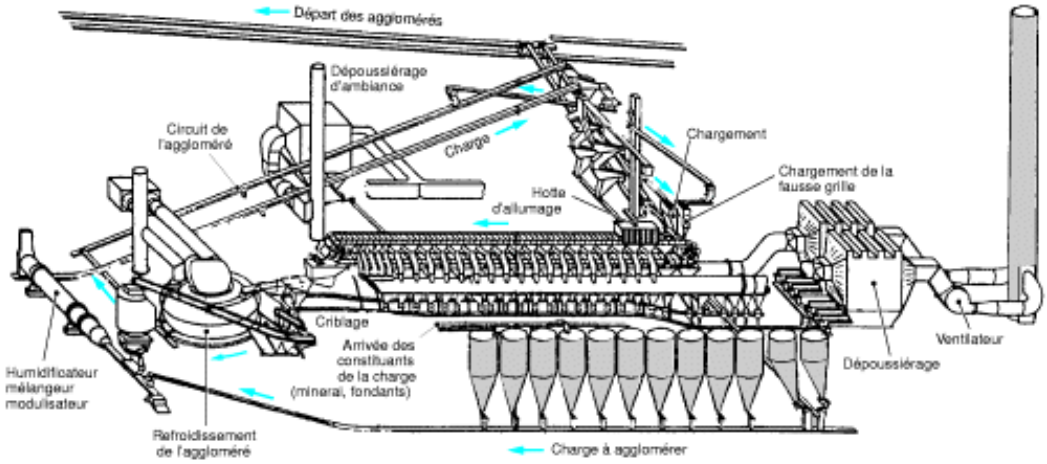


Figure 27: Iron ore grate sintering plant[28].

3.2.1.1.2. Pelletising

While grate sintering is typically conducted on integrated sites, pellet production (or "pelletisation") is in general conducted close to the mine where the iron ore is extracted. The Swedish company A.G. Andersson was the first to patent a process of this type in 1912[25].

The fines are first mixed with a hydraulic binding agent (typically bentonite), coal fines and additives (such as lime and dolomite for correction of basicity). The pellets are formed by sintering using a precise quantity of water and a pelletisation bed. The so called "raw" pellets are then screened to remove the fines, which are then recirculated. Pellets of the correct size and composition are dried and gradually heated to around 1,300°C to achieve hardening by heat (see Figure28).

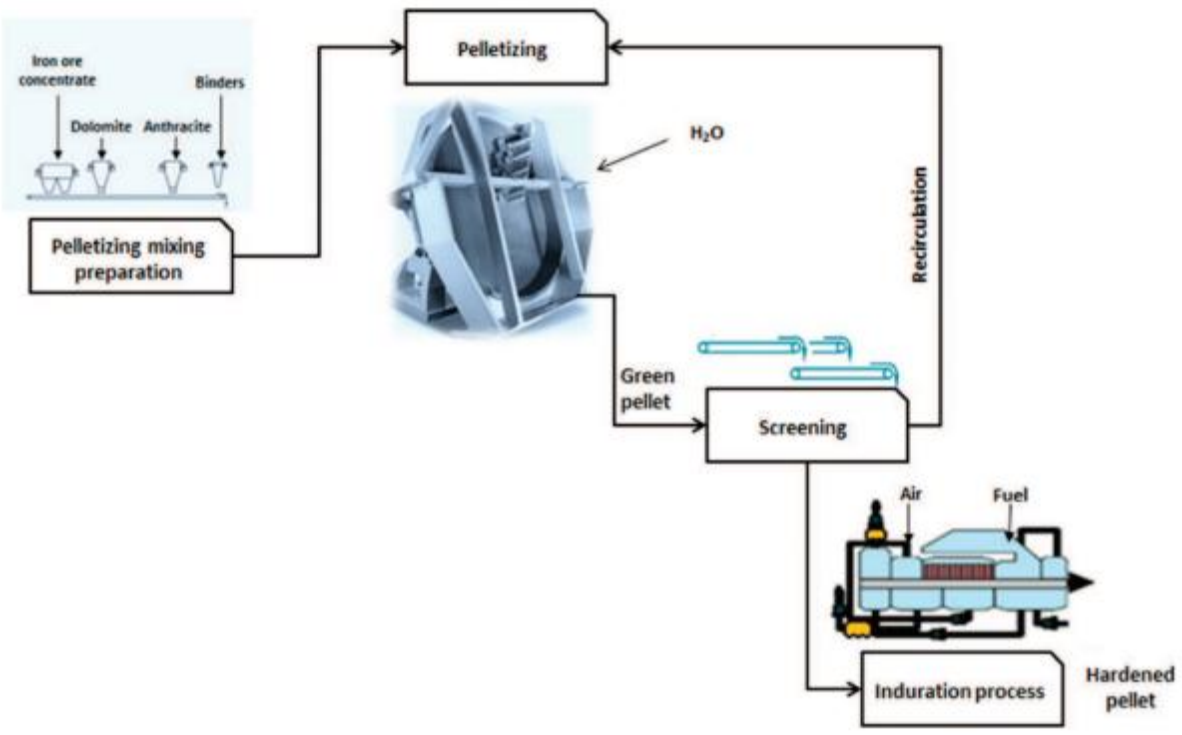


Figure28: Diagram of a pellet plant using a pelletising disc[25].

3.2.1.2. Coking Plants

In addition to its chemical role in the blast furnace, coke has a mechanical function: as the only permanent solid in the reactor, coke ensures permeability within the load, which means that it needs to allow gases and liquids to circulate while ensuring good mechanical resistance[30].

Coke, which is in fact the principal source of carbon in the blast furnace, is produced from metallurgical (coking) coal. It has higher purity and carbon content than thermal coal. At high temperatures of around 1,100°C and in an oxygen-poor environment, coal undergoes pyrolysis, which removes all of the volatile components it contains, leaving only the carbon. Coal pyrolysis is conducted in furnace batteries and may take from 16 to 20 hours, which is why coke is produced in batches. After being removed from the oven, the coke is cooled and then screened to separate the smallest particles, which are used elsewhere as fuel ("coke dust"). A range of equipment is used to treat the water and gases leaving the furnaces in order to eliminate tars, sulphur, ammonia and other hydrocarbons. The process also generates coke oven gas, which is of the same nature as coal gas, which was once used for lighting in towns. It is principally composed of hydrogen (~60%), methane (~25%), nitrogen and carbon monoxide (CO), and is in general recovered as energy after cleaning in order to directly cover the coking plant's thermal requirements, or for electricity production in certain cases [1], [21], [27], [31][23]. The high proportion of H_2 in coke oven gas is explained by the coal pyrolysis process, which removes the volatile components and produces light compounds, including hydrogen, leaving a carbonaceous solid: coke[32].

3.2.1.3. Blast Furnaces

A blast furnace (Figure29 and Figure 30) is a counter-current chemical reactor in which iron oxides are reduced. The coke and iron ore are fed through the top of the reactor, the "top" or "charging door". Pulverised coal (dried and finely ground) is also injected through the tuyères below [33]. This replaces part of the coke, which is more expensive. The coal used for injection through the tuyères is typically high quality thermal coal or metallurgical coal not usable for coking, both of which are cheaper than coke. The overall reaction produces hot metal containing around 4-5% carbon and a slag, which floats above the molten metal. The two products are recovered separately at the bottom of the blast furnace, in the "crucible", under the hot air injection tuyères.

The blast is preheated by Cowper stoves before being blown into the blast furnace. These are heating apparatuses that operate in a cyclical manner: cold air that has previously been oxygen enriched is heated to between 1,200 and 1,250°C by means of a burner, principally fuelled with blast furnace gas, the cheapest energy source of all, and sometimes enriched with coke oven gas ("gas" operation), then the hot blast is blown into the blast furnace ("blast" operation) [21], [34], [35].

The first chemical reaction that occurs is that of combustion of the coke by the oxygen in the hot air. This exothermic (i.e. heat-releasing) reaction, which takes place in the crucible, is the principal heat input to the blast furnace. The temperature reached by the gas in the tuyères, known as the "flame temperature", is generally speaking between 1,900 and 2,100°C [27].

$C + O_2 \rightarrow CO_2$

At high temperatures, an endothermic (i.e. energy-consuming) reaction immediately ensues between the CO_2 produced by the previous reaction and the solid carbon. This chemical reaction is an equilibrium reaction, the Boudouard reaction. It regenerates carbon monoxide as it is consumed by the reduction of oxides.

$CO_2 + C \leftrightarrow 2\ CO$

Dihydrogen (H_2), a second reducing gas, is also produced by thermal decomposition of the water vapour present in the air injected through the tuyères. This gas is also produced from the hydrogen contained in the injection coal, which has a higher hydrogen content than coke, and from the moisture in the incoming charge. For example, in the operation of blast furnace 1 at ArcelorMittal in Fos in 2015, with a high level of coal injection, 62% of the H_2 gas was produced from hydrogen from the injection coal and 25% from the moisture in the charge [27], [36]. In the presence of water, the general equation for H_2 production is:

$H_2O + C \leftrightarrow H_2 + CO$

In ore, iron is mainly present in three forms of oxides: haematite (Fe_2O_3), magnetite (Fe_3O_4) and wüstite (FeO), here shown from the most oxidised to the least oxidised form. In the reaction chain, haematite Fe_2O_3 (+III) is first reduced to magnetite Fe_3O_4 (+II, +III), then to wüstite FeO (+II) and finally to iron Fe. When it comes out of the tuyère, the reducing gas is composed of around 35% CO, and 5% H_2, the remainder being composed of nitrogen. The latter rises in the blast furnace against the flow of solid matter and contributes to the so called "indirect" reduction of Fe_2O_3 and Fe_3O_4 iron oxides, which are reduced to FeO in the upper part of the shaft. Inside blast furnaces, between 70 and 80% of the reduction of oxides is attributable to

[23] The composition of coke oven gas makes it a resource for energy uses, and moreover for chemical uses, through the reducing power of dihydrogen (H_2) and carbon monoxide (CO). This is the purpose of the injection of coke oven gases into blast furnaces as reducing agents.

CO and between 20 and 30% to H_2[37]. In the lower part of the shaft, in the "barrel", the wüstite FeO is reduced to Fe above 1,000°C indirectly by the reducing gases and directly by the carbon contained in the coke and injection coal. The overall reduction reaction for the iron oxides is[27]:

$Fe_2O_3 + 3\ C \rightarrow 2\ Fe + 3\ CO$

Part of the coke is dissolved in the molten metal, thus producing pig iron by carburisation. Other elements present in the form of oxides in the charge are also reduced inside the blast furnace, and are divided between the pig iron and the slag. These elements include manganese, silicon, phosphorus, aluminium, magnesium, calcium, titanium, vanadium, chromium, copper, nickel, cobalt, zinc, lead, sodium, potassium and sulphur [27].

The role of lime (and of limestone decarbonated into lime by the reaction $CaCO_3 \rightarrow CaO + CO_2$) is to remove sulphur and acidic impurities from the charge through the formation of slag [38].

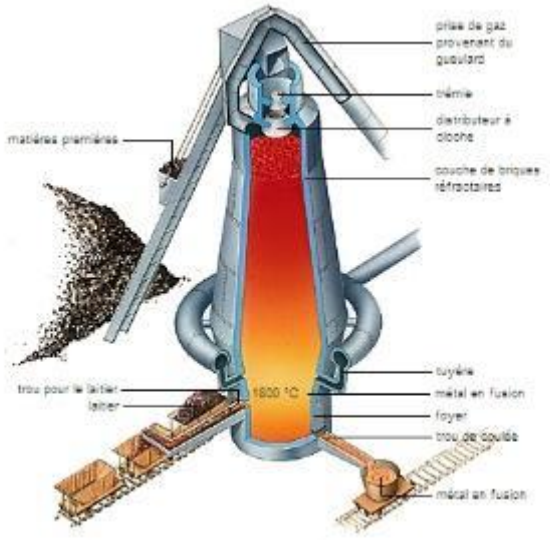


Figure29: Cross-section of a blast furnace [39].

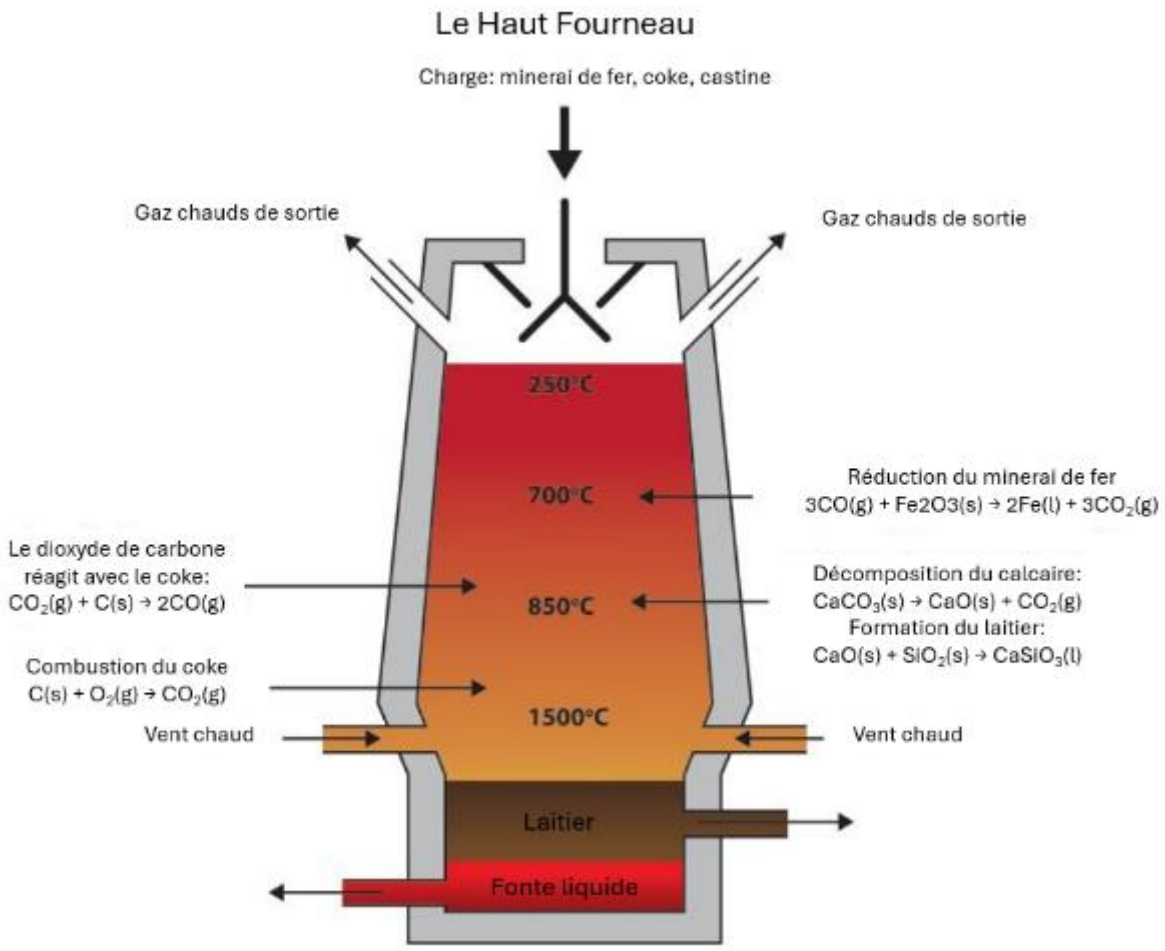


Figure 30: Cross-section diagram of a blast furnace [40].

3.2.1.4. Oxygen Converter Steelmaking

An oxygen converter is a reactor that enables the production of steel from pig iron through the reduction of its carbon content by blowing in pure oxygen (> 99%) [21], unlike the oxygen used to enrich the air blast in blast furnaces, which only requires a minimum purity of 95% [31]. The degree of oxidation of the pig iron depends on the required quality of steel. The overall reaction, which is simply the oxidation of different elements, is exothermic, which makes it possible to maintain heat input in the liquid metal, but the temperature needs to be regulated. This temperature control is achieved in particular by the addition of scrap, which also makes it possible to reduce the quantity of pig iron required for the production of a tonne of steel [31].

When it leaves the blast furnace, the hot metal is transported to the steelworks in transfer ladles or "bottle cars". The molten pig iron is then desulphurised by injecting a desulphurising agent, usually calcium carbide (CaC_2) but also sometimes lime or magnesium [21]. In the presence of calcium carbide, the sulphur present in the pig iron then appears in the slag in the form of calcium sulphide (CaS). The molten pig iron is then poured into a charging ladle, and if the desulphurisation operation has not been completed beforehand, it is usually done at this stage. In the charging ladle, the sulphur-rich slag is removed by slagging: this involves scraping the slag off the surface of the liquid in a recovery tank using a rake. Once the slag has been removed, the molten pig iron is poured into the converter by tilting the charging ladle. Scrap is increasingly placed in the furnace before the hot metal is poured in, in order to avoid dusty bursts of flame. Scrap may come from internal recycling and “selected scrap” (coils, solid pig iron, etc.) or from an external recycler. Other iron sources such as solid pig iron, DRI (direct reduced iron) and iron ore may be added. Lime (CaO) and magnesia (MgO) are also introduced into the converter in order to facilitate the formation of slag. In a “lance” converter, oxygen is injected from the top of the reactor through a lance. Injection tuyères may also be present at the bottom of the converter. They enable stirring of the hot metal via the injection of oxygen (at a lower rate of flow than the lance) and inert gases such as nitrogen N_2 and argon Ar at the end of the blowing. The operation produces non-deoxidised steel , which is separated from the slag by an alternating tilting movement of the converter. The ‘wild’ or ‘unkilled’ (i.e. non-deoxidised) steel is transferred to a steel ladle where it is refined by various treatments: this is secondary steelmaking, which will be detailed in the next section.[41], [42].

Several reactions take place in the converter due to the presence of different elements in the molten metal. The latter principally contains iron, and moreover carbon (4.4 to 4.8%), silica (0.36 to 0.63%), manganese (0.22 to 1.04%), phosphorus (0.04 to 0.09%), sulphur (0.004 to 0.06%) and aluminium. In Europe, blast furnaces produce pig iron with a low phosphorus content (less than 0.15%), known as “hematite pig iron” [41].

Silicon oxidation (removal of silicon) is one of the first reactions to take place. The silica (SiO_2) thus obtained reacts with the lime to form slag. Similarly, aluminium can be oxidised into alumina.

$$Si + O_2 \rightarrow SiO_2$$

$$SiO_2 + CaO \rightarrow CaSiO_3$$

$$4\ Al + 3\ O_2 \rightarrow 2\ Al_2O_3$$ [21]

The iron in the molten metal also undergoes oxidation from the start of the blowing process, following the following reactions. Oxides form one of the constituents of the dust, but they are mostly found in the slag. This process therefore tends to reduce the ferric yield insofar as the oxidised iron is "lost".

$$2\ Fe + O_2 \rightarrow 2\ FeO$$

$$4\ FeO + O_2 \rightarrow 2\ Fe_2O_3 \text{ (partial oxidation)}$$

Manganese behaves like iron and its oxide is dissolved in the slag.

$$2\ Mn + O_2 \rightarrow 2\ MnO$$

The carbon contained in the molten metal is oxidised into carbon monoxide, which in turn is partially oxidised into carbon dioxide: this is the decarburisation reaction. Below a carbon content of 0.02% to 0.04% in the steel, the loss of iron into the slag and the oxygen content in the steel become too great and injection is halted [41], [42].

$$2\ C + O_2 \rightarrow 2\ CO$$

$$2\ CO + O_2 \rightarrow 2\ CO_2$$

Phosphorus is also removed into the slag through a dephosphorisation reaction.

$$2\ P + 5\ O + 3\ CaO \rightarrow (3CaO.P_2O_5)$$ [21]

Finally, sulphur is discharged by the slag, flue gases and steel. Since converters are not capable of producing steels with very low sulphur content, it has become common practice to desulphurise the liquid metal and steel in a ladle [41], [42].

3.2.1.5. Secondary Steelmaking

Once the liquid steel has been transferred into the steel ladle, it can undergo various treatments according to the quality of steel required. Secondary steelmaking makes it possible to meet increasingly stringent requirements in terms of the chemical composition and properties of steels. On leaving the converter, the ‘unkilled’ steel is over-oxidised and therefore has to undergo deoxidation.

Whatever the process used to obtain the crude liquid steel, it is then refined in other special furnaces in order to adjust the alloy element content and then cast in continuous casting machines where it is solidified and formed into semi-finished products. 95% of world production is cast into billets, blooms and slabs, while the remaining 5% is cast into ingots, which require further processing into semi-finished products.

In the RH (Ruhrstahl-Heraeus) process or its oxygen-blowing version RH-OB (Oxygen Blowing), the most widely used circulation process, the steel is degassed and decarburised. The ladle containing the liquid steel is covered by a chamber in which a vacuum is created by removal of the air (see Figure 31). The liquid steel circulates in the chamber through snorkels, through the injection of argon gas. The gases dissolved in the steel escape under the effect of the very low pressure in the chamber. The initial aim of vacuum treatments was to degas the steel and, in particular, to eliminate dissolved hydrogen, nitrogen and oxygen. These processes also enable the removal of residual carbon (decarburisation) via the injection of oxygen, thus producing alloys with a very low carbon content (less than 0.002%).

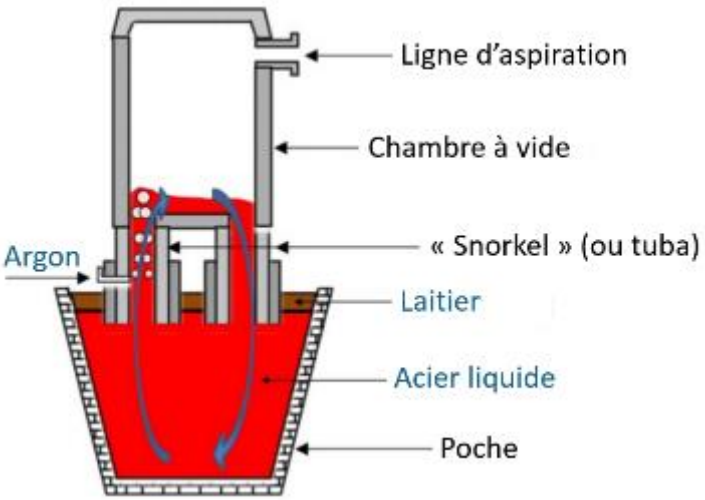


Figure 31: Diagram of the Ruhrstahl Heraeus process [43].

In order to lower the oxygen content and eliminate its inclusion in the metal, it is necessary to add deoxidising elements, the most common of which are silicon, manganese and aluminium. The reaction of oxygen with these deoxidising agents, and in particular aluminium, releases energy in the form of heat. When these elements are present, the steel is said to be "killed". These additions are made in a vacuum, on the bare metal, in order to avoid losses through oxidation.

The composition of the steel is adjusted using the CAS (Composition Adjustment by Sealed argon-bubbling) process or a variant of the latter, the CAS-OB (Oxygen Blowing) process Figure 32). In both of these processes, ferro-alloys (FeNi, FeMo, FeMn, FeCr, etc.) are added and the liquid metal is stirred by injection of a neutral gas such as argon. In this configuration, an inverted vessel is immersed in the metal in order to separate it from the slag and maintain it in a neutral atmosphere, which makes it possible to avoid oxidation of the ferro-alloys and reoxidation of the steel, and therefore to obtain very good addition yields. The CAS-OB process also includes heating by means of aluminothermic reaction. This is a thermochemical heating technique that involves adding aluminium to cause an exothermic oxidation reaction with oxygen blown through a lance [21], [44], [45].

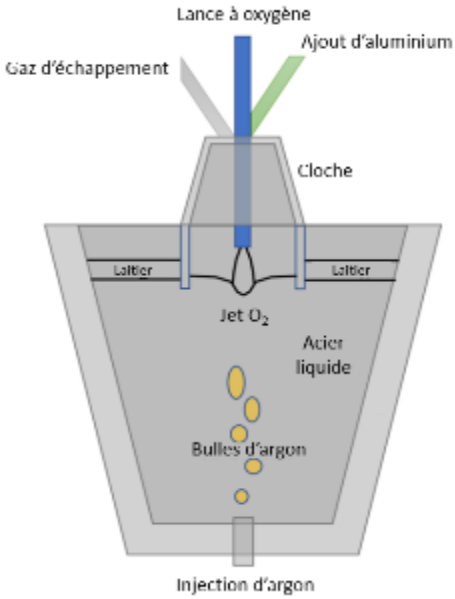


Figure 32: Diagram of the CAS-OB process [46].

3.2.1.6. Steelmaking Gases

Steelmaking gases refer to the three main types of gas that are co-produced on an integrated site. These are coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG). As a result of incomplete utilisation (e.g. the case of CO in converters) and the production of certain molecules during the process (e.g. The case of H_2 in coking plants), steelmaking gases contain non-inert compounds in varying proportions, which give them a calorific value (quantified by "LHV" or lower

heating value). Table 4 presents the composition of these three gases according to a number of bibliographical sources. These gases can then be used in energy-consuming parts of the plant, such as the rolling plant, or in a cogeneration plant. Moreover, thus is one of the reasons why a blast furnace plant is described as an “integrated site”.

In practice, coke oven gas has the highest energy yield of the three, due to its high H_2 and CH_4 content. Conversely, blast furnace gas has the lowest energy yield because the carbon contained in the incoming charge has been used to reduce metal oxides (the role of the blast furnace) and converted into CO_2. The presence of nitrogen (N_2) as an inert gas added at the time of the hot air blast also contributes significantly to diluting the other compounds. However, despite its low calorific value, the total amount of energy provided by blast furnace gas is much greater than that of other gases (almost twice as much as coke oven gas). This is due to the fact that, for a given level of steel production, the volume production of blast furnace gas is greater than that of the other gases. lastly, basic oxygen furnace gas for its part has an energy content intermediate between that of blast furnace gas and coke oven gas, in particular due to the presence of CO.

Steelmaking Gas	Source	%CO	%CO_2	%CH_4	%H_2	%H_2O	%N_2	% others	LHV
Coke oven gas (COG)	H. Wang et al. (2016) [47]	6.7%	2.2%	26.6%	60.7%	0%	4.0%	0%	-
	B. Bieda et al. (2015) [48]	6.6%	2.6%	23.7%	57.3%	0%	7.2%	2.4%	17.17 MJ/m³
	Average BREF (2013) [21]	4.6%	3.2%	21.4%	48.9%	0%	3.3%	1.9%	14 MJ/Nm³
	S. Garcia et al. (2020) [49]	5.4%	1.4%	24.4%	58.1%	2.2%	5.6%	1.2%	16.70 MJ/Nm³
	P. Hellberg et al. (2005) [50]	6.3%	1.3%	24.1%	62.9%	0.5 %	3.9%	0%	-
	A.M. Iosif (2006) SP9 data [51]	4.9%	1.5%	24.7%	62.9%	0%	2.0%	4%	20.59 MJ/Nm³
Blast furnace gas (BFG)	H. Wang et al. (2016) [47]	19.9%	23.4%	0%	3.3%	1.7%	51.7%	0%	-
	Average BREF (2013) [21]	23%	21%	0%	4.5%	0%	51%	0%	3.3 MJ/Nm³
	K. Afanga (2014) experimental values [24]	21.8%	22.5%	0%	4.4%	0%	51.3%	0%	-
	A.M. Iosif (2006) SP9 data [51]	23.1%	23.8%	0%	4.4%	0%	48.7%	0%	3.4 MJ/Nm³
Basic oxygen furnace gas (BOFG)	BREF (2013) [21]	72.5%	16.2%	0%	3.3%	0%	8%	0%	9.58 MJ/Nm³
	S. Garcia et al. (2020) [49]	68.2%	13.4%	0%	1.1%	3.4%	13.0%	0.6%	8.79 MJ/Nm³
	P. Hellberg et al. (2005) [50]	55.3%	14.7%	0.6%	1.0%	0.5%	27.9%	0%	-
	A.M. Iosif (2006) [51]	87.3%	9.9%	0%	0.8%	1.9%	0.1%	0%	9.24 MJ/Nm³

Table 4: Composition of coke oven gases in percentage by volume, according to various sources.

When steelmaking gases are not recovered, they are burned in flares. The latter are safety devices used to ensure the internal balance of the gas network. Flaring is used when the gasholders are no longer sufficient to store the surplus, regulate network pressure and secure the network in case of abnormal operation. Insofar as this represents a loss of earnings for the plant, integrated sites optimise gas flows in real time in order reduce the flaring rate as much as possible. However, in practice it is not possible to completely eliminate flaring, if only because certain gas production and consumption facilities are unstable and unsynchronised. Indeed, while coke oven gas and blast furnace gas come from relatively stable, continuous processes, steelworks gas is produced in a highly variable batch process (hence a higher flare rate). Similarly, consumption by Cowper stoves (which produce the hot air for blast furnaces) is stable, while energy demand from rolling mills is variable.

3.2.2. Modelling of the Blast Furnace Sector

In the modelling, integrated blast furnace sites are represented by a single reference plant (REF1), which includes coking plant, sintering plant, the blast furnaces themselves, the steelworks (which includes in particular the basic oxygen furnace and secondary steelmaking), continuous casting plant, the hot rolling plant and a thermoelectric power station, which converts steelmaking gases into electricity and heat for the plant’s requirements. In short, it is modelled as though the whole of French output from the pig iron sector (in practice from the ArcelorMittal Dunkirk, ArcelorMittal Fos-sur-Mer and Saint-Gobain PAM sites) were taken care of by a single factory with average energy consumption and average specific emissions on a national scale.

Figure 33 presents a process diagram of this reference plant. The REF1 reference plant was constructed on the basis of a study of confidential data sources on the French sites and several bibliographical sources which model an integrated site. The sources in question, from which a number of numerical assumptions are derived, are J. Song et al. (2019) [52], H. He et al. (2017) [53], A. Keys et al. (2019) [31] and D. Isler (2016) [32]. Although none of the values contained therein were used as modelling assumptions for the REF1 plant, four other sources were also studied, namely K. Afanga (2014) [24], E. Ubieto Udina (2012) [54], M. McBrien et al. (2016) [55] and P. Jin et al. (2017) [56], in order to back up the orders of magnitude. The modelling assumptions for the reference plant were selected so as be as close as possible to the actual operation of existing French plants, without disclosing any confidential information about them. As shown in Figure 33, the operation of an

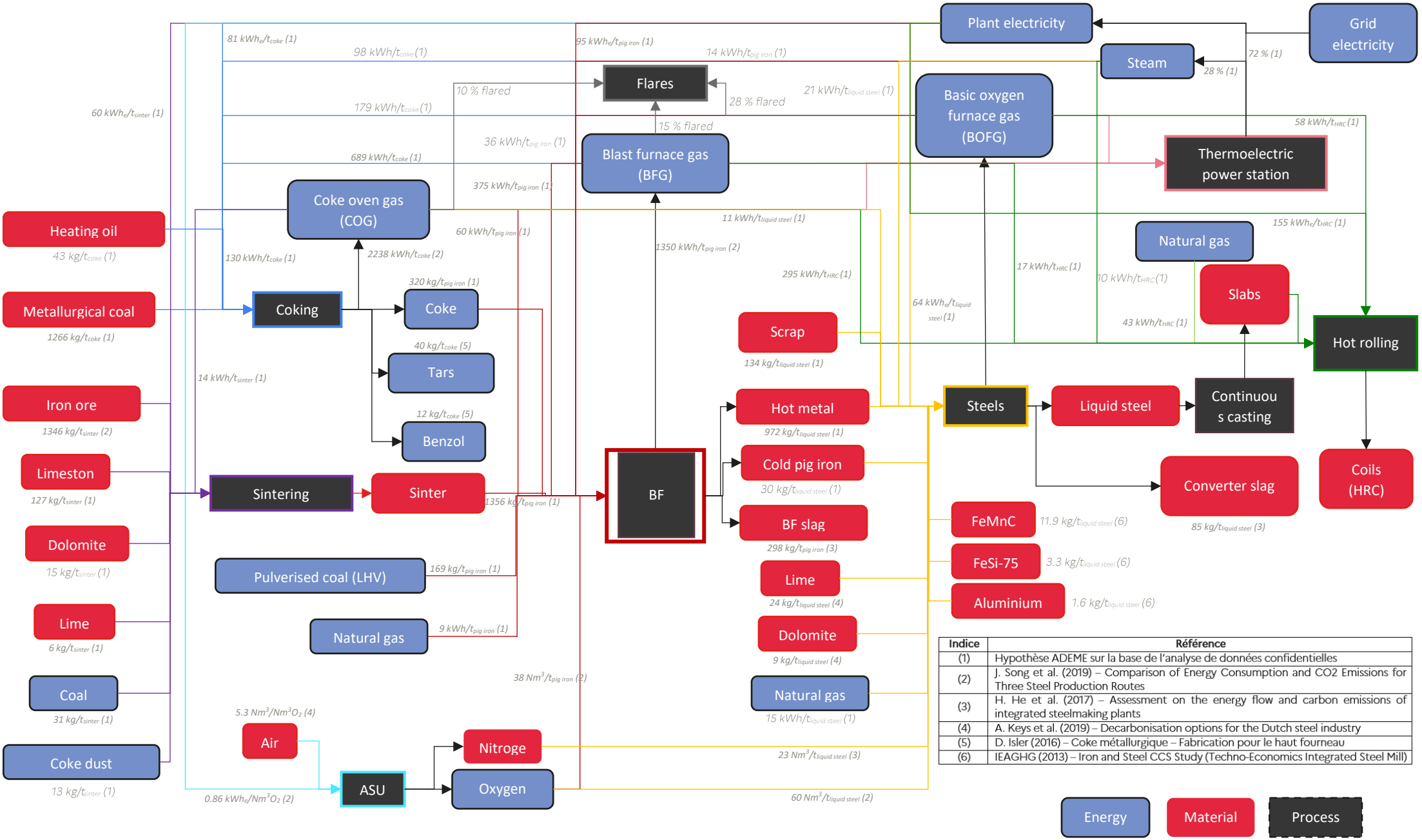
integrated blast furnace site is very complex, in particular due to the production and consumption of steelmaking gases. For each specific production and consumption value, the origin of the source is indicated in brackets. The vast majority of the values presented are ADEME assumptions formulated on the basis of the analysis of confidential data. None of these figures correspond to actual values for existing sites.

In addition to processes directly connected with steel production (sintering, blast furnaces, rolling, etc.), the reference plant includes flares and a thermoelectric power station producing steam and electricity. In the modelling, the flaring rate for each of the three steelmaking gases was set before calculating the remaining energy available for recovery at the thermoelectric power station. The latter converts the energy contained in the steelmaking gases into useful energy with an assumed efficiency of 36%, which is then divided between steam production and electricity generation. However, it should be noted that before being recovered at the thermoelectric power station, the steelmaking gases are directly consumed by combustion to meet the heat requirements of certain consumption points (sinter plant, coking plant, etc.). The key to allocation between steam and electricity production was selected so as to cover the whole of the plant's steam requirements as a priority (gas cleaning in the coking plant, vacuum pumps for the Ruhrstahl-Heraeus process in the steelworks, etc.), with the remainder being used to generate electricity. It is also assumed that the whole of the power station's electricity generation is consumed internally, which covers almost 45% of the modelled plant's needs. Connection to the national grid meets remaining electricity requirements (around 65%). The oxygen consumed by the blast furnaces and the converter is produced on site using an Air Separation Unit (ASU). It also produces nitrogen, which is used in the steelworks as an inert gas for stirring the metal. Ferro-alloys are also consumed in the steelworks. On the basis of IEAGHG (2013) [57], it was assumed that hot coil production required FeMnC (carburised ferromanganese) at around 12 $kg/t_{liquid\ steel}$ and FeSi-75 (75% ferrosilicon) at around 3 $kg/t_{liquid\ steel}$. It was also assumed that the steelworks consumes aluminium in the form of deoxidation wire at a rate of around 2 $kg/t_{liquid\ steel}$.

The composition of steelmaking gases has also been modelled. In particular, this is subsequently necessary in order to model steelmaking gas recirculation technology. Once the volumetric composition had been defined, the average Lower Heating Value (LHV) of each gas was calculated on the basis of the volumetric energy content of each of its compounds. Table 5 details the composition of steelmaking gases. In addition, the emission intensity (in $kgCO_2/Nm^3$) was calculated on the basis of the carbon content of each of the gases, assuming complete combustion and that the only compounds that contribute to generating CO_2 are CO_2, CO and CH_4. It is thus possible to reassess the physico-chemical characteristics of steelmaking gases (LHV and emission intensity) in the event of a change in composition. Coke oven gas is abbreviated COG, blast furnace gas is abbreviated BFG and basic oxygen furnace gas is abbreviated BOFG.

Compound	LHV (MJ/Nm^3)	Carbon content (kgC/Nm^3)	COG (%vol)	BFG (%vol)	BOFG (%vol)
H_2	12.8	0	60.7%	4.5%	1.1%
CO	12.7	0.49	6.7%	23%	68.2%
CO_2	0	0.51	2.2%	21%	13.4%
CH_4	35.9	0.49	26.6%	0%	0 %
N_2	0	0	4.0%	51%	13.0%
H_2O	0	0	0%	0%	3.4%
Other	0	0	0 %	0 %	0.6%
Bibliographical source	Miscellaneous	Miscellaneous	H. Wang et al. (2016) [47]	Average BREF (2013) [21]	S. Garcia et al. (2020) [49]
Average LHV (MJ/Nm^3)	-	-	18.13	3.49	8.77
Emission intensity ($kgCO_2/Nm^3$)	-	-	0.64	0.81	1.47
Emission intensity ($kgCO_2/GJ$)	-	-	35.4	231.0	167.9

Table 5: Reference plant REF1 Integrated blast furnace site - Characteristics of steelmaking gases.



Indice	Référence
(1)	Hypothèse ADEME sur la base de l'analyse de données confidentielles
(2)	J. Song et al. (2019) – Comparison of Energy Consumption and CO2 Emissions for Three Steel Production Routes
(3)	H. He et al. (2017) – Assessment on the energy flow and carbon emissions of integrated steelmaking plants
(4)	A. Keys et al. (2019) – Decarbonisation options for the Dutch steel industry
(5)	D. Isler (2016) – Coke métallurgique – Fabrication pour le haut fourneau
(6)	IEAGHG (2013) – Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)

Energy | Material | Process

Figure 33: Reference plant REF1 Integrated blast furnace site - Process diagram.

The REF1 reference plant was also constructed from the viewpoint of the GHG emissions it generates, in order to be as close as possible to the actual total emissions in 2015 within the scope of the blast furnaces. Figure 34 enables visualisation of the reconstructed emissions for the REF1 reference plant, using input-output carbon accounting for each of the various items. With a margin of error of less than 0.5%, the total emissions are very close to the actual emissions in 2015 within the scope of the blast furnaces. In this respect, the representation of the REF1 reference plant may be deemed very satisfactory. Although steelmaking processes are responsible for the production of gases containing carbon, 40% to 45% of CO_2 emissions physically occur at the thermoelectric power station and in the flares that consume the steelmaking gases, which shows how heavily these gases weigh in the energy consumption of an integrated site. Apart from these items, blast furnaces also produce high levels of emissions, principally through the energy consumed by Cowper stoves to produce the hot blast, followed by the coking plant due to the energy consumed to heat up the furnaces, then sintering through the combustion of coal and coke to agglomerate the ore, as well as process emissions connected with decarbonation of the limestone and dolomite used as a flux.

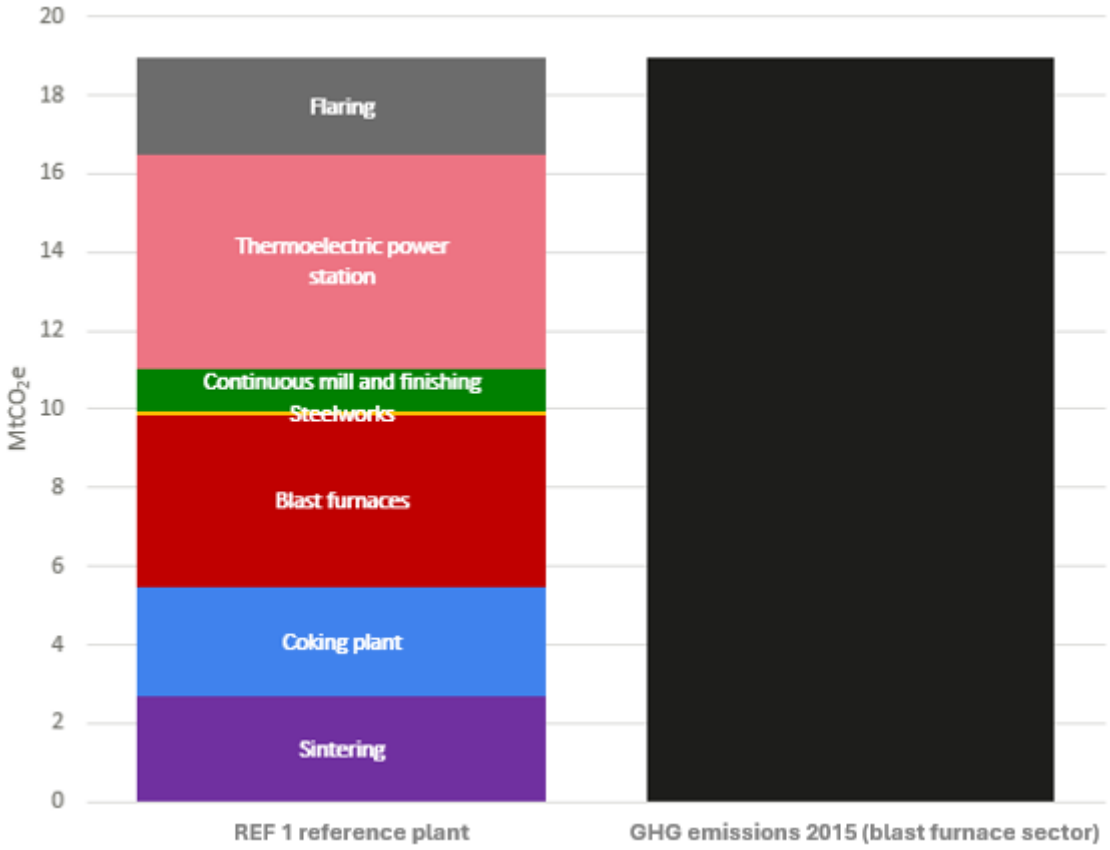


Figure 34: Reference plant REF1 Integrated blast furnace site - GHG emissions.

3.2.2.1. Modelling of the Sintering plant

The sintering plant was modelled in accordance with the input-output balance shown in Table 6. In practice, the solid fuel consumed in sintering is a mixture of coal and coke waste (or "dust"), but by way of simplification for the carbon accounting, it was assumed to be coke, indeed for this reason coke is shown in the table rather than coke dust. This is equivalent to assuming that the emission intensity is identical for coke and coke dust.

Commodity	Unit	**Consumption for 1 t of sinter**	Source
Coke	kWh	120	ADEME
Coke oven gas	kWh	14	ADEME
Electricity	kWh	60	ADEME
Lime	t	0.006	ADEME
Dolomite	t	0.015	ADEME
Iron ore	t	1.346	[52]

Limestone	t	0.127	ADEME
Coal	kWh	279	ADEME
CO_2	tCO_2	*Carbon accounting*	

Table 6: Modelling of the sintering plant.

3.2.2.2. Modelling of the Coking Plant

The coking plant was modelled in accordance with the input-output balance shown in Table 7. When consumption is shown with a minus sign, this means that the item in question produces materials or energy rather than consuming them. This is the case here with coke oven gas, benzol and tar.

Commodity	Unit	**Consumption for 1 kWh of coke**	Source
Coke oven gas (consumption)	kWh	0.017	ADEME
Coke oven gas (production)	kWh	-0.288	[52]
Blast furnace gas	kWh	0.089	ADEME
Basic oxygen furnace gas	kWh	0.023	ADEME
Electricity	kWh	0.010	ADEME
Steam	kWh	0.013	ADEME
Heating oil	kWh	0.006	ADEME
Metallurgical coal	kWh	1.447	ADEME
Benzol	kWh	-0.018	[32]
Tar	kWh	-0.060	[32]
CO_2	tCO_2	*Carbon accounting*	

Table 7: Modelling of the Coking plant.

3.2.2.3. Modelling of the Blast Furnace

The blast furnace was modelled in accordance with the input-output balance shown in Table 8. The operating variable *prop_biochar_BF* is defined to represent the possible integration of biochar as a replacement for fossil pulverised coal.

Commodity	*Unit*	*Consumption for 1 t of pig iron*	*Equation*	*Source*
Coke	kWh	2491		ADEME
Sinter	t	1.356		ADEME
Coke oven gas	kWh	60		ADEME
Blast furnace gas (consumption)	kWh	375		ADEME
Blast furnace gas (production)	kWh	-1350		[52]
Basic oxygen furnace gas	kWh	36		ADEME
Electricity	kWh	95		ADEME
Steam	kWh	14		ADEME
Oxygen	Nm3	38		[52]
Network gas	kWh	9		ADEME
Blast furnace slag	t	-0.298		[53]
Pulverised biochar	kWh	$1501 \cdot prop\_biocharbon\_BF$	*Equation 1*	ADEME
Pulverised coal	kWh	$1501 \cdot (1 - prop\_biocharbon\_BF)$	*Equation 2*	ADEME
CO_2	tCO_2	*Carbon accounting*		

Table 8: Modelling of Blast Furnace.

3.2.2.4. Modelling of Oxygen Converter Steelmaking

Oxygen converter steelmaking was modelled in accordance with the input-output balance shown in Table 9.

Commodity	Unit	Consumption for 1t of liquid steel	Equation	Source
Pig iron	*t*	$1.1 - \text{converter\_scrap\_rate}$	*Equation 3*	
Scrap iron	*t*	$\text{converter\_scrap\_rate}$	*Equation 4*	
Basic oxygen furnace gas	*kWh*	$190.2 \cdot \text{converter\_scrap\_rate} - 209{,}3$	*Equation 5*	*ADEME*
Coke oven gas	*kWh*	11		*ADEME*
Electricity	*kWh*	64		*ADEME*
Steam	*kWh*	21		*ADEME*
Oxygen	*Nm3*	60		[52]
Network gas	*kWh*	15		*ADEME*
Lime	*t*	0.024		[31]
Dolomite	*t*	0.009		[31]
Nitrogen	*Nm3*	23		[53]
FeMnC	*t*	0.0119		[58]
FeSi-75	*t*	0.0033		[58]
Aluminium for deoxidation	*t*	0.0016		[58]
Converter slag	*t*	-0.085		[53]
CO_2	*tCO_2*	*Carbon accounting*		

Table 9: Modelling of the Steelworks (Oxygen Converter).

This model comprises three equations representing the following characteristics:

- Ferrous inputs are divided between pig iron from the blast furnaces (*Equation 6*) and scrap (Equation 7). The levels of consumption thereof depend upon the proportion of scrap in the converter, which is defined as the mass of scrap incorporated in relation to the mass of liquid steel produced[24] and is represented by the variable $taux\_de\_ferrailles\_convertisseur$. The process was considered to induce a constant loss of material, such that the quantity of ferrous inputs required to produce liquid steel follows a ratio of 1.1: 1. In practice, this is not entirely accurate: the addition of scrap tends to reduce material losses.

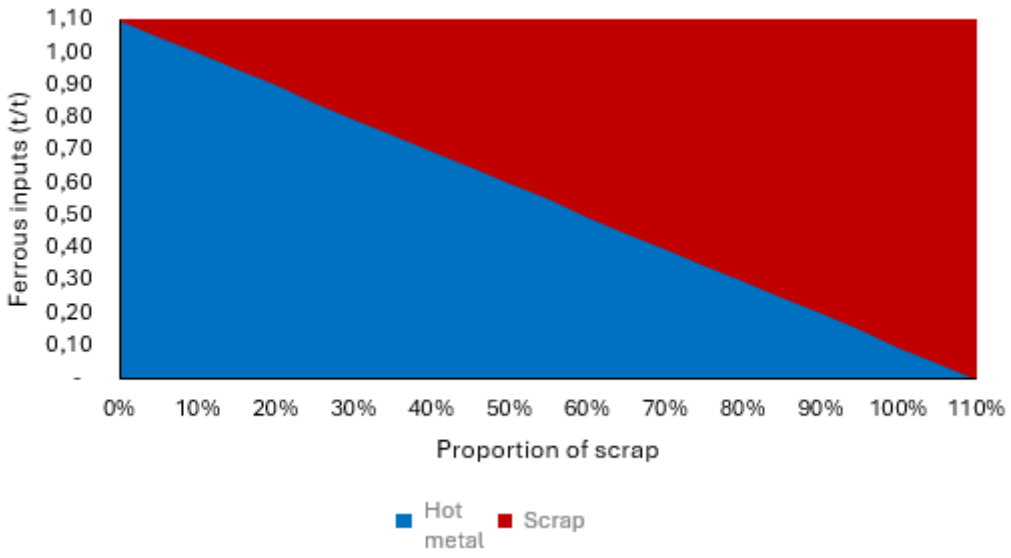


Figure35: Modelling of the specific consumption of ferrous inputs in the oxygen converter.

[24] It is therefore not a question of the proportion of scrap relative to inputs, but relative to the output produced. This could lead to confusion when compared with the proportion of scrap in electric arc furnaces, which is defined, in this instance, relative to the mass of inputs. Moreover, the foresight assumptions relating to the tolerable proportion of scrap for steelmakers' order books are made on the basis of the metrics relating to the mass of inputs, and therefore also differ from the variable considered here.

3.2.2.5. Modelling of Primary Processing

Continuous casting, reheating and rolling were modelled as a whole, according to the input-output balance shown in Table 10.

Commodity	**Unit**	**Consumption for 1t of coil**	**Source**
Liquid steel	*t*	1	ADEME
Coke oven gas	*kWh*	295	ADEME
Blast furnace gas	*kWh*	17	ADEME
Basic oxygen furnace gas	*kWh*	58	ADEME
Electricity	*kWh*	155	ADEME
Internal steam	*kWh*	10	ADEME
Network gas	*kWh*	43	ADEME
CO_2	*tCO_2*	*Carbon accounting*	

Table 10: Modelling of continuous casting and hot rolling.

3.2.2.6. Modelling of the Air Separation Unit

The air separation unit (ASU) was modelled in accordance with the input-output balance shown in Table 11.

Commodity	Unit	**Consumption for 1 Nm^3 of oxygen**	Source
Electricity	kWh	0.86	[52]
Air	Nm^3	5.3	[31]

Table 11: Modelling of the ASU.

3.2.3. Blast Furnace Decarbonisation Technologies

3.2.3.1. Increase in the Proportion of Scrap in the Converter

Scrap or DRI (direct reduced iron) may be injected into the oxygen converter, to replace smelting, thereby enabling a reduction in consumption per tonne of steel produced. As smelting is the part of the process responsible for the vast majority of emissions, this decarbonisation lever is particularly effective. However, the substitution rate is limited by the cooling effect of DRI and scrap, the presence of impurities in scrap, and the temperature of the molten metal, and is dependent on the facilities [59].

In its annual reports [60], the ArcelorMittal group, which is the only player producing steel using the blast furnace process in France, gives the proportion of scrap used in the pig iron sector (i.e. in the oxygen converter process) as well as the volumes recycled. The data is set out in Figure 36. Since 2017, the proportion of scrap in the pig iron sector (including the recycling of used scrap as well as new scrap from steel production and product manufacturing) has been between 14% and 20%, and the volume of scrap recycled has averaged 1.7 Mt/year. In China, for example, the average scrap content in oxygen converters has risen to around 20% [61]. The addition of external scrap to the converter has the effect of cooling the steel and lowering the so called "end of blowing" temperature. It may therefore be necessary to correct this temperature, for example by means of an electric reheating furnace downstream of the conversion process, as in the case of the recent ArcelorMittal Fos-sur-Mer project [62]. In addition to the CO_2 saving, the replacement of pig iron with scrap in the converter provides a number of other advantages: reduced wear and tear on refractories, reduction of oxidation of the metal charge and therefore of iron losses, and reduction of the quantity of slag, which is principally produced from molten metal and overoxidation.

It is estimated that around a third of the scrap used in the pig iron sector in France comes from external end-of-life waste; while the remaining two-thirds comes from new in-house scrap or from scrap connected with steel processing at other sites[25].

[25] This estimate is based on public data. In Dunkirk, 1 to 1.4 Mt of scrap is consumed, 60% of which is internal scrap and 40% external scrap from sorting centres [63], [64], [65] i.e. 0.5 Mt. On the basis of ArcelorMittal's total scrap consumption in France, it can be estimated that the Fos site consumes between 0.4 and 0.8 Mt of scrap, of which around 100 kt is external scrap (i.e. around 10 to 20%) [66], [67]. The total consumption of external scrap in converters is therefore around 0.5 + 0.1 = 0.6 Mt out of a total scrap consumption of approximately 1.7 Mt, i.e. a ratio close to 1/3.

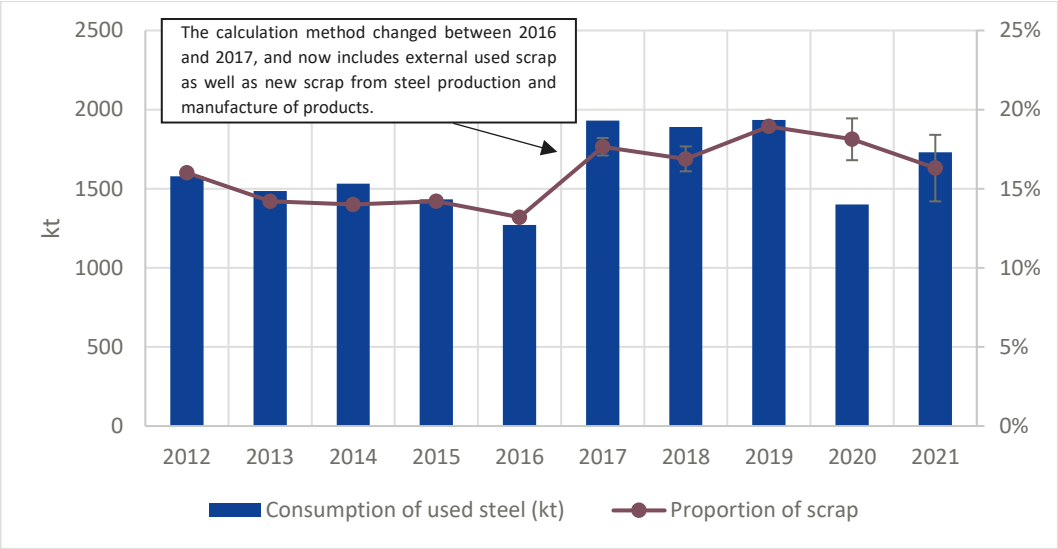


Figure 36: Changes in the ArcelorMittal group's recycling of scrap in the pig iron sector in France[26].

According to B. Voraberger et al. (2022) [68], in the absence of special measures, the maximum scrap rate in the converter is limited to around 20%. However, certain technological devices, such as preheating by means of the lance in the converter, pre-melting in an auxiliary furnace and optimisation of heat flows, make it possible to achieve a rate of 30%. G. Brooks et al. (2022) [69] also draws the conclusion of a maximum rate of 29%. Scrap rates of even higher than 30% are thought to be achievable [68]. Indeed, T. Bradaric et al. (2016) [70] reports on the case of Mittal Steel USA, which, after having tested about twenty measures on several sites, concludes that it is possible to achieve a hot metal rate of 66% in the converter, i.e. a scrap rate of 34%. In the modelling, the maximum scrap rate in the converter was set at 30%.

Moreover, good scrap quality can be ensured by scrap resources containing little impurity (purchase of a particular grade or in-house scrap), or by on-site sorting and cleaning. The modelling takes into account on-site processing in order to make it possible for CAPEX and the increase in production costs connected with this scrap processing to be taken into account. ADEME adopted the assumption of an investment cost of EUR 140/$t_{additional\ scrap}$.

3.2.3.2. Modelling Increase in the Scrap Rate

In the modelling, it was assumed that furnace charging of scrap represented 170 kg/t_{scrap} between 2015 and 2022, of which 64% came from external end-of-life waste.

Increase in the scrap rate is modelled as a simple adjustment to the associated operating variable in the oxygen converter ($taux\_de\_ferrailles\_convertisseur$ – see Table 9). Increasing this rate above 20% implicitly requires the putting in place of measures for the processing and preheating of scrap, and is otherwise reflected in the modelling by taking into account capital expenditure (amounting to €140/$t_{additional\ scrap}$.year)[27].

3.2.3.3. Change of Reducing Agents

Substituting other reducing agents for coke in the blast furnace is common practice, principally undertaken for economic reasons (coke is an expensive input). To date, pulverized coal is the principal auxiliary reducing agent used to replace coke, but hydrocarbon oils and natural gas are also commonly injected into blast furnaces [71]. Since the 1960s and following the oil crises, improvements have made it possible (to reduce consumption of reducing agents in blast furnaces, in particular coke (Figure 37)[28] , by about half[72]. Total consumption of reducing agents fell to a low in around 2000 before rising slightly once again due to the ever increasing replacement of coke by pulverised coal (pulverised coal is slightly less efficient than coke). Today, average consumption of reducing agents tends towards a plateau of around 500 kg/$t_{pig\ iron}$, with a coke rate of around 330 kg/$t_{pig\ iron}$. Certain blast furnaces in Europe operate with a coke rate of between 220 and 250 kg/$t_{pig\ iron}$[73]. It is estimated that a theoretical minimum coke rate of 200 kg/$t_{pig\ iron}$ is required [71], since coke still remains essential, performing a mechanical function. In addition, the rate of injection of pulverised coal in replacement of coke is limited in practice due to

[26] The uncertainty bar with regard to the proportion of scrap is due to variations in the same indicators according to ArcelorMittal's various CSR reports and in relation to the calculated values for the proportion of scrap (volume of used steel consumed in relation to liquid steel production in the pig iron sector).

[27] Implementation of the technology therefore implicitly means extending the domain of definition of the variable $taux\_de\_ferrailles\_convertisseur$ beyond 20%.

[28] NG = Natural gas, PC = Pulverised coal

incomplete combustion of the latter. For this reason the idea of using a reducing gas instead of a solid reducing agent was introduced at the beginning of the 20th century[71].

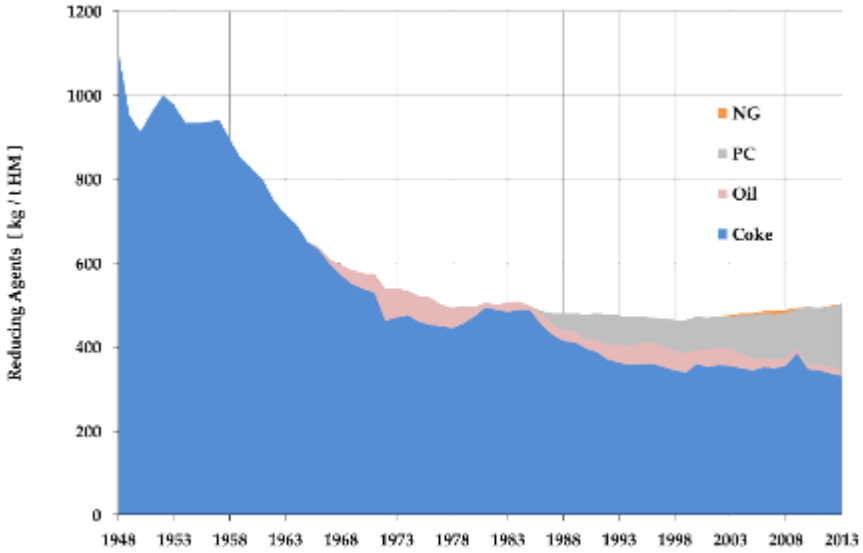


Figure 37: Historical changes in the consumption of reducing agents in blast furnaces in Europe [72].

*3.2.3.3.1.*Injection of Natural Gas into Blast Furnaces

The direct injection of natural gas into blast furnaces makes it possible to replace part of the coke and reduce CO_2 emissions, however, in order to do so the natural gas has to be preheated and the air potentially enriched with O_2. This technique has already been used in the United States for over twenty years, where the average consumption of natural gas in 2015 was around 60 kg/$t_{hot\ metal}$. According to C. De Maré (2022) [37], with preheating to 320°C, the maximum injection rate in the main tuyère is 140 kg/$t_{hot\ metal}$. According to M. Jampani (2016) [74], with a hot blast temperature of 900°C, the maximum injection rate in the main tuyère is 150 kg/$t_{hot\ metal}$ and, with a blast of 1,100°C, the maximum rate increases to 175 kg/$t_{hot\ metal}$. The injection may be made through the main tuyères or moreover through the shaft, just above the barrel (see Figure 38) [74].

The injection of natural gas has an endothermic effect and therefore tends to lower the flame temperature. For this reason the air has to be enriched with oxygen. However, oxygen enrichment has the effect of reducing the nitrogen content, which tends to lower the exit temperature of the gases at the top of the blast furnace. However, this temperature must remain above the dew point (at around 110°C for the exit gases) to prevent condensation of water in the upper part of the blast furnace. Tuyère injection of natural gas is thus technically limited by the flame temperature and the gas exit temperature [74]. Shaft injection makes it possible to partly circumvent this limit, enabling a wider injection range without compromising the operation of the blast furnace. Calculations by M. Jampani (2016) [74] make it possible to estimate a maximum injection rate of around 200 kg/$t_{hot\ metal}$ for shaft injection of natural gas.

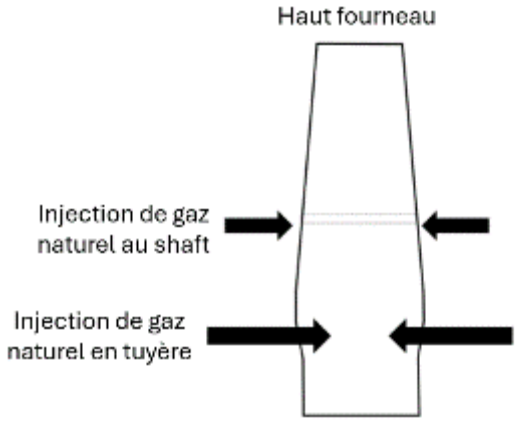


Figure 38: Diagram of a blast furnace with natural gas injection into the main tuyère as now used and the configuration with shaft injection (adapted from[74]).

Modelling of Natural Gas Injection in Blast Furnaces

Natural gas injection was not taken into account in the decarbonisation trajectories: priority was given to the technologies of coke oven gas injection and recirculation of blast furnace gases.

Had this lever been modelled, shaft injection of natural gas would have been selected, with a maximum injection rate of 200 kg/$t_{hot\ metal}$. For the calculation of CO_2 emission savings and impact on energy consumption, the replacement of coke by natural gas injection can be approached by means of a linear function, as presented in Figure 39 from M. Jampani (2016) [74]. By way of graphical approximation, a natural gas injection rate of 200 kg/$t_{hot\ iron}$ results in a coke consumption of 225 kg/$t_{hot\ metal}$. For shaft injection, the demand for additional oxygen is 1 kgO_2 per kilogram of natural gas and the additional energy required in order to preheat the gas is 2.45 MJ per kilogram of natural gas, with a preheating device whose efficiency can be estimated at 60%.

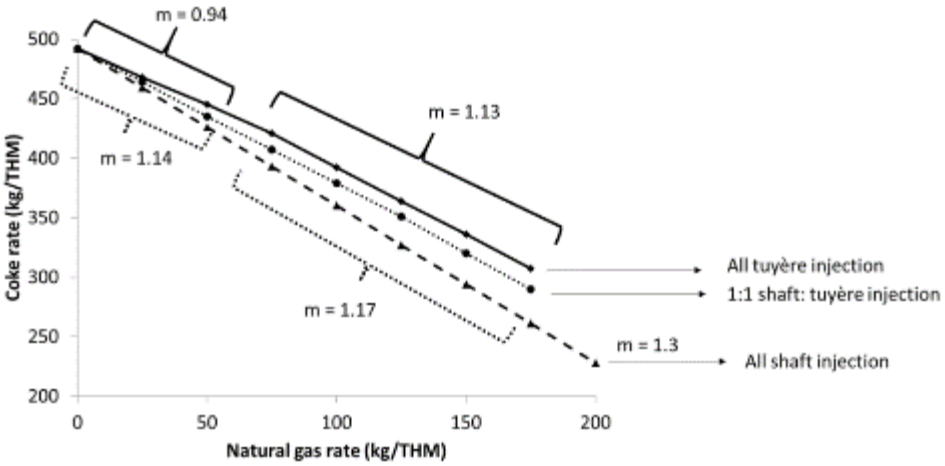


Figure 39: Estimate of the coke rate according to the natural gas injection rate for three injection scenarios: all tuyère injection (main tuyère), all shaft injection and 50/50 shaft and tuyère injection.[74].

The use of natural gas also has an impact on blast furnace productivity[29], according to whether the injection takes place through the main tuyères or the shaft (see Figure 40). Lastly, injection of natural gas also modifies the composition of the blast furnace exit gases. In particular, these gases are enriched in H_2 and H_2O and depleted in CO_2 and N_2, which has the effect of increasing average calorific value. It can be assumed that the calorific value increases in a linear manner with the natural gas injection rate.

The investment cost of making the necessary arrangements for natural gas injection was taken as EUR 10 M [75] for a blast furnace with a capacity of 2 Mt$_{hot\ metal}$/year.

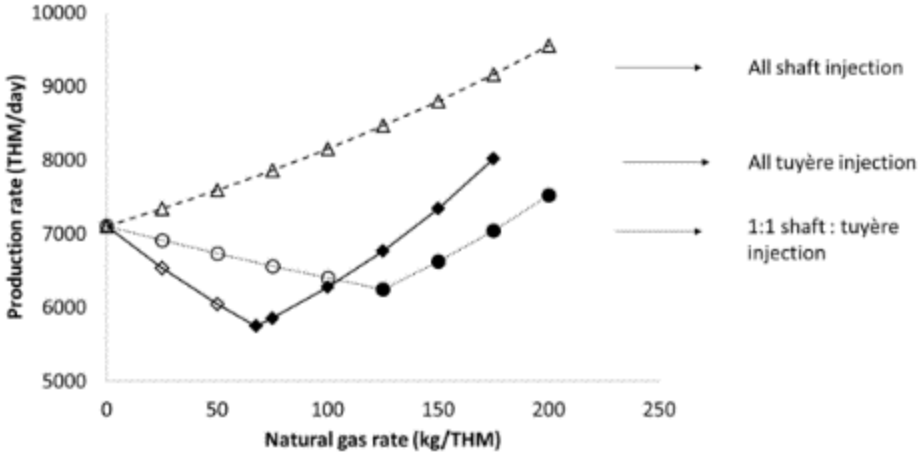


Figure 40: Estimate of the impact of natural gas injection on blast furnace productivity according for three injection scenarios: all tuyère injection (main tuyère), all shaft injection and 50/50 shaft and tuyère injection [74].

[29] "Productivity" is understood as maximum daily output.

3.2.3.3.2. Hydrogen Injection in Blast Furnaces

The direct injection of hydrogen for the reduction of iron ore in blast furnaces is an innovation and a decarbonisation lever for steel production, reducing the use of coal and coke [71]. For steelmakers, this is in general a short-term solution, extending the lifespan of blast furnaces. This solution may be implemented in conjunction with recirculation of steelmaking gases (see 3.2.3.3.4). If hydrogen is produced by electrolysis of water, the oxygen by-product may be used to enrich the hot blast or combustion air in Cowper stoves, which are air heaters designed to supply hot air blown into blast furnace tuyères (see Figure 41 Figure 41).

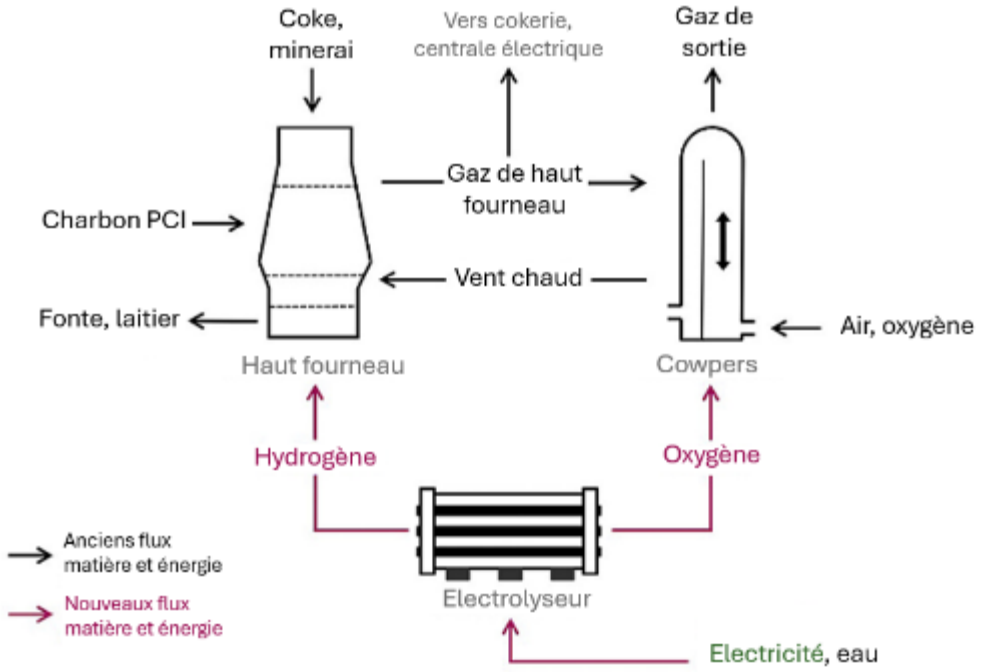


Figure 41: Hydrogen produced by electrolysis as an auxiliary reducing agent within the blast furnace (diagram adapted from [71]).

Industrial-scale trials have been conducted by the Thyssenkrupp Group at the Duisburg site in Germany. However, theoretical modelling shows that this direct injection of hydrogen into blast furnaces would be able to replace a maximum of 21.4 to 24% of the carbon usually required. This limit is connected with the mechanical function of the coke in the reactor[76].

Within the framework of a cross-border IPCEI project for the transport of hydrogen between France and Germany, the Saarstahl and Dillinger steel groups launched the H2Syngas project at the integrated site of ROGESA Roheisengesellschaft Saar mbH. The project consists in enriching coke oven gas with hydrogen for direct use in the blast furnace as a reducing gas, thereby lowering coke consumption. This reuse of reducing gas within the process itself would would make it possible to reduce CO_2 emissions by up to 12%[77]. In April 2023, the Indian group Tata Steel began hydrogen injection tests in one of the six blast furnaces at the Jamshedpur steelworks in the east of the country. Eventually, injection tests will have the potential to reduce coke consumption by 10%, i.e. a reduction in CO_2 emissions of 7 to 10%[78].

Because hydrogen has a high heat capacity, direct injection of hydrogen at a low temperature (as with natural gas) tends to reduce the flame temperature below the operating threshold. To maintain stable operating conditions, it is therefore necessary to reduce the blast flow, enrich it with oxygen in order to burn more coke, and preheat the hydrogen [71]. Hydrogen injection also has the effect of increasing blast furnace productivity, up to almost 14% in the best case according to V. Shatokha (2022) [79]. The maximum H_2 injection rate was estimated at 27.5 kg/$t_{hot\ metal}$ according to C. Yilmaz et al. (2017) [71] and at 28.3 kg/$t_{hot\ iron}$ according to V. Shatokha (2022) [79] when the air is oxygen enriched by 33 $\%_{vol}$. Lastly, the literature indicates that hydrogen injection is preferable via the main tuyères. Indeed, experimental results conducted on hydrogen injection via the shaft show that the hydrogen tends to escape along the inner walls due to excessively strong upward flow, which greatly limits its iron ore reduction potential [79]. In this work, it was therefore assumed that hydrogen was injected via the main tuyères. However, even in this case, it is important to note that the hydrogen is not entirely consumed in the reduction of oxides. The hydrogen utilisation rate in the reaction is around 50-55%, with the remainder ending up in the blast furnace exit gases [79].

Modelling of Hydrogen Injection in Blast Furnaces

Hydrogen injection was not taken into account in the decarbonisation trajectories: priority was given to the technologies of DRI-H2, coke oven gas injection, and recirculation of blast furnace gases.

The data and results of V. Shatokha (2022) [79] may be used in order to model this decarbonisation lever. By way of simplification, it is assumed that the blast air is 33%$_{vol.}$ oxygen enriched, thus enabling a wider range of H_2 injection, up to a maximum of 28.3 kg/$t_{hot\ metal}$. In spite of the positive impact of the preheating of hydrogen on coke consumption and CO_2 emissions, hydrogen is assumed to be injected cold due to the technical risks of flammability posed by heating. Under these conditions, it is possible to quantify the impact of direct hydrogen injection on CO_2 emissions on the basis of Figure 42, its impact on the coke replacement rate on the basis of Figure 43 and its impact on blast furnace productivity on the basis of Figure 44.

The investment cost of this technology can be estimated at EUR 150 M [75]for a blast furnace with a capacity of 2 $Mt_{hot\ metal}$/year. It is assumed that this amount also includes the cost of the electrolyser.

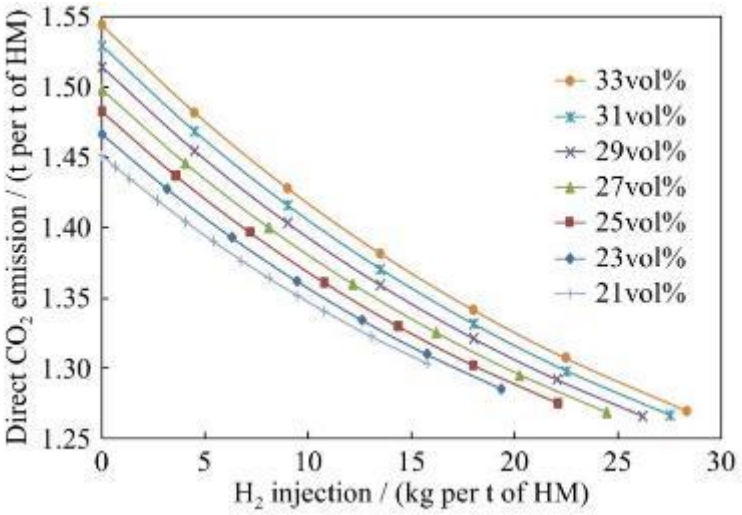


Figure 42: Effect of hydrogen injection on direct CO2 emissions with a blast oxygen content of between 21 and 33% and a temperature of 1,200°C[79].

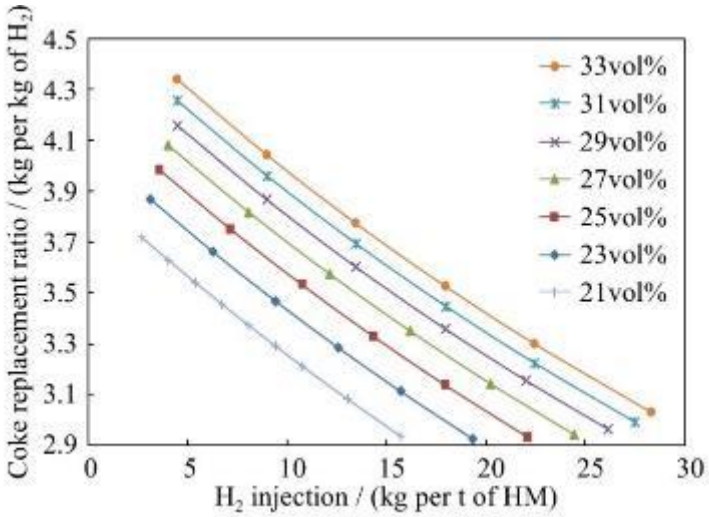


Figure 43: Coke replacement rate with a blast oxygen content of between 21 and 33% and a temperature of 1,200 °C[79].

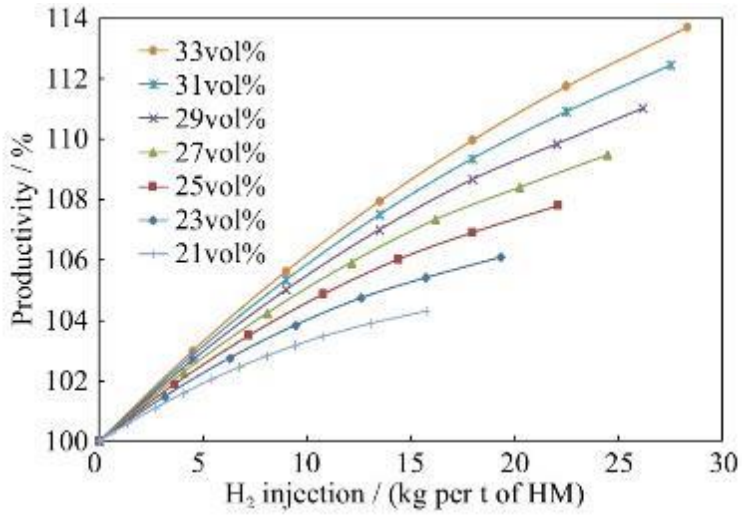


Figure 44: Effect of hydrogen injection on productivity with a blast oxygen content of between 21 and 33% and a temperature of 1,200°C[79].

3.2.3.3.3. Injection of Coke Oven Gas into Blast Furnaces

Since coke oven gas is particularly rich in hydrogen (H_2) and methane (CH_4), it may be entirely appropriate for it to be used for injection into blast furnaces as a reducing agent. From the point of view of the blast furnace, this is ultimately a kind of combination of the two preceding techniques. The first injection trials were conducted in the United States, in the mid-1990s [80]. Today, the technique is not yet widely deployed. However, it was implemented on an industrial scale in 2021, in blast furnace B at the ArcelorMittal Gijón site in Spain [81]and moreover in 2019 at the Saarstahl group's ROGESA Roheisengesellschaft Saar mbH site in Dillingen, Germany[82].

According to the results of H. Wang et al. (2016) [47], coke oven gas injection reduces CO_2 emissions from blast furnaces by 6 to 7% and, as similarly in the case of hydrogen injection, results in an increase in blast furnace productivity of around 20%. Coke oven gas injection can also be combined with recirculation of steelmaking gases (see part 3.2.3.3.4).

Modelling of Coke Oven Gas Injection in Blast Furnaces

In the case of injection of coke oven gas alone, the results of H. Wang et al. (2016) [47] enable adoption of the assumption that specific consumption of coke is lowered to 309.3 kg/$t_{hot\ metal}$[30], while that of pulverised coal is lowered to 120.6 kg/$t_{hot\ metal}$[31]. In addition, on the basis of the composition of the gases, it was estimated that the injection of coke oven gas would have the effect of increasing production of blast furnace gas to 1,500 kWh/$t_{hot\ metal}$ as compared with 1,350 kWh/$t_{hot\ metal}$ in the REF1 reference plant. As in the case of natural gas injection, the investment cost for coke oven gas injection was taken as EUR 10 M [75] for a blast furnace with a capacity of 2 $Mt_{hot\ metal}$/year.

Commodity	*Unit*	*Original value /$t_{hot\ metal}$*	*New value /$t_{hot\ metal}$*
Coke	kWh	2491	2406
Blast furnace gas (production)	kWh	-1350	-1500
Pulverised biochar	kWh	$1501 \cdot prop\_biocharbon\_BF$	$1072 \cdot prop\_biocharbon\_BF$
Pulverised coal	kWh	$1501 \cdot (1 - prop\_biocharbon\_BF)$	$1072 \cdot (1 - prop\_biocharbon\_BF)$
CO2	tCO2	*Carbon accounting*	

Table 12: Effect of coke oven gas injection on blast furnace input-output modelling

3.2.3.3.4. Recirculation of Steelmaking Gases (TGR-BF)

Gases escaping from blast furnaces and coking plants contain large quantities of hydrogen (H_2) and carbon monoxide (CO). Today, these gases are principally used for combustion in thermal power stations, and in downstream primary processing on-

[30] I.e. 309.3*28/3.6 = 2,406 kWh/$t_{hot\ metal}$, taking into account a lower heating value (LHV) of 28 GJ/t for coke.
[31] I.e. 120.6*32/3.6 = 1,072 kWh/$t_{hot\ metal}$, taking into account a lower heating value (LHV) of 28 GJ/t for pulverised coal.

site. Using them as a reducing agent in the blast furnace would reduce the amount of coke required in the production of primary steel.

TGR-BF (Top Gas Recycling Blast Furnace) technology consists in recirculating steelmaking gases with a reduction potential in the blast furnace, in order to reduce coke consumption and cut CO_2 emissions. Furthermore, during recirculation, the CO_2 is separated from other gases, thus generating a very pure stream that can be easily captured for geological storage. Several versions of the process have already been put forward and tested in 2007 on an experimental blast furnace owned by LKAB in Luleå, Sweden. Blast furnace gases may be injected either via the tuyères (at the base of the reactor) or via the shaft after reheating. The best configuration in terms of emissions (version 4 in Figure 45) indeed corresponds to a situation in which coke oven gases are injected via the tuyères and blast furnace gases are injected via the shaft after reheating. In this case, CO_2 emissions were reduced by 24%, with stable operation of the equipment and high quality pig iron [31], [47], [83]. Coke oven gases, which are rich in H_2, can also be recirculated for injection into the blast furnace. Due to the greater reactivity of H_2 as compared with CO, recirculation of blast furnace gases has the effect of increasing blast furnace productivity, by 15.7% according to M. Chu & J.I. Yagi (2010) [84], while reducing CO2 emissions by 16.8%.

Before achieving these levels of performance and stabilised operations, the installation of a TGR-BF system in a blast furnace would cause a shutdown of considerable length, and thus loss of production capacity and profits for the company, at least for the duration of the work[31].

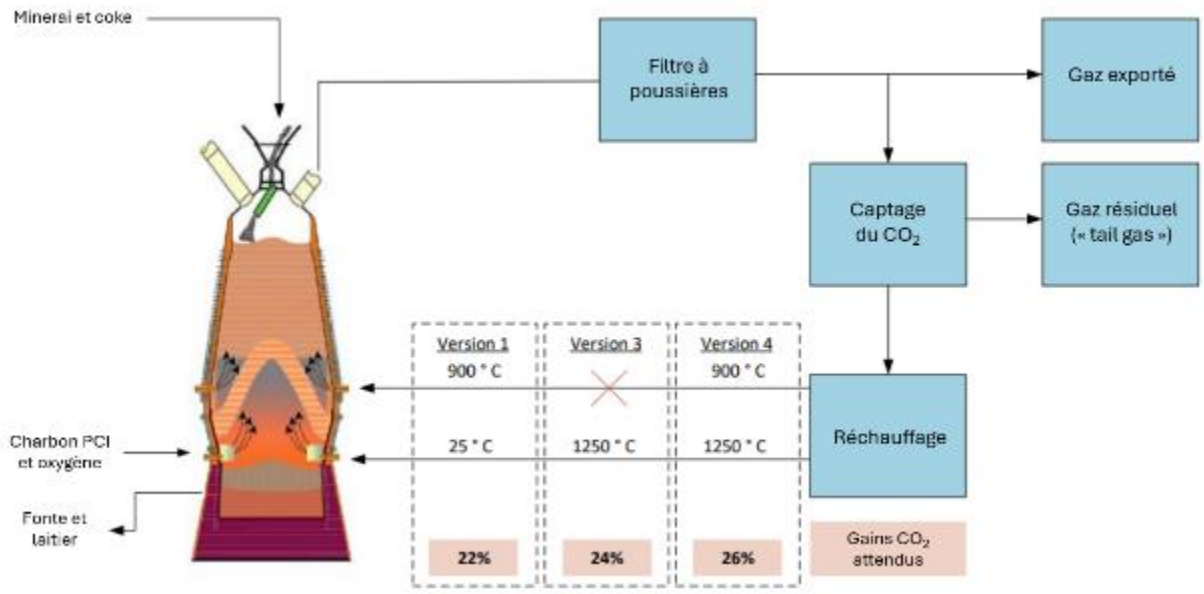


Figure 45: Simplified diagram of the TGR-BF blast furnace gas recycling process (adapted from [31]).

The putting in place of TGR-BF technology has the effect of reducing the energy value of steelmaking gases production by around half (see Figure 46 from the study by J. Song et al. (2019) [52]). Indeed, on the one hand, the production of blast furnace gas is very substantially reduced since its reducing potential is recovered by recirculation and, on the other hand, the production of coke oven gas also falls due to lower coke consumption in the blast furnaces. In this configuration, the energy production station becomes entirely or almost obsolete, since there are no longer any residual steelmaking gases to be recovered. At the same time, electricity consumption at the blast furnace increases by 89% due to the elimination of CO_2 by VPSA [56].

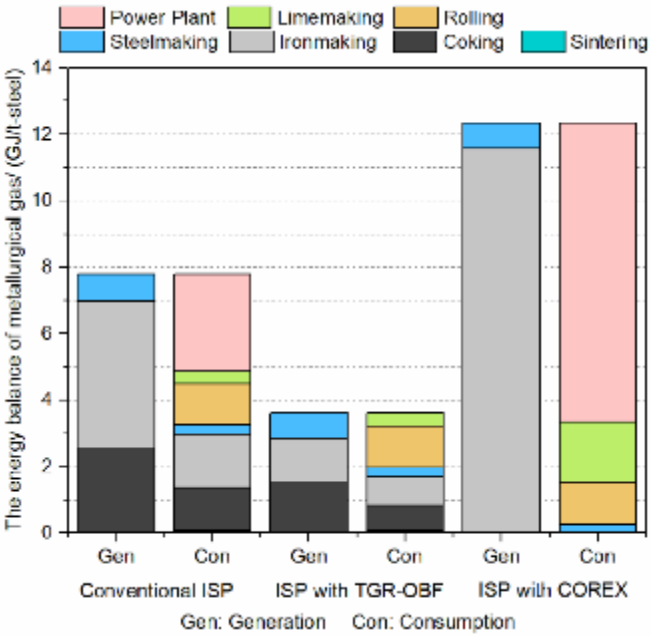


Figure 46: Comparison of the balance of steelmaking gases in a conventional integrated steel plant (ISP), with TGR-BF technology and with COREX technology.[32] [52].

CO_2 is eliminated from the recirculation circuit using capture technology of the VPSA type. Once it has been removed, it can be sent for transport and storage, with an additional cryogenic capture and purification stage. In the modelling, CO_2 transport and storage is viewed as an additional option once the TGR-BF technology has been put in place. In this regard, the assumptions adopted are detailed in part 3.2.3.4.

Modelling of the Recirculation of Blast Furnace Gases

The modelling of TGR-BF technology is principally based on the assumptions and results of J. Song et al. (2019) [52], and P. Jin et al. (2017) [56], and a study by IEAGHG (2013) [57]. On the basis of data from D. Santis et al. (2021) [75], it was assumed that the investment cost for TGR-BF technology without capture would be EUR 110/$t_{hot\ metal}$.year (i.e., for example, a total investment cost of EUR 220 M for a blast furnace with an annual capacity of 2 Mt) and EUR 150/$t_{hot\ metal}$.year with CO_2 capture (a figure which moreover includes the purification and compression stages).

As the technology is modelled, recirculation of steelmaking gases makes it possible to reduce direct emissions from the REF1 reference plant by 22%, as shown in Figure 47. The graph also makes visible a redistribution of the sources of CO_2 emissions. In the first place, recirculation of gases makes it possible to reduce coke consumption in the blast furnaces, which has the effect of lowering coking plant production and therefore CO_2 emissions from the latter. Secondly, this recirculation has the effect of considerably reducing the availability of coke oven gas and blast furnace gas for the thermoelectric power station. The output of the power station was maintained at a minimum level in order to meet the site's steam requirements, supplemented by combustion of natural gas. It is equivalent to a situation in which the carbon contained in the coke and injection coal were in fact much more efficiently used for reduction of iron oxides. Moreover, in this sense, the recirculation of steelmaking gases may be considered an energy efficiency technology. Whereas blast furnace gases were previously distributed to many other consumption points (in particular the thermoelectric power station), thus generating CO_2 emissions at these points, the recirculation of steelmaking gases has the effect, so to speak, of concentrating emissions at the blast furnace, since the use of carbon (and therefore, inevitably, its conversion into CO_2) is henceforth far more optimised. This is the reason for such a sharp rise in CO_2 emissions from blast furnaces. However, it should be noted that any electricity not produced by the thermoelectric power station by means of steelmaking gases has to be replaced by electricity from the grid, which has the effect of raising indirect Scope 2 emissions (not shown in Figure 47).

Commodity	*Unit*	*Original value* /t_{coke}	*New value* /t_{coke}

[32] "COREX" technology is a so called smelting reduction process presented as an alternative to the blast furnace route. In particular, the process makes direct use of iron ore and coal as inputs in their basic form, instead of sinter and coke. It thus bypasses sintering and the coking. Despite the partial saving in CO_2 that it is capable of providing, this technology was not modelled because it was not viewed as a prospect within decarbonisation trajectories for French steelworks.

Coke	kWh	2,491	1,478
Coke oven gas	kWh	60	0
Blast furnace gas (consumption)	kWh	375	256
Blast furnace gas (production)	kWh	-1350	-384
Electricity	kWh	95	252
Oxygen	Nm3	38	215
Pulverised biochar	kWh	$1501 \cdot prop\_biocharbon\_BF$	$1511 \cdot prop\_biocharbon\_BF$
Pulverised coal	kWh	$1501 \cdot (1 - prop\_biocharbon\_BF)$	$1511 \cdot (1 - prop\_biocharbon\_BF)$

Table 13: Effect of recirculation of blast furnace gases on blast furnace input-output modelling.

Commodity	Unit	Original value /$t_{hot\ metal}$	New value /$t_{hot\ metal}$
Coke oven gas (consumption)	kWh	0.017	0.091
Blast furnace gas	kWh	0.089	0.038

Table 14: Effect of recirculation of blast furnace gases on coking plant input-output modelling.

Commodity	Unit	Original value /t_{coke}	New value /t_{coke}
Coke oven gas	*kWh*	295	245
Blast furnace gas	*kWh*	17	8
Network gas	*kWh*	43	102

Table 15: Effect of recirculation of blast furnace gases on hot rolling input-output modelling.

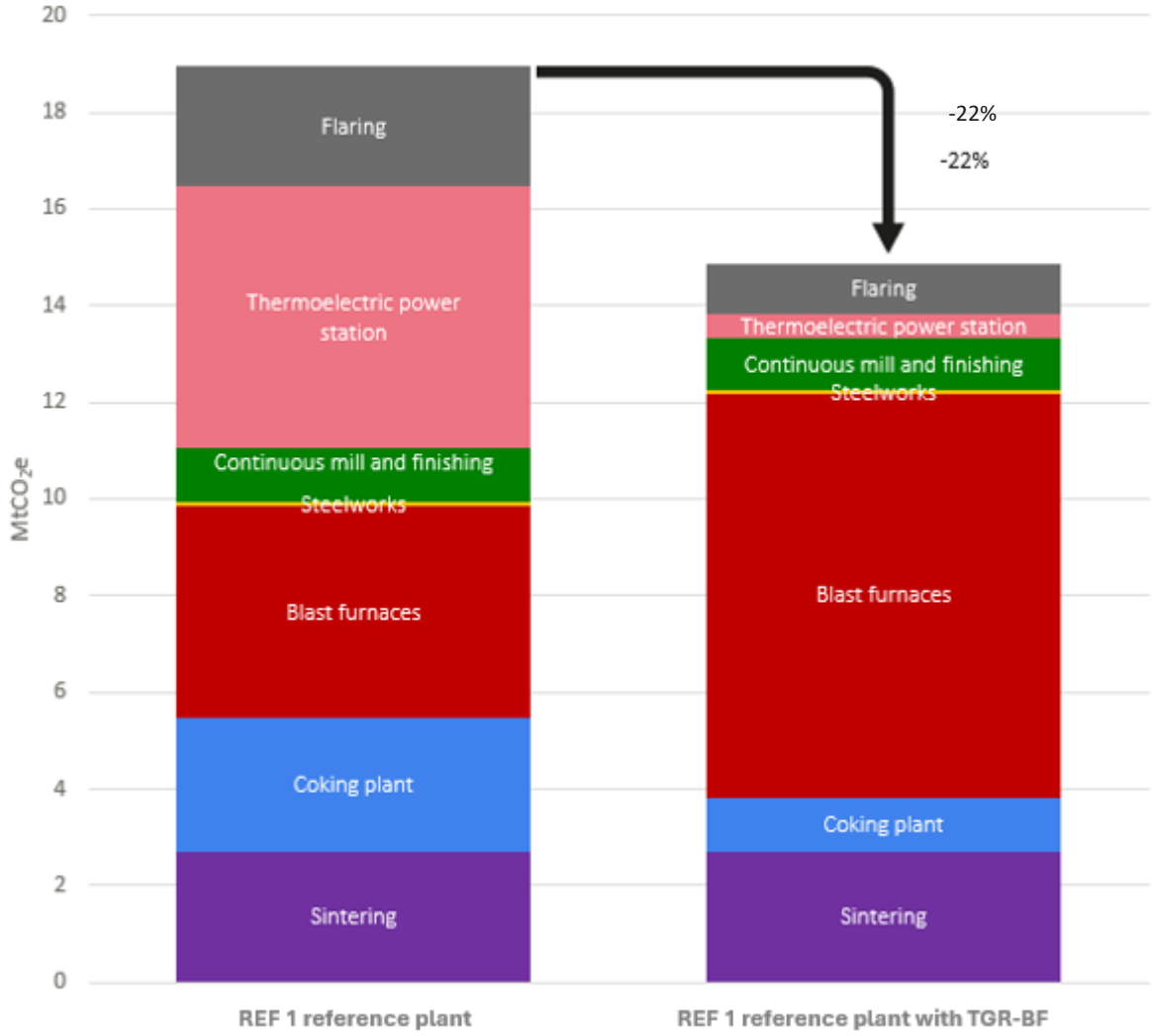


Figure 47: Reference plant REF1 - Effect of recirculation of steelmaking gases on GHG emissions.

3.2.3.3.5. Injection of Plastics in Blast Furnaces

As sources of carbon and hydrogen, waste plastics may be added for co-injection with pulverised coal into the blast furnace. This is referred to as WPI, or Waste Plastic Injection. In 2010, only certain blast furnaces in Austria, Germany and Japan were using injection of plastics. Thermoplastics are the principal family of plastics that can be used in BF co-injection, principally polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) and polystyrene (PS). Polyvinyl chloride (PVC) is also among the usable thermoplastics, but the presence of chlorine in it is problematic since it is largely transformed into hydrochloric acid which, though partly removed in the slag, can eventually corrode the piping and gas processing equipment. For this reason injection of PVC is limited to a few percent.

The injection of 1 kg of waste plastics is capable of replacing around 1.3 kg of pulverised coal in the blast furnaces of JFE Steel, in Japan, and around 1 kg of heavy oil at Stahlwerke Bremen, in Germany. This use of plastic, which appears to be more efficient than pulverised coal, can be explained by the fact that waste plastics generally have higher calorific value, a lower rate of residues (or ash) and higher carbon and hydrogen content. However, replacement of coke by waste plastics is limited to around 30%. The high cost of collection and treatment, and the difficulty of putting in place a reliable, high-quality supply, constitute the two main obstacles to the use of waste plastics in blast furnaces[38].

Insofar as the hydrogen content of waste plastics is generally higher than that of coke and injection coal (14-15% for PE and PP, for example, as compared with 4-5% for coal), their use in most cases leads to lower CO_2 emissions per tonne of hot metal produced. One LCA estimated that WPI would make it possible to lower emissions by around 0.16 $tCO_2/t_{hot\ metal}$[38], i.e. a reduction of around 10% on the basis of a carbon footprint of 1.5 $tCO_2/t_{hot\ metal}$. Among the different types of waste plastics, it would appear that PE and PP offer the greatest potential for reducing emissions [38].

Modelling of Injection of Plastics in Blast Furnaces

The injection of plastics into blast furnaces was not taken into account in the modelling due to lack of technical data.

3.2.3.3.6. Bio-Based Coal

Pulverised coal may be replaced in the blast furnace by coal produced from biomass, known as “biochar”, so that the direct emissions associated with coal injection become biogenic. This technique requires torrefaction (roasting) units that convert biomass sources (such as waste wood) into biochar through pyrolysis. Biomass can also be used in coking plants for the production of bio-coke, as a fuel in the sintering process and moreover as a source of carbon for recarburisation of steel in ladle metallurgy. This part only deals with the replacement of injection coal with biochar, since it represents the most technically advanced option. Use of biomass for the production of bio-coke poses technical challenges connected with the quality and mechanical priorities of the coke obtained [85].

The use of biomass in blast furnaces is already widely employed in Brazil, which produces 25-30% of its steel from biochar. However, the production of biochar for use in the steel industry has led to deforestation in Brazil, involving indirect emissions in particular, with little effort being made to limit this problem [86].

According to the Finnish VTT research centre, 20% of pulverised coal can be replaced by biochar today using current techniques, and potentially more with modification of injection systems [87]. There is a technical limit due to the higher content of phosphorus and alkaline elements in biochar [85]. However, according to E. Mousa et al. (2016) [88], pulverised coal could, in theory, be entirely replaced by biochar.

Modelling of Biochar Injection

In the modelling, it was considered possible for the whole of the pulverised coal to be replaced by biochar.

The rate of pulverised biochar is modelled by means of an operating variable specific to blast furnaces ($part\_biocharbon\_HF$ – see Table 8). Increasing this rate above 0% requires the installation of torrefaction units. This is expressed by taking capital expenditure into account, amounting to EUR 690/$t_{biochar}$.year, based on ArcelorMittal’s Torero project [89], which is aimed at the consumption of 80 kt/year of biochar at the Ghent site in Belgium.

3.2.3.4. CO_2 Capture and Geological Storage

On an integrated site, sources of CO_2 principally derive from blast furnace gases (with a concentration of around 22% CO_2) and oxygen converter BOF gases (with a concentration of around 14%) [90, p. 2].

The challenges of CO_2 capture in the steel industry are attributable, in particular, to the multiplicity of sources of CO_2, which are distant from one another within integrated sites, and to variability in the composition of steelmaking gases, with, in particular, variable concentrations of CO_2. In a study by IEAGHG (2013) [57], the steel production reference plant that was modelled has 23 CO_2 emission points. These sources of emissions are physically concentrated at the energy generation plant, which recovers steelmaking gases from blast furnaces, sintering and coking (see Figure 48).

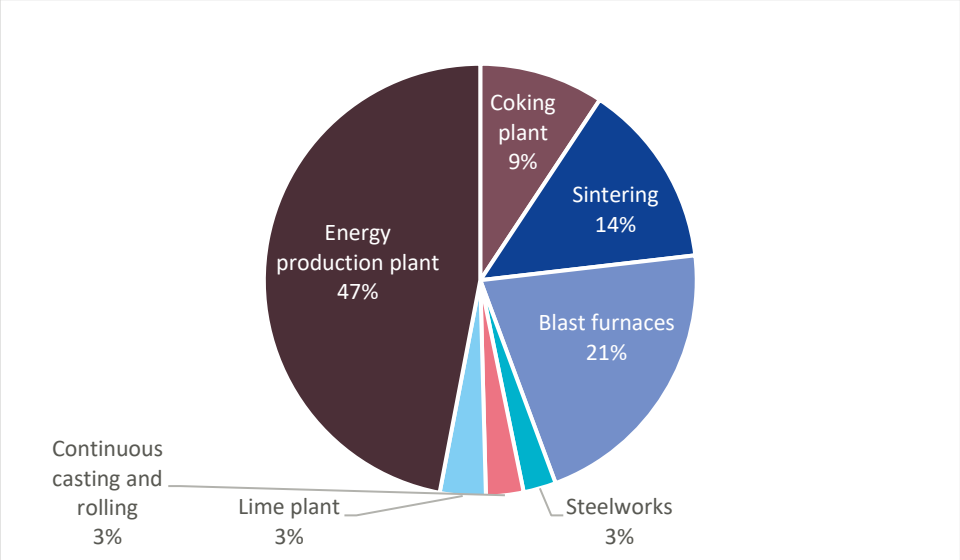


Figure 48: Origin of annual CO_2 emissions on integrated site as modelled by IEAGHG (2013) [57].

A number of different configurations were studied for capture of the CO_2 emitted on an integrated site. With post-combustion technology using a solvent, CO_2 can be captured at the Cowper stoves, which are used to preheat the blast, at the boiler, which produces the steam required to make up for the energy loss due to capture, at the coking plant heaters and at the lime kilns on integrated sites that have them[57]. In the end, only the TGR-BF (Top Gas Recycling Blast Furnace) and rolling CO_2 capture technologies were dealt with, in particular due to a lack of technical data on the other options. Moreover, CO_2 capture by TGR-BF appears to be the most effective method, since it initially optimises the potential of reducing agents at the blast furnace inlet. As explained in part 3.2.3.3.4, the technology has the effect of concentrating CO_2 emissions at the blast furnace, meaning that CO_2 capture options at the thermoelectric power station and coking plant lose their value.

3.2.3.4.1.CO_2 Capture by TGR-BF

In a configuration using recirculation of steelmaking gases, a VPSA-type capture technology is used to eliminate the CO_2 as it is produced. TSA (Temperature Swing Adsorption) technology was studied by N. Jiang et al. (2020) [91] with regard to CO_2 capture but proved to be relatively inefficient as compared with VPSA and TVSA (Temperature/Vacuum Swing Adsorption) technologies in terms of productivity, energy consumption, purity and rate of CO_2 capture.

These technologies are considered mature, and in particular already have applications for production of oxygen from air, purification of hydrogen and CO_2 capture [91]. CO_2 capture by VPSA has already been tested within the framework of the ULCOS project in Luleå, Sweden, in a configuration with recirculation of blast furnace gases (abbreviated TGR-BF or "Top Gas Recycling Blast Furnace")[92], the modelling of which is detailed in 3.2.3.3.4. The VPSA would be located in the "CO_2 Capture" square in Figure 45. However, it was only sized for removal of part of the CO_2, in order to ensure proper operation of the recycling of steelmaking gases. In the exit gas ('Tail gas' in Figure 45), the CO_2 is present with a concentration of 87% (the remainder being principally CO), which is insufficient for transport and storage. For the latter, the CO_2 needs to have a concentration of 95% for transport by pipeline and more than 99.9% for transport by ship in liquid form [93]. In order to obtain a CO_2 stream that meets the criteria for transport and storage, additional cryogenic purification and compression stages are required [57], [92]. Cryogenics is a capture technique suitable for streams with a high concentration of CO_2 [31].

Two configurations of the TGR-BF recirculation of blast furnace gases technology were taken into account in the modelling: (1) TGR-BF technology with VPSA alone and without CO_2 transport and storage and (2) TGR-BF technology with VPSA, cryogenic purification and compression for CO_2 transport and storage. This latter option may be selected after the former, with the effect of adding investment costs and increasing energy consumption.

The data presented in the IEAGHG study (2013) [57] makes it possible to estimate the additional electricity consumption required for cryogenic capture and CO_2 compression, once the VPSA capture stage has been completed. There are two possible configurations: capture by so called flash cryogenics and capture by cryogenic distillation. The first case is less energy-intensive, but only makes it possible to achieve a CO_2 concentration of 96.3%, which is insufficient for transport by ship, whereas cryogenic distillation makes it possible to achieve CO_2 concentration of close to 100%, but inevitably involves higher electricity consumption. In view of the CO_2 hub projects currently in course of development, it appears more probable that the CO_2 would be transported by ship via the potential CCS zones of Dunkirk and Fos-sur-Mer (where France's two principal steelworks are located). In order to be compliant for transport of CO_2 by ship (which requires a concentration of over 99.9%), it was assumed that the final capture stage would be based on cryogenic distillation technology.

Modelling of CO_2 Capture by TGR-BF

On the basis of the IEAGHG study (2013) [57], it was assumed that the additional electricity consumption would be 210 kWh/tCO_2 for cryogenic capture and 195 kWh/tCO_2 for its compression to 110 bars, i.e. a total electrical consumption of 405 kWh/tCO_2. CO_2 capture in conjunction with recirculation of blast furnace gases was modelled *via* modification of the blast furnace input-output description and the introduction of an input-output table for the capture process.

Commodity	*Unit*	*Original value* /$t_{hot\ metal}$	*New value* /$t_{hot\ metal}$
CO_2	tCO_2	*Carbon accounting*	$SELF + 0{,}6$
CO_2 captured	tCO_2	-	- 0.6

Table 16: Effect of CO_2 capture after recirculation of blast furnace gases on blast furnace input-output modelling.

Commodity	*Unit*	*Original value* / $t_{CO2\ captured}$	*New value* / $t_{CO2\ captured}$
Electricity	kWh	-	-405

Table 17: Input-output modelling of CO_2 capture after recirculation of blast furnace gases[33].

The result of the application of TGR-BF technology with CO_2 capture is set out in Figure 49. Once the first stage of recirculation of blast furnace gases has been completed, emissions from the site are concentrated at the blast furnace, as explained in section 3.2.3.3.4. A fraction of these emissions (shown in the hatched area) corresponds to the stream of CO_2 which is continuously evacuated from the recirculation circuit using VPSA technology. This is the stream that can be processed and sent for transport and storage. This means that so many emissions are thus abated for the site. The other fraction of the emissions from the blast furnace corresponds to emissions connected with preheating of the blast by the Cowper stoves, which do not come within the framework of the recirculation circuit. Overall, more than 50% of the site's emissions can thus be abated using a combination of TGR-BF and CO_2 capture technologies.

[33] Electricity consumption for 1 (positive) tonne of captured CO_2 is negative since the flow of captured CO_2 conventionally takes a negative value, given that it is an outflow and not an inflow. In practice, therefore, the quantity of electricity consumed is indeed positive for -1 t of captured CO_2.

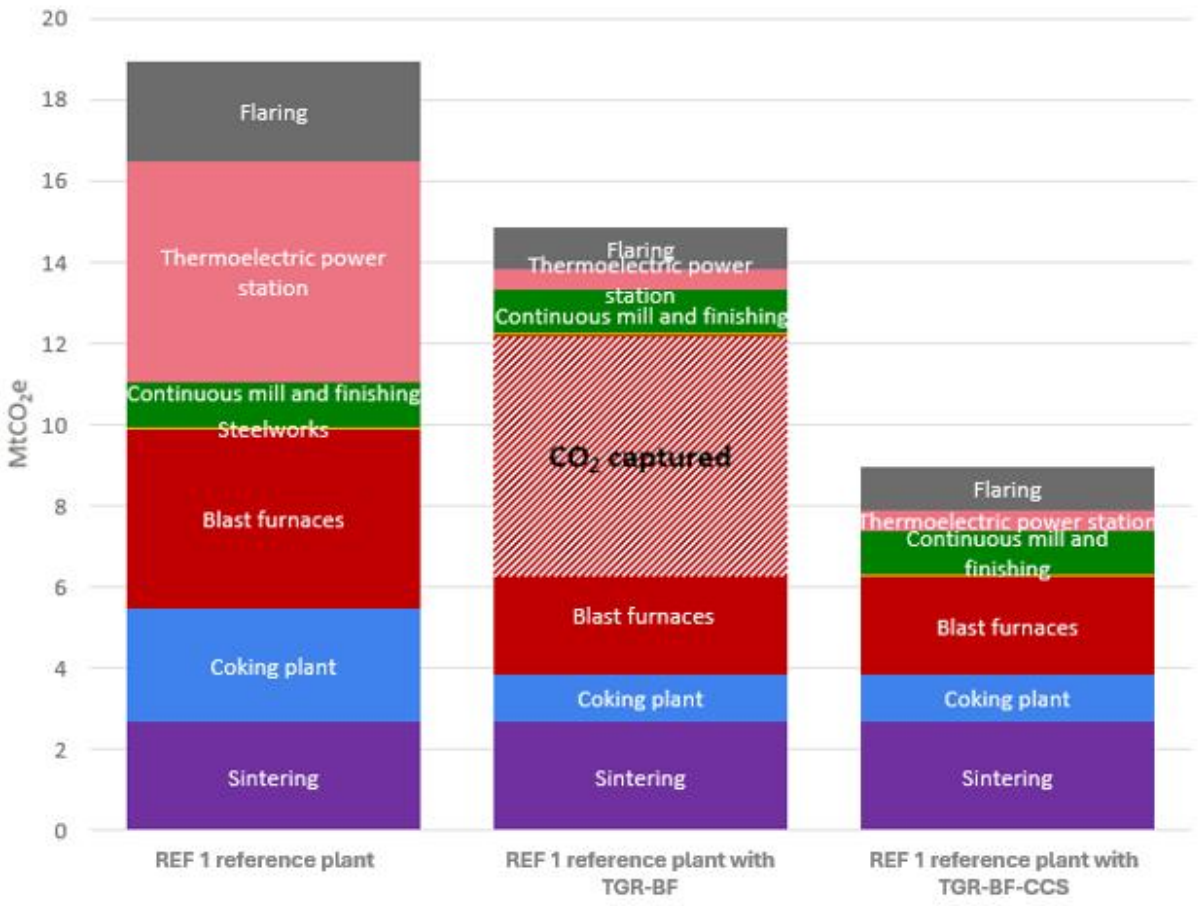


Figure 49: Reference plant REF1 - Effect of recirculation of steelmaking gases with and without capture on GHG emissions.

3.3. Electrical Sector

3.3.1. Electrical Sector Processes

An alternative to the blast furnace route is steel production from scrap in an electric arc furnace (EAF route). The principal source of iron is scrap, but EAFs can also be used with direct reduced iron (DRI / HBI) or with a mixture of DRI and scrap. The principal source of energy for an EAF site is electrical energy and also natural gas to a certain extent, above all for hot rolling. Scrap and other sources of iron are melted in an electric arc furnace at temperatures of up to 1,600°C. Lime, coal and oxygen are injected in order to remove impurities. Natural gas is also commonly injected in order to improve the energy performance of the process and fill certain so called 'cold' spots within the furnace: electricity may represent up to 60% of the furnace's energy consumption, with the remaining 40% being represented by chemical energy (natural gas, coal and oxygen) [94]. In general, electric arc furnaces have a lower production capacity than blast furnaces (in general between a few dozen and a million tonnes a year).

An electric arc furnace is fundamentally composed of a tilting shell, lined with refractories. A basket of scrap metal, in general supplemented with additives such as coal, lime and ferro-alloys, provides the charge at the top of the furnace. During operation, a dome (also known as the 'roof'), through which one or more graphite electrodes are placed inside, covers the shell containing the charge. A high voltage is applied between the electrodes and the metal in order to create an electric arc and melt the metal.

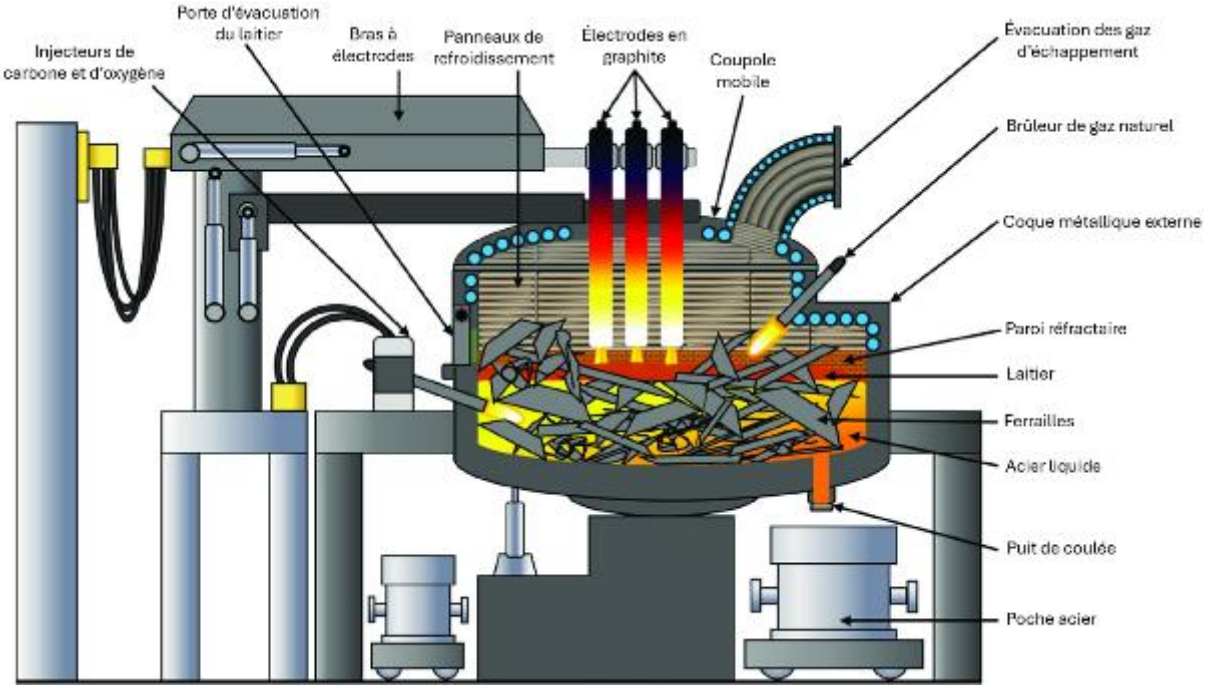


Figure 50: Diagram of an electric arc furnace (adapted from [95]).

Once the metal is molten, it is necessary to remove certain elements such as carbon and phosphorus. Historically, decarburisation and dephosphorisation were achieved by the addition of iron ore, but this has gradually been replaced by a process of blowing oxygen into the liquid metal through a lance in order to cause oxidation of these elements. Oxygen also enables removal of silicon [21]. Oxygen is now also blown in during the molten phase in order to speed up the process by burning the carbon provided in the charge, converting it into CO and CO_2 (in a ratio of 90% CO/10% CO_2 [96]), and moreover to form 'foamy' slag that protects the inner walls of the shell from radiation from the electric arc, thereby improving the transfer of thermal energy to the melt. The latter may also be stirred by means of the injection of an inert gas via the bottom (argon or nitrogen, for example), which improves heat exchange in the melt and the balance between metal and slag. [21], [97]. The carbon also makes it possible to reduce the iron oxides present in the charge (according to the reaction FeO + C → Fe + CO_2 [98]) and thus to increase the ferric yield of the fusion process. The presence of volatile elements in coal tends to provide hydrogen to the melt, which contributes to reduction of the iron oxides [98]. The injection of sources of fossil carbon from coal represents in the order of 40% to 70% of direct CO_2 emissions from an electric arc furnace. The remainder of the emissions come from the consumption of graphite electrodes, the decarbonation of the limestone and dolomite to form slag, and the use of natural gas [99]. At the end of each cycle, the slag floating on top of the liquid steel is separated from the metal by tilting the furnace back and forth. Due to all of the reactions listed above, in practice fusion in an electric arc furnace always generates some material losses: L. Yang et al. (2017) [96] gives a value of 1,044.69 kg of scrap per tonne of liquid steel produced. It is also possible for electric steelworks to consume pig iron or DRI. Moreover, for certain sites that have the possibility, it also a way of reducing production costs in times of scrap scarcity.

Input	Role
Scrap, pig iron	Source of iron and carbon
Lime, dolomite	Forming of the initial slag in order to separate impurities
Coal (anthracite)	Formation of foamy slag to protect the internal walls of the furnace and improve heat transfer, partial reduction of iron oxides
Natural gas	Additional thermal energy, in the “cold spots” in particular
Oxygen	Oxidation of carbon, phosphorus and silicon
Ferro-alloys	Deoxidation, desulphurisation, adjustment of the composition

Table 18: Role of different inputs in the electric arc furnace.

Figure51: Charging of an electric arc furnace with a scrap metal basket [21].

The specific energy consumption of a site (i.e. the quantity of energy consumed per tonne of steel produced) is highly dependent on its production level: this may vary by as much as double depending on monthly production fluctuations. In the modelling, these variations were not taken into account: this is equivalent to an assumption that monthly fluctuations are smoothed out over the course of the year.

Once the metal has been brought to liquid state, the next stage of the process is similar to the blast furnace route: the steel undergoes ladle treatment (so called "secondary" steelmaking), then it is cast, generally in the form of blooms which are then rolled to form long products (beams, tubes and bars). In France, electrical steelworks produce two main types of steel: low alloy “carbon” steels and high alloy steels. Moreover, electrical steelworks were taken into account in the modelling via two reference plants of this type (see section3.3.2). Carbon steels and other low alloy steels make up the majority of electric furnace output by volume. They contain little or no alloy elements and are produced thanks to the type of scrap used and the moment of refining. In cases where the charge is composed of 100% scrap, the level of carbon contained in the liquid steel is relatively low. For reasons of productivity, manufacturers tend to lower the carbon content in the metal to around 0.05% at the time of melting in the electric arc furnace. Below this level, the ferric losses due to oxidation become too great [100].

As with carbon steels, the production of stainless steels begins with the melting of raw materials in an electric arc furnace. The charge placed in the furnace principally consists of scrap metal, scrap steel and ferro-alloys. Unlike carbon steels, stainless steels require a very low carbon content (often less than 0.03%), and at the same time need to maintain a high chromium content (typically 17 to 18%), which makes special refining processes necessary [101]. Once the liquid metal is transferred from the electric arc furnace, it has to undergo decarburisation by the blowing in of oxygen. However, the chromium also tends to oxidise and is lost in the form of Cr_2O_3 in the slag. In order to avoid this reaction, and the risk of having to add refined ferrochromium, which is very expensive, it is necessary to strongly facilitate the carbon oxidation reaction, which can be done by lowering the partial pressure of carbon monoxide. To this end, it is possible to dilute the CO with oxygen and another inert gas, typically argon or nitrogen: this is the principle behind the AOD process (Argon Oxygen Decarburisation, see Figure 52) which, with its derivatives, represents around 75% of global capacity. The other solution is to work in a vacuum, which also has the effect of lowering the partial pressure of CO: this is the principle of the VOD process (Vacuum Oxygen Decarburisation, see Figure 53), which moreover makes it possible to achieve even lower carbon contents, in the order of 0.005%. Decarburisation of the molten metal is then followed by a deoxidation stage by the addition of ferrosilicon, and then a desulphurisation stage by the addition of CaO which, with the sulphur, forms calcium sulphide CaS before being eliminated via the slag.

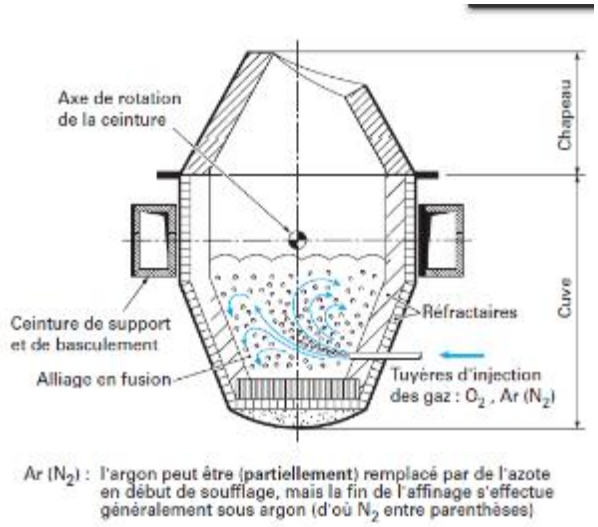


Figure 52: Cross-section diagram of an AOD converter [101].

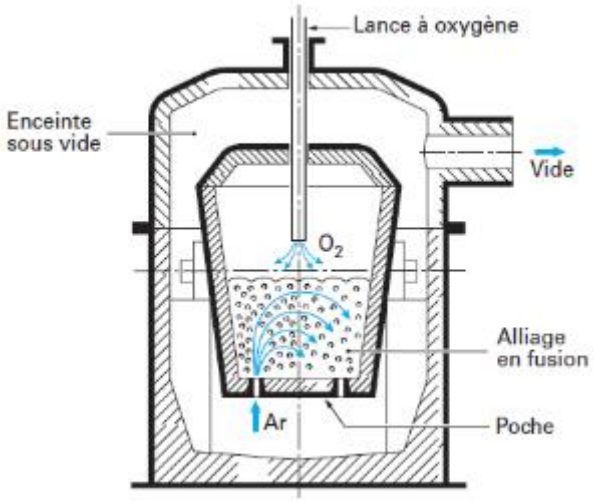


Figure 53: Cross-section diagram of a VOD (Vacuum Oxygen Decarburisation) process[101].

3.3.2. Modelling of the Electrical Sector

It has been estimated that the maximum liquid steel production capacity for the whole of France's electrical steelworks is 6 Mt/year. In the modelling, two reference plants were constructed to represent the output of France's electrical steelworks. It was assumed that the first EAF plant produces a range of carbon and low-alloy steels (REF2-1 plant, see Figure 54), while the second produces stainless and high-alloy steels (REF2-2 plant, see Figure 55). Assumptions concerning specific energy consumption and sources of process emissions are detailed in Table 19 and Table 20 and for the REF2-1 plant and in Table 21 and table 22 for the REF2-2 plant. These assumptions were made on the basis of a study of the whole of France's electrical steelworks. In order to ensure their consistency, the values were also cross-checked again with sources from the scientific literature, such as L. Yang et al. (2017) [96], T. Echterhof (2021) [98] and ESTEP (2021) [102]. In addition to these technical characteristics, it was assumed that the specific consumption of scrap would be 1,050 $kg_{scrap}/t_{liquid\ steel}$ on the basis of L. Yang et al. (2017) [96]). This value is common to both reference plants and to any future electric arc furnaces coupled with a DRI reactor.

The choice of modelling electrical steelworks by means of two reference plants rather than one was principally made for two reasons. In the first place, it is possible to roughly identify the two principal categories of steels according to market applications. To be specific, carbon and low alloy steels tend to be used in the building industry and infrastructures, whereas stainless and high alloy steels have a wide range of applications, including in the aeronautics industry and industrial machinery, as well as capital goods and consumer goods. Furthermore, there is a certain homogeneity in terms of processes and specific consumption between these two major categories of plants. For example, the production of stainless and high-alloy steels in general requires an AOD or VOD type of process at the secondary steelmaking stage, which is not the case for

carbon and low alloy steels. Their consumption of alloy elements is also higher. For these two reasons, it appeared appropriate to segment the representation of electrical steelworks between two reference plants.

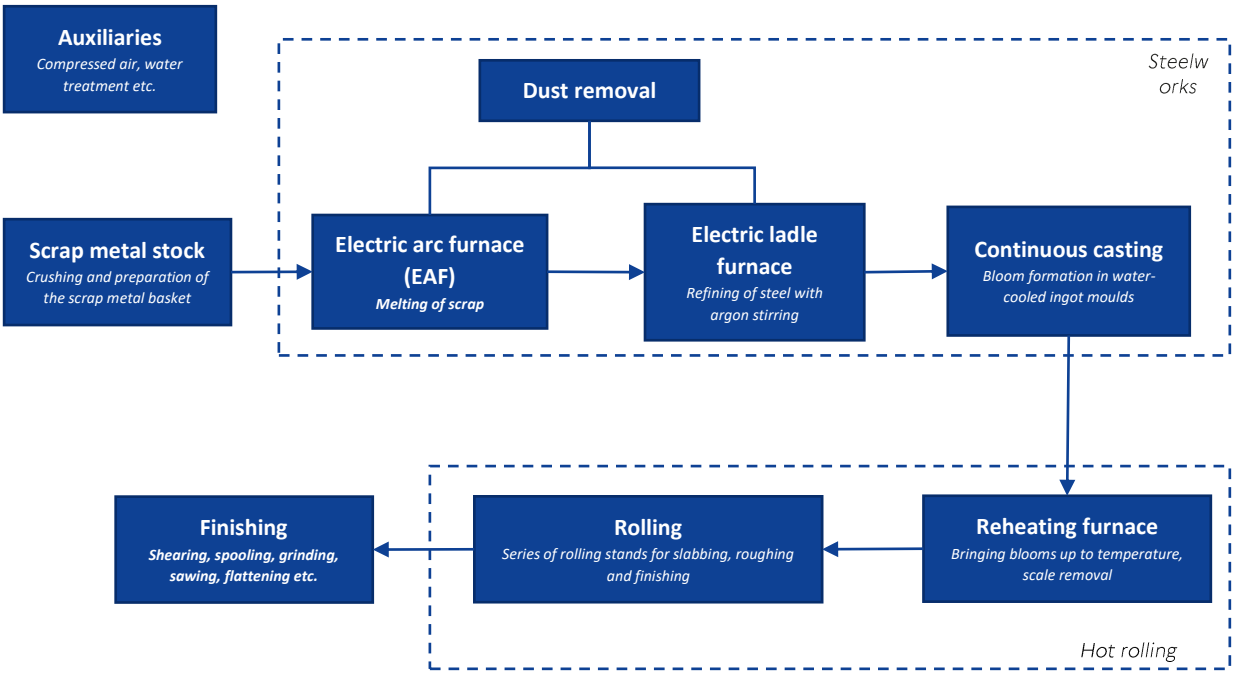


Figure 54: Reference plant REF2-1 Carbon and low alloy steels - Process diagram.

Stage of process	Energy carrier	Specific consumption
Electric arc furnace	Electricity	450 kWh/$t_{liquid\ steel}$
	Natural gas	50 kWh/$t_{liquid\ steel}$
	Oxygen	70 kWh/$t_{liquid\ steel}$ (i.e. 18.2 $Nm^3/t_{liquid\ steel}$)[34]
Electric ladle furnace	Electricity	20 kWh/$t_{liquid\ steel}$
	Natural gas	30 kWh/$t_{liquid\ steel}$
Dust removal	Electricity	50 kWh/$t_{liquid\ steel}$
Reheating furnace	Natural gas	300 kWh/$t_{rolled\ steel}$
Rolling	Electricity	100 kWh/$t_{rolled\ steel}$
Auxiliaries	Electricity	75 kWh/$t_{liquid\ steel}$

Table 19: Reference plant REF2-1 Carbon and low alloy steels - Specific energy consumption.

Source of process emissions	GHG intensity
Anthracite, coke and other sources of carbon (graphite, tyres, etc.)	35 $kgCO_2e/t_{liquid\ steel}$
Consumption of graphite electrodes	5 $kgCO_2e/t_{liquid\ steel}$
Lime and dolomite for slag formation	2 $kgCO_2e/t_{liquid\ steel}$
Additional carbide metals (ferrosilicon, ferromanganese, etc.)	0 $kgCO_2e/t_{liquid\ steel}$

Table 20: Reference plant REF2-1 Carbon and low alloy steels - Sources of process emissions.

[34] On the basis of a coefficient of equivalence of 3.85 kWh/Nm^3.

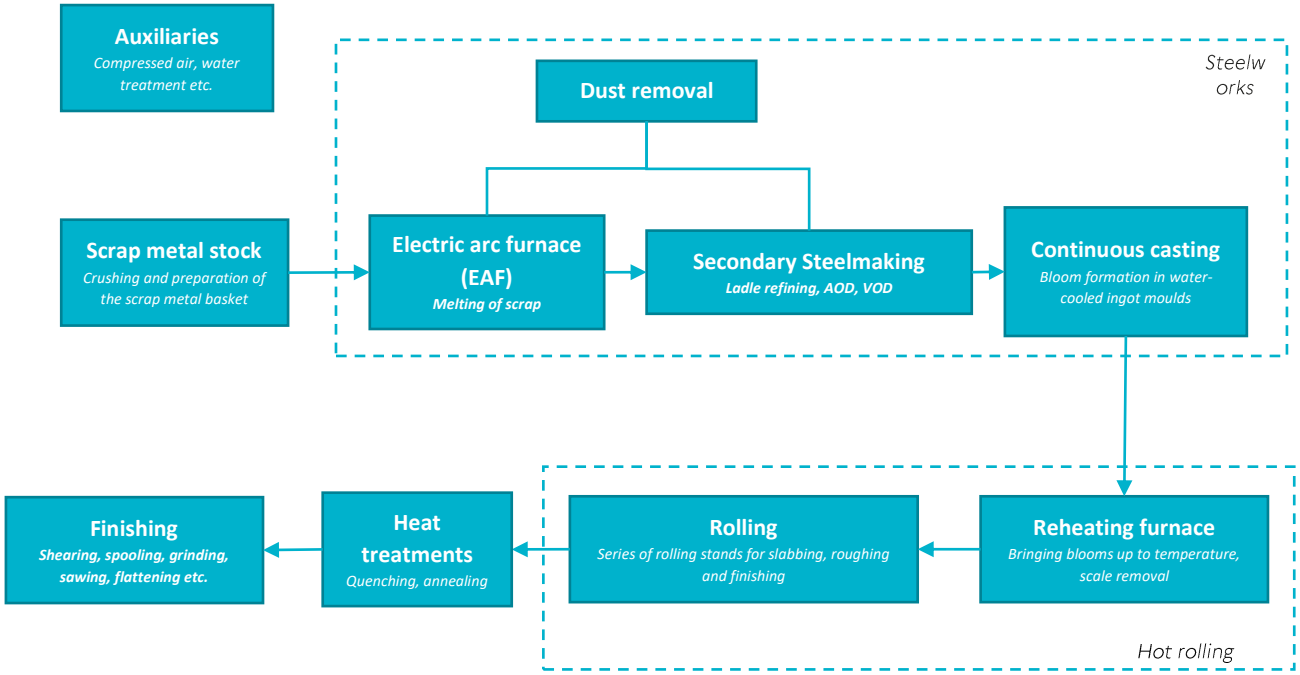


Figure 55: Reference plant REF2-2 Stainless and high alloy steels - Process diagram.

Stage of process	Energy carrier	Specific consumption
Electric arc furnace	Electricity	500 kWh/$t_{liquid\ steel}$
	Natural gas	60 kWh/$t_{liquid\ steel}$
	Oxygen	70 kWh/$t_{liquid\ steel}$ (i.e. 18.2 $Nm^3/t_{liquid\ steel}$)[35]
Secondary Steelmaking	Electricity	100 kWh/$t_{liquid\ steel}$
	Natural gas	100 kWh/$t_{liquid\ steel}$
Dust removal	Electricity	50 kWh/$t_{liquid\ steel}$
Reheating furnace	Natural gas	600 kWh/$t_{rolled\ steel}$
Rolling	Electricity	200 kWh/$t_{rolled\ steel}$
Heat treatments	Electricity	250 kWh/$t_{rolled\ steel}$
	Natural gas	300 kWh/$t_{rolled\ steel}$
Auxiliaries	Electricity	75 kWh/$t_{liquid\ steel}$

Table 21: Reference plant REF2-2 Stainless and high alloy steels - Specific energy consumption.

Source of process emissions	GHG intensity
Anthracite, coke and other sources of carbon (graphite, tyres, etc.)	35 $kgCO_2e/t_{liquid\ steel}$
Consumption of graphite electrodes	15 $kgCO_2e/t_{liquid\ steel}$
Lime and dolomite for slag formation	2 $kgCO_2e/t_{liquid\ steel}$
Additional carbide metals (ferrosilicon, ferromanganese, etc.)	20 $kgCO_2e/t_{liquid\ steel}$

Table 22: Reference plant REF2-2 Stainless and high alloy steels - Sources of process emissions.

[35] On the basis of a coefficient of equivalence of 3.85 kWh/Nm^3.

3.3.3. Electrical Sector Decarbonisation Technologies

3.3.3.1. Treatment and Cleaning of Lower Quality Scrap

High quality scrap, and in particular the absence of inert materials, make it possible to reduce the quantity of energy used in the electric arc furnace in order to melt the inputs. After a number of discussions with manufacturers, it was agreed that the maximum energy efficiency savings would be 10% for the electric arc furnaces, i.e. around 50 kWh/$t_{liquid\ steel}$.

3.3.3.2. Energy efficiency

3.3.3.2.1. Digitalisation

The large number of parameters to be managed in real time in an electric arc furnace have made computer control almost essential. Although already in place in many steelworks, it was considered that optimised management of electric furnaces by computer would enable electricity savings of around 15 kWh/$t_{liquid\ steel}$.

3.3.3.2.2. Electromagnetic Stirring

The circulation of a low-frequency electric current in the stirrer windings produces a progressive magnetic field, which penetrates the furnace from the bottom and sets the liquid steel in motion. Tests have shown that electromagnetic stirring enables improvement of heat transfer, productivity and metal yield [103]. According to the literature, this technology enables reduction of the energy input by 14 kWh/$t_{liquid\ steel}$, principally in the form of chemical energy (natural gas, carbon and oxygen). It also enables reduction of electrode consumption by 4 to 6%. [103].

3.3.3.2.3. Preheating of Scrap

The waste heat from the furnace flue gases can be used to preheat the scrap before it enters the electric arc furnace to a temperature of between 300 and 600°C [104]. It is estimated that around 20% of the energy supplied to the furnace (in electrical or chemical form) is lost as heat in the combustion gases [105]. Recovery of this heat therefore represents a major source of energy efficiency if it has not already been put in place. Preheating of scrap is a widespread technique in Japan, and increasingly also in the United States. It also improves productivity by reducing tap-to-tap times by 8 to 10 minutes [106]. Several techniques exist for recovering heat from flue gases, such as recovery by means of ducts to the scrap charging basket, or moreover the use of a shaft furnace located above the electric arc furnace. The most effective technique is probably continuous preheating, in which the scrap is continuously preheated in a counter-current on a conveyor by the flue gases escaping from the furnace (Figure 56) [104].

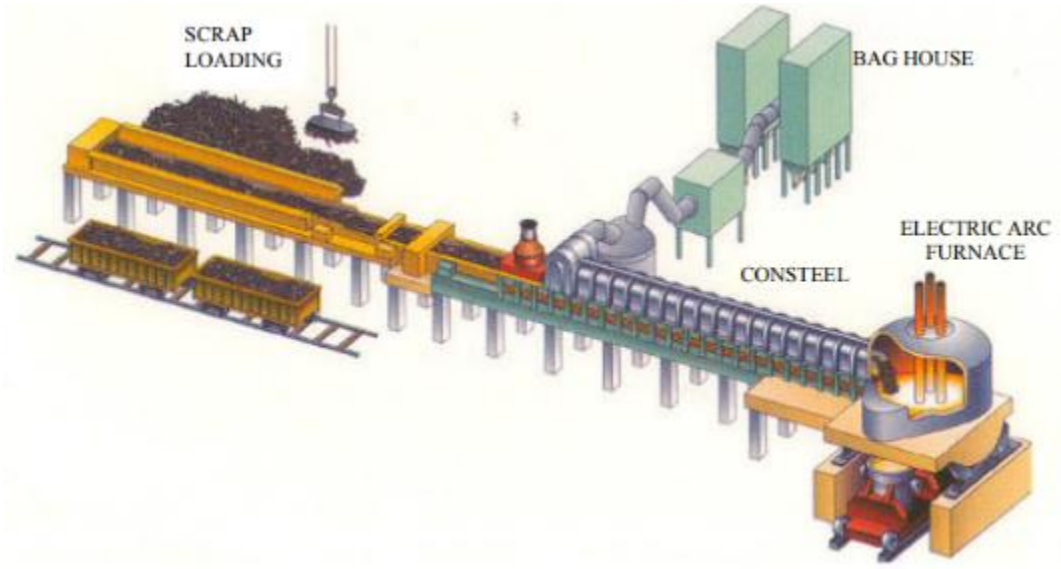


Figure 56: Schematic Depiction of Consteel® System [104].

Certain facilities of this type were in operation in France but had to be shut down because this technology has the effect in particular of generating emissions of pollutants and other environmental nuisances such as volatile organic compounds (VOCs), dioxins and furans [106], [107]. These emissions occur in particular due to preheating of the charge to a relatively low temperature, which would make complex gas treatment systems necessary that are expensive to implement. For these reasons, the industry sees little future for this type of preheating in France. However, it should be noted that in 2012, 99 scrap preheating systems were in operation in Europe [105]. Today, the process, which is considered to be mature [108], is

primarily based on four technologies: the Comelt, Twin Shell, Shaft and Consteel® processes. This last mentioned Consteel® technology is used in particular by the CELSA group in a factory in Norway [109]. In March 2023, Tenova announced that it would supply a new electric arc furnace equipped with a Consteel® preheating system to the Tenaris Campana steel plant, in Argentina, with a production capacity of 950 kt/year. [110]. The furnace will also be equipped with a Consteerrer® electromagnetic stirring system developed in partnership with ABB (see part 3.3.3.2.2). In comparison to the electricity consumption specific to the electric arc furnace, which is set at between 450 and 500 kWh/t_{steel} in the modelling, the literature indicates that the Consteel® process makes it possible to achieve consumption in the order of 369 to 391 kWh/t_{steel}.[111].

The electricity savings generated by this technique are estimated at 25 kWh/$t_{liquid\ steel}$ i.e. around 5% of consumption by electric arc furnaces. In addition to the energy saving, preheating of scrap makes it possible to improve productivity by 33%, reduce electrode consumption by 40% and reduce dust emissions [106]. It should be noted that the introduction of this technology theoretically makes it possible to improve the energy efficiency and profitability of sites, but does not make it possible to reduce direct CO_2 emissions (though very small reductions may be possible, via reduction of electrode consumption). In terms of cost, N. Pardo et al. (2012) [105] estimate an investment total of EUR 2.3 M for the implementation of this technology on an electrical steelworks with a capacity of 500 kt_{steel}/year, i.e. a cost of 4.6 EUR/t_{steel}.year.

3.3.3.2.4. Improved Sealing of the Electric Furnace

This technique consists of placing an airtight cover over the arc furnace in order to reduce heat loss via the flue gases and limit the entry of air. It has been estimated that this technique would enable savings of around 20 kWh/$t_{liquid\ steel}$ in electricity consumption.

3.3.3.2.5. Regenerative Burners

A regenerative burner (Figure 57) is a combustion technology found in the metallurgy sector, based on the principle of preheating the combustion air using pumped hot gases. Preheating of the air makes it possible to recover the heat contained in the exit gases, and therefore to considerably improve the energy efficiency of the furnace. A regenerative burner consists of a combustion chamber supplied with heat by two burners operating in an alternating manner: while one burner is firing, the combustion gases pass through the body of

the second burner combustion firing port and the heat they contain is transferred to a refractory material (usually ceramic alumina balls[112]). In the next cycle, the second burner fires up and its combustion air is preheated by the heat released by the refractory material. The role of each burner is reversed with each cycle, acting alternately as burner and chimney [112], [113].

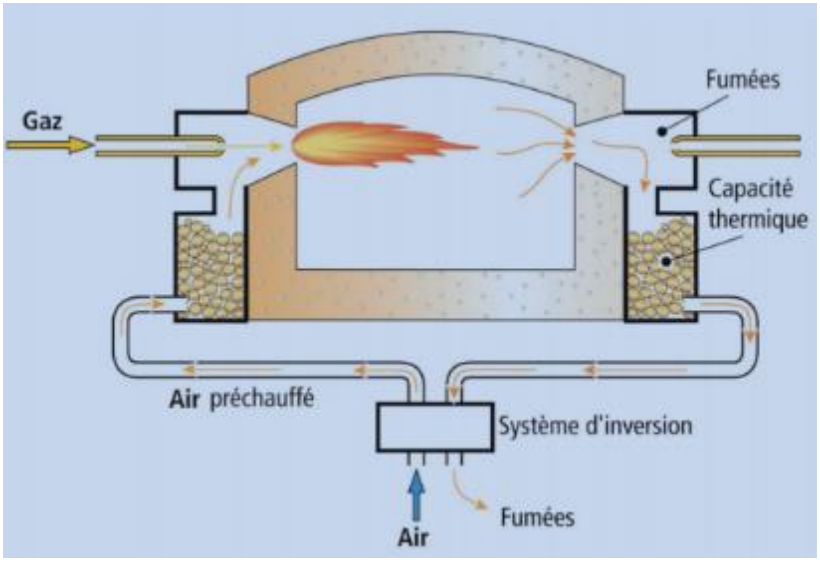


Figure 57: Diagram of the operation of a regenerative burner [113].

The regenerative burner is considered to be an improved version of the recuperative burner, of which the principle of operation is more or less the same [112]. It is estimated that recovery systems of this kind are capable of converting between 80 and 85% of the energy input into "useful" heat, thus reducing the furnace's energy consumption by 40 to 50% as compared with a conventional cold air burner system [113]. These regenerative burners are not particularly limited in capacity or power,

unlike certain electric furnaces. They nevertheless require greater space in order to accommodate refractory trays close to the combustion chamber [113]. This type of equipment is also eligible for Energy Savings Certificates [36].

3.3.3.2.6. Oxy-Fuel Burners

The principle of an oxy-fuel burner is to enrich the combustion air with oxygen, which presents several advantages. Above all, this avoids "unnecessary" heating of the other components of the air that do not take part in the reaction, in particular nitrogen. Furthermore, in combustion gases, radiant heat principally comes from CO_2 and H_2O molecules which, when present in very high concentrations, as in the case of oxy-fuel combustion, makes it possible to maximise heat transfer [114]. These burners reduce energy consumption by 30 to 45% and NO_X emissions by 60 to 90% as compared with cold air burners[115]. J. von Schéele (2010) [114] even reports an efficiency gain of 50%.

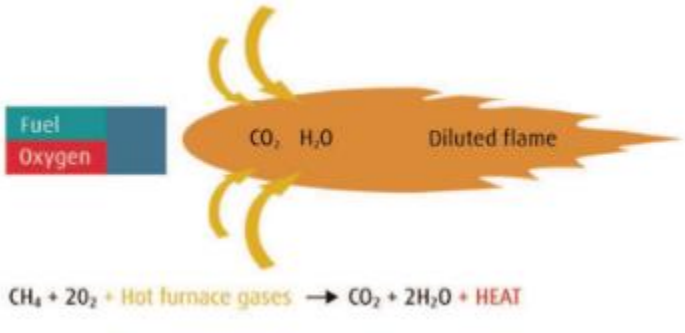


Figure 58: Oxy-fuel combustion diagram[114].

The natural gas burners present in electric arc furnaces which are used to preheat cold spots between the electrodes are generally speaking oxy-fuel burners. In any case, this is the assumption made for the modelling of France's industrial facilities. However, oxy-fuel technology can also be used for the preheating of ladles and for the reheating of semi-finished products at the processing stage. It was assumed that installation of oxy-fuel burners for the preheating of ladles would reduce natural gas consumption by 35% as compared with cold air burners. In terms of cost, N. Pardo et al. (2012) [105] estimate an investment total of EUR 2.8 M for a steelworks with a capacity of 500 kt_{steel}/year, i.e. a cost of 5.6 EUR/t_{steel}.year.

3.3.3.2.7. Direct Current Electric Arc Furnaces

Arc furnaces are traditionally powered by (so called "AC") alternating current: this is a three-phase operating system, with three graphite electrodes passing through the roof. Since the 1990s, the (so called "DC") direct current electric arc furnace (see Figure 59) has gained popularity throughout the world for a number of reasons [97]:

- It causes less electrical disturbance (or "flicker").
- It generates less noise.
- It reduces consumption of graphite electrodes.
- It enables a slight increase in productivity and energy efficiency.

[36] Standard form IND-UT-118

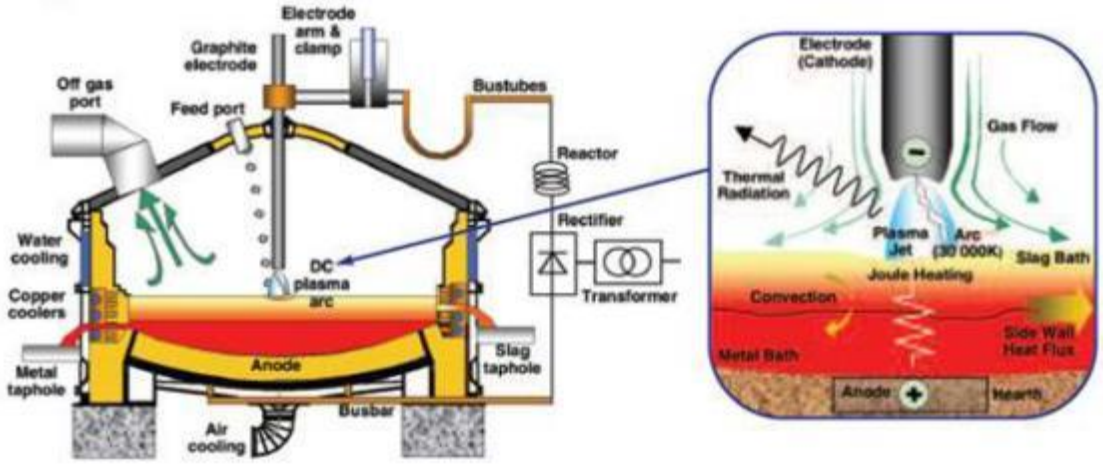


Figure 59: Diagram of a DC electric arc furnace [116].

Unlike the AC arc furnaces used in all French electrical steelworks, DC arc furnaces operate with a single electrode, which improves the stability of the arc and the operating efficiency. It is estimated that installing this technology could result in a gain in electrical efficiency of around 70 kWh/$t_{liquid\ steel}$.

3.3.3.3. Electrification

3.3.3.3.1. Induction Furnaces

Under the effect of a magnetic field, metal products can be heated by the action of an induced current. At the stage of primary processing of steel, the induction technique can be used for the reheating of semi-finished products before rolling, forging, and any heat treatments (annealing, quench hardening etc.)[86]. For these stages, which in the modelling are assumed to be fuelled by natural gas, it was estimated that the consumption of 1 kWh of natural gas could be replaced by 0.75 kWh of electricity after changing to induction. However, the amount of investment required for the purchase and integration of a new induction furnace appears high. On the basis of an internal ADEME estimate, an assumed investment cost of EUR 500/t_{steel}.year was adopted.

3.3.3.3.2. Electrical Resistance

The use of electrical resistance for the reheating of semi-finished products constitutes a decarbonisation technology in the sense that it enables replacement of natural gas. This heating technology has been known for more than 80 years [117]. The specific electricity consumption of an electrically-powered reheating furnace is around 275 kWh/t_{steel} (corresponding to a conversion efficiency of 85%), as compared with 350 to 390 kWh/t_{steel} typically for gas furnaces [118]. Unlike a change to induction, which a priori makes it necessary to change the entire gas furnace, electrification using electrical resistance can be implemented in several stages by means of modifications to the existing gas reheating furnace, thus resulting in much lower investment costs. Among the resistive materials studied, $MoSi_2$ resistors of the Kanthal Super type appear to be well-suited to the reheating of steel products [117].

On the basis of an internal ADEME estimate, an assumed investment cost of EUR 30/t_{steel}.year was adopted. This assumption corresponds to the cost of 70 % electrification of a reheating furnace using electrical resistance heating by retrofitting of an existing gas furnace. In other words, 30% of the energy continues to be supplied by gas (for reaching the final temperature levels).

3.3.3.3.3. Vacuum Pumps for VOD

For stainless steel, replacement of the vacuum production mechanism for VOD (Vacuum Oxygen Decarburisation) makes it possible to avoid the consumption of vapour (and therefore of natural gas). The assumption was made that electrification of the VOD degassing process would make it possible to save 40 kWh/$t_{liquid\ steel}$ of natural gas in the "secondary steelmaking" stage and that, at the same time, this would result in additional electricity consumption of 2 kWh/$t_{liquid\ steel}$. OPEX not connected with energy consumption (other inputs, utilities, maintenance) are lower in the case of vacuum pumps.

3.3.3.3.4. Direct Combustion of Hydrogen

In an electrical steelworks, direct combustion of hydrogen as a substitute for natural gas may principally be envisaged for the preheating of ladles, for the reheating of semi-finished products before processing and for heat treatment furnaces. In 2020, Swedish steelmaker Ovako, in collaboration with equipment manufacturer Linde, reportedly successfully tested the reheating of ingots by means of combustion of hydrogen in pit furnaces, without affecting the quality of the steel [119], [120].

It was assumed in the modelling that direct combustion of hydrogen would be applied for the preheating of ladles (which appears difficult to electrify directly), and for the final temperature levels in reheating furnaces. On the basis of a review of data from ADEME projects, an assumed investment cost of EUR 30/t_{steel}.year was adopted for complete retrofitting of gas burners into H_2 burners. This cost includes H_2 electrolysis capacity, which moreover represents most of the associated equipment costs.

3.3.3.4. CCUS

3.3.3.4.1.CO_2 Capture and Storage

To date, carbon capture and storage in electrical steelworks has barely been studied in the scientific literature, with the majority of research focusing on the capture of CO_2 from blast furnaces. However, it should be noted that the technique appears to be theoretically possible, provided of course that access to a storage area is available. According to D. E. Wiley et al. (2011) [121], the CO_2 contained in the flue gases emitted by an electric arc furnace ("mini mill") has a concentration of 40%, the remainder being principally composed of N_2 (56%). It should be noted that these figures were obtained on the basis of calculations and not on the basis of measurements. This level of concentration can qualify the process for the setting up of a capture component. In an experimental study, K. Dong et al. (2015) [122] measured that the concentration of CO_2 in the furnace flue gases from an electric arc furnace was between 24 and 28% during the molten steel phase and between 30 and 39% during the oxidation phase. The cost of CO_2 capture in an electric arc furnace is estimated at AUD 250/tCO_2 according to D. E. Wiley et al. (2011) [121] i.e. around EUR 170/tCO_2[37].

3.3.3.4.2. Recarbonation of Slag

Steelmaking slags are alkaline products rich in calcium oxides (CaO) and magnesium oxides (MgO), which makes them potentially reactive with carbon dioxide. Sequestration of CO_2 in slags makes them more stable and facilitates their use in various applications. A number of parameters have an influence on the process of recarbonation of slags. An excessively high temperature, for example, tends to reduce the efficiency of the reaction, while a fine particle size in the slag promotes diffusion and sequestration of CO_2 [123]. S. Kombathula (2020) [123] tested carbonation of electric arc furnace slag of standard composition on a laboratory scale. Under the best possible conditions, the maximum sequestration rate obtained was 53 kgCO_2e/t_{slag}. Given that production of slag by an electric arc furnace comes to around 126 kg/$t_{liquid\ steel}$, a maximum capture rate of 53 * 126 = 6.7 kgCO_2e/$t_{liquid\ steel}$ can be envisaged. In comparison, the rate of direct emissions comes to around 70 kgCO_2e/$t_{liquid\ steel}$ in the modelling (for the "steelworks" part alone).

It is also possible to recarbonate a proportion of the dust emitted at the time of the melting of scrap, which is rich in CaO. On a laboratory scale, M. H. El-Naas et al. (2015) [124] obtained a sequestration rate of 0.657 kgCO_2 per kilogram of dust and a maximum carbonation rate of 42.5%. In the absence of additional information, this decarbonisation lever was not taken into account.

3.3.3.1. Change of Reducing Agent

3.3.3.1.1. Use of biomass

The use of carbon from biomass as a substitute for coal in electric arc furnaces is currently the subject of both research and industrial-scale trials. Various sources of biomass have been studied, such as biochar, wood chips, palm kernel shells, pumpkin seed and olive kernels [98].

The principal possible solution studied for the replacement of coal in EAFs remains biochar prepared from sources of biomass. The latter is in fact more reactive than coal, hence the need to stabilise it by conditioning it in the form of briquettes. It is technically feasible to replace up to 100% of coal with biochar, with a substitution rate of 1.5 tonnes of biochar for one tonne of coal [125]. The reason for this is that biomass (which has a higher volatile matter content) is much less efficient than coal for carburisation of liquid steel. Around 55-60% of the carbon content in biochar is not dissolved in the molten bath, but is transformed to a gaseous state.

*3.3.3.1.2.*Use of Organic Waste

[37] Assumed exchange rate: 1 EUR = 1.5 AUD

As with blast furnaces, waste with carbon content such as plastics and tyres can be used in electric arc furnaces in replacement of coke and coal. On certain sites, this is a standard industrial practice, at least with limited rates of substitution. Moreover, the charging of plastic waste in scrap baskets for melting in EAFs is also considered to be a TRL9 technology [126]. It has been shown experimentally that the injection of plastic has the effect of accelerating the formation of foamy slag, thus improving the productivity and energy efficiency of the process [111]. Electricity consumption would be reduced by 12 kWh/tonne of plastic in the charge [111], [127]. In a blast furnace, it is estimated that 1 kg of PE plastic would replace 0.75 kg of coke, with a maximum of 30 % substitution of coke. According to discussions with manufacturers, it already appears to be technically possible to achieve a substitution rate of 50%, and this conclusion is also reached by F. Cirilli et al. (2022) [128] in an experimental study. Moreover, the latter study shows that the use of 1 kg of plastic enables the replacement of 1.13 kg of anthracite in EAFs. The chlorine contained in plastics can be neutralised by lime. Moreover, the hydrogen content is higher than in coke, thus contributing to the reduction of iron oxides in partial replacement of carbon (see equations below).

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2 \text{ (coke, pulverised coal)}$$

$$Fe_2O_3 + 2CO + H_2 = 2Fe + 2CO_2 + H_2O \text{ (plastics) [127]}$$

In Europe, the OnlyPlastic project [129], coordinated by the Italian RINA Consulting group, is aimed at studying substitution of the whole of the fossil carbon sources traditionally used in EAFs (anthracite, coke etc.) by means of densified polymers derived from waste plastics. The injection of plastics as a substitute for coal was modelled on the basis of the results of the study by F. Cirilli et al. (2022) [128]). To be specific, it was assumed that the waste plastics used had an LHV of 32 MJ/kg and an emission intensity of 0.65 kC/$kg_{plastic}$ (i.e. 2,383 $kgCO_2/t_{plastic}$). The substitution ratio adopted is 1 kg of plastic for the replacement of 1.13 kg of anthracite, and the maximum substitution rate was set at 50%. With regard to tyres, 1.7 kg are required in order to replace 1 kg of anthracite. The natural rubber from which tyres are partly made, which contains biogenic carbon, contributes to lowering fossil carbon emissions from the process [127].

3.4. The Direct Reduction Sector

The direct reduction steelmaking sector (hereinafter abbreviated “DRI-EAF route”) currently principally operates with processes using natural gas. The use of hydrogen as a substitute for natural gas in order to decarbonise steel is the subject of research and development and is henceforth approaching the industrial and commercial stage. Moreover, this is also the technology indirectly referred to when speaking of “hydrogen steel”. This part is aimed at describing in detail how the process works and the reactions involved, from the current configuration with 100% natural gas to the achievement of 100% H_2 operation. It should be noted that, in the modelling, the DRI-EAF route is treated as a reference plant rather than a decarbonisation lever that would be activated in an existing plant (see part 3.4.2).

3.4.1. Direct Reduction Sector Processes

3.4.1.1.Conventional Processes

In the process known as “direct reduction”, iron ore is reduced to a solid state in order to obtain sponge iron (solid primary iron) commonly referred to as DRI (Direct Reduced Iron). The DRI can then be used in an electric arc furnace, an oxygen converter and indeed also directly in a blast furnace. Once the sponge iron has been obtained, it can be compacted into briquettes commonly referred to as “HBI” or Hot-Briquetted Iron (see Figure 60). This conversion into HBI enables it to be transported over long distances while limiting the risk of reoxidation of the ore. The emergence of this direct reduced iron production sector is closely linked to the growth of the electrical sector, which requires scrap metal as well as substitutes, including reduced ores. On certain sites, direct reduction may be integrated into the electrical process. Non-integrated direct reduction plants (i.e. those that do not directly consume the DRI they produce) in general meet international demand by exporting HBI [130]. To date, the direct reduction sector represents around 5% of the steel produced worldwide [131].

Figure 60: Direct reduced iron in the form of hot-briquettes iron, or HBI [38].

The main advantage of the integrated DRI-EAF sector above all lies in the significant savings generated by the direct use of hot DRI immediately after its production in an electric arc furnace. Because DRI is a highly porous material, it tends to oxidise very rapidly According to the carbon content of the direct reduced iron (between 2.2 and 4%), charging DRI at a temperature of 600°C in an electric arc furnace results in savings of around 25 to 30% in specific electricity consumption as compared with a situation in which it were charged at room temperature [132].

In practice, DRI production is currently located in countries where natural gas is economical because it is cheaper than coke. This technology, developed in the 1960s, has only become established in the Middle East (particularly in Iran, which has around thirty plants of this type), Latin America and the United States [131]. There is only one plant of this kind in Europe, in Hamburg, owned by the ArcelorMittal group. A number of different direct reduced iron production processes exist, which are summarised in Figure 61.

[38] Photo credit: Borvan53/Wikimedia Commons

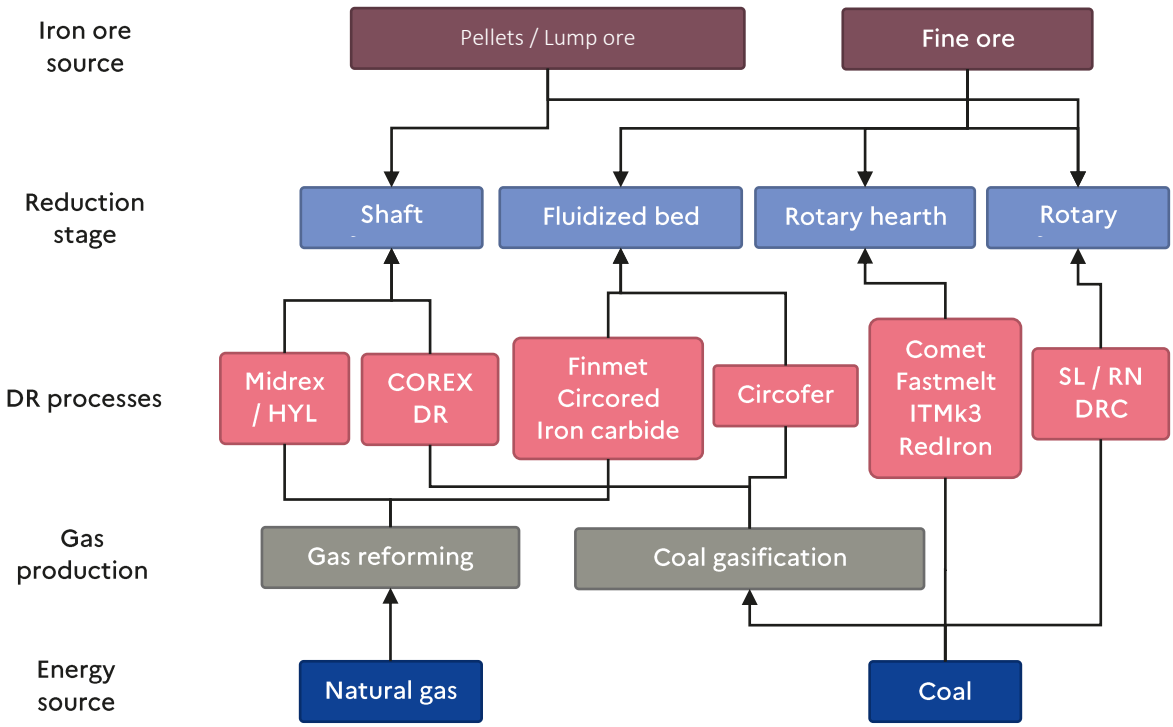


Figure 61: Main direct reduction processes (diagram adapted from P. Cavaliere et al. (2022 [133]).

Processes based on natural gas and the shaft furnace (MIDREX and Energiron/HYL) are the most highly developed processes for direct reduction and account for almost 80% of world DRI production. The reducing gas, composed of H_2 and CO, is produced by reforming natural gas outside the reactor (shaft furnace), unlike in blast furnaces (example of the MIDREX process Figure 62). Inside a DRI reactor, 60 to 70% of the oxide reduction comes from H_2 and 30 to 40% from CO[37]. Gas escaping from the top of the shaft furnace at the top is washed and separated into two streams, one of which is directly mixed with natural gas as a material input, while the other is used as a fuel to supply the heat required by the reformer.

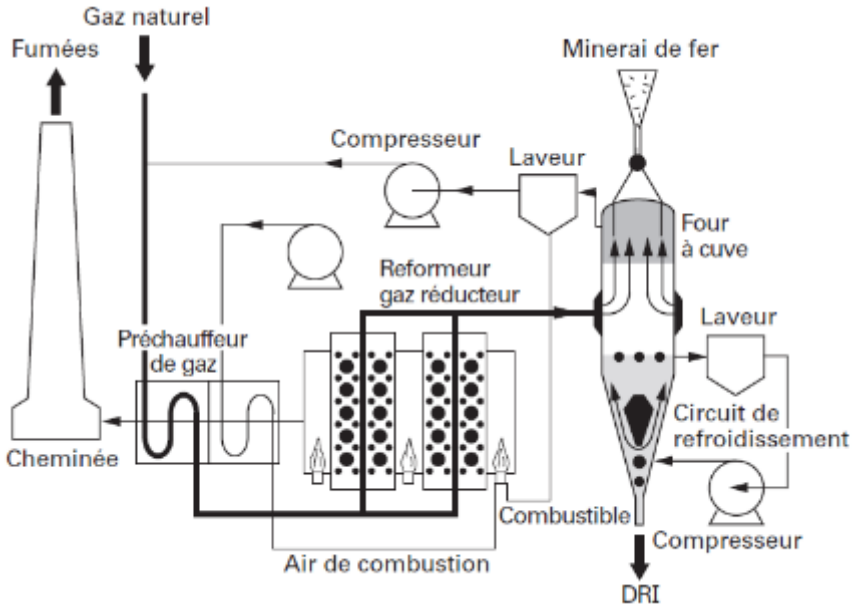


Figure 62: Diagram of the MIDREX process [130].

Fluidised bed processes are capable of operating with both natural gas (e.g. Finmet, Circored) and coal (e.g. Circofer). Rotary hearth processes (e.g. Fastmelt and ITMk3) are other well-developed processes. Smelting reduction processes were developed in order to produce hot liquid metal from iron ore without the use of coke. Several processes have been put forward using ore or sintered ore (e.g. COREX, AISI and Technored) and processes using fines (e.g. Finex, Dios, Hismelt).

Historically, the blast furnace and DRI sectors produced primary steel. But as the challenges of decarbonisation become ever more pressing, processes are tending to incorporate more and more scrap metal. With regard to the direct reduction sector, the rest of the report and the modelling are solely focused on MIDREX and HYL type processes based on shaft furnaces, since to date these processes are the most mature and widely-used.

3.4.1.2. Mixed Natural Gas/Syngas Process

Insofar as the reducing gas produced from natural gas is already composed of 55% hydrogen, natural gas can immediately be partially replaced by hydrogen, up to around 1/3 without any major change to the existing process [134]. A large number of experts and the literature on the subject agree that this is the most promising technological route in order to achieve almost complete decarbonisation of primary steel production. The first hydrogen injection trials for production of DRI were conducted in the 1990s, thus demonstrating the operation of the concept on an industrial scale with a hydrogen fraction of 90% in the reduction gas in an Energiron/HYL type process [76]. **There are several aspects to be taken into account in the partial replacement of natural gas with hydrogen.**

In a direct reduction process operating with a mixture of reduction gases, as in the Energiron/HYL process presented in Figure 63, the shaft furnace is a counter-current reactor in which the iron oxides present in the form of pellets come into contact with reduction gases, which have an upward movement. On leaving the shaft furnace, the residual gases contain CO_2 and H_2O, which are in fact produced by the reduction of iron oxides by hydrogen and carbon, and moreover compounds that still have reducing power (H_2, CH_4 and CO). These gases are then recirculated to the mixture so that they can be reused, with elimination of water by condensation and of CO_2 by washing with solvents, in the process. Otherwise, these compounds, lacking any reducing power, would accumulate in the recirculation circuit. Moreover, the CO_2 eliminated from this circuit by solvent washing (sometimes referred to as “selective” CO_2) constitutes an almost pure captured flow ready for transport and storage. In the concept put forward by N. Müller et al. (2021) [76] in Figure 63, a part of the heat from the exhaust gases (temperature of 400 - 450°C) is used to offset the energy loss connected with regeneration of the solvent for CO_2 capture. The reduction gas circuit is continuously fed with a new mixture of natural gas (CH_4) and syngas (H_2, H_2O, , and potentially CO and CO_2). Part is used for combustion to preheat the mixture of reduction gases to around 900°C. In the next stage, oxygen is injected into the gas circuit in order to partially oxidise the methane according to the following reaction:

$$2\ CH_4 + O_2 \rightarrow 4\ H_2 + 2\ CO$$

Since this reaction is exothermic, it raises the reduction gas mixture to a temperature of greater than 1,050°C before being injected into the shaft furnace. Hydrogen and carbon monoxide reduce the iron oxides, thus producing CO_2 and H_2O. In addition to the H_2 and CO already present in the injected gas, the direct reforming of CH_4 within the reactor generates even more. The methane thus undergoes a steam reforming reaction with water (1) and a dry reforming reaction with the CO_2 (2), both of which are moreover catalysed by the metallic iron present on the surface of the pellets. At the same time, a water-gas reaction (3) also takes place, increasing the H_2 fraction at the expense of CO.

$$CH_4 + H_2O \rightarrow 3\ H_2 + CO\ (1)$$

$$CH_4 + CO_2 \rightarrow 2\ H_2 + 2\ CO\ (2)$$

$$H_2O + CO \rightarrow CO_2 + H_2\ (3)$$

The DRI henceforth leaves the lower section of the shaft furnace at a temperature of around 600 to 700°C. It is then charged and melted in an electric arc furnace, possibly mixed with scrap metal.

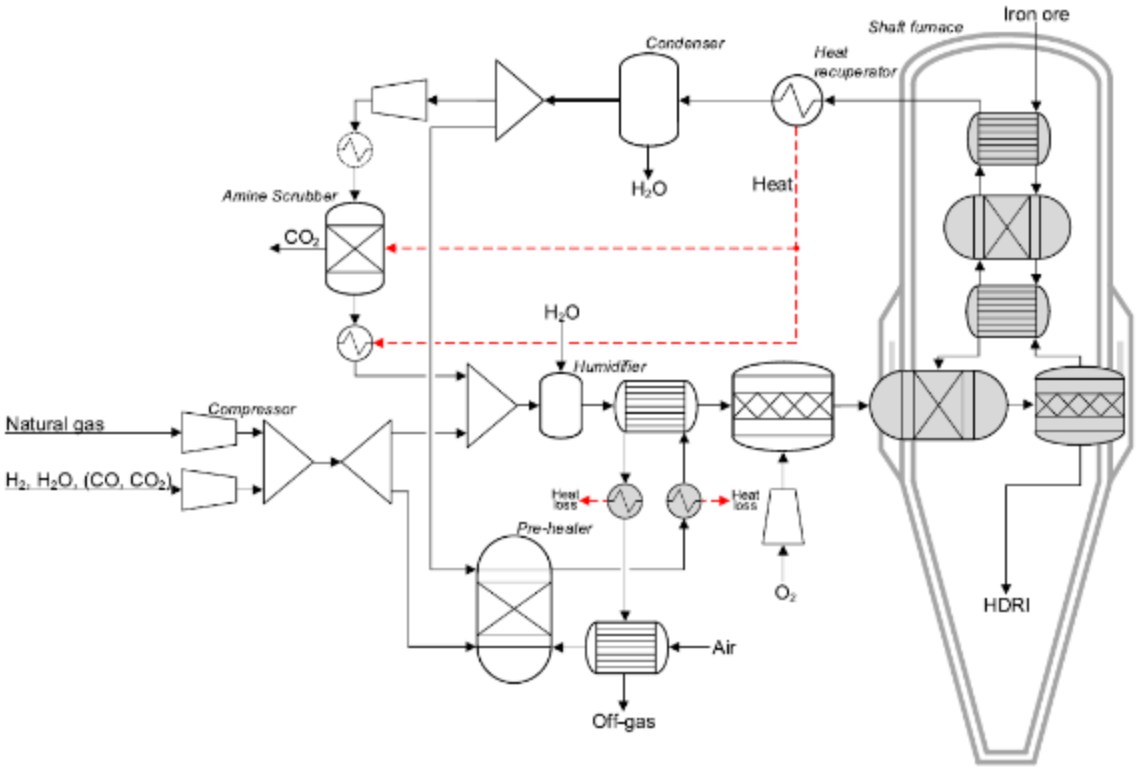


Figure 63: Process scheme of the Energiron/HYL direct reduction process [76].

It is important to note that, even with more favourable hydrogen kinetics between 800 and 900°C, it has been found experimentally that the higher the H_2 content relative to CO, the lower the degree of metallisation (Figure 64). F. Patisson and O. Mirgaux (2020) [135] give a twofold explanation for this phenomenon, which at first sight appears counter-intuitive. Firstly, the final reaction of reduction of wüstite (FeO) to iron is thermodynamically facilitated for CO as a reducing agent when the temperature decreases, unlike H_2. Furthermore, the overall iron oxides reduction balance is endothermic with H_2 and exothermic with CO. Methane (CH_4) is in general present in the syngas and cracking it in the shaft furnace tends to lower the temperature locally in the centre of the reactor (endothermic reaction), while the reduction of oxides by CO tends to maintain a high temperature. When these phenomena are combined, the presence of an excessive quantity of H_2 as compared with CO hampers reduction of the wüstite (FeO) into iron in the cooler central zone of the shaft furnace, which is why reduction by CO (at least in this zone) is essential for the overall rate of metallisation. It should be noted that this technical problem does not a priori concern future processes that may potentially be developed operating with 100% H_2. Indeed, if a system is designed to operate with 100% H_2, it may be advantageous to select a design of shaft furnace giving it a more elongated shape in height and a smaller diameter. **Thus, at the time of the final investment decision and the launching of the engineering studies, it is important to plan from the outset whether the system will operate with 100% H_2, as this will determine the optimal design of the shaft furnace.**

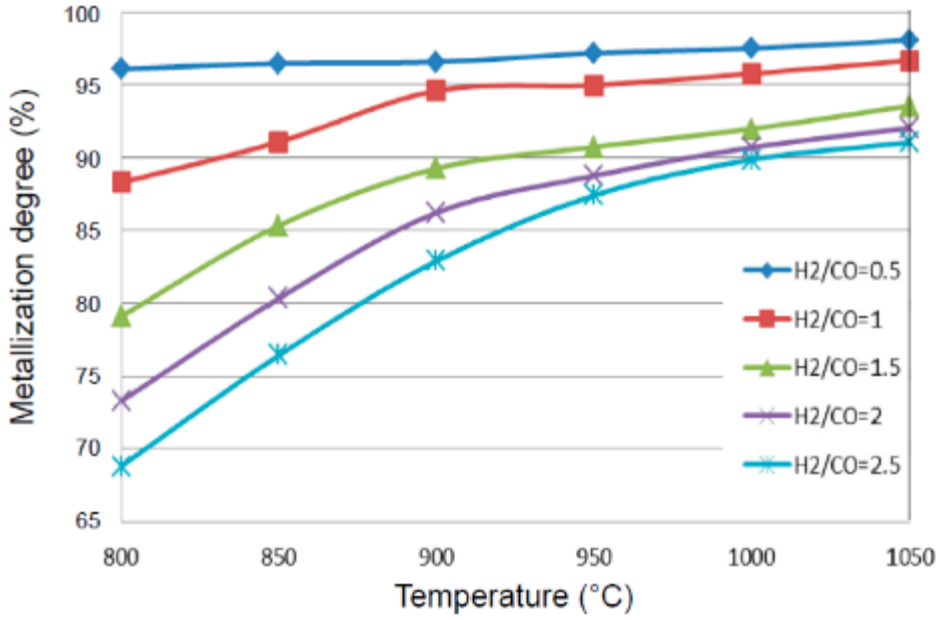


Figure 64: Degree of Metallisation of the DRI at the exit of a MIDREX shaft furnace as a function of temperature and H_2/CO ratio [135].

Finally, another fundamental aspect involves controlling the carbon content of DRI. At the production stage, a change in reducing input between natural gas and syngas (composed of H_2 and CO) can change the carbon content of the DRI. The work of N. Müller et al. (2018) [136] tends to show that the carbon content in DRI remains stable up to an injection rate of 65%$_{vol}$ of hydrogen before declining rapidly to almost zero from around 85%$_{vol}$ of hydrogen (see Figure 65). This carbon content of the DRI is decisive in the remainder of the process, since it determines the quantity of coal and oxygen to be injected into the electric arc furnace. High carbon content in the DRI makes it necessary to inject a greater amount of oxygen in order to remove this carbon which, due to a secondary reaction, tends to oxidise a part of the iron, which is finally lost in the form of FeO in the slag. Moreover, Considering that the rate of reduction of oxides increases with the H_2 content, the theoretical studies come to the conclusion that an increase in the H_2 fraction in the DRP indirectly tends to improve the overall ferric yield of the EAF output (up to a maximum of around 5 % according to the results given by N. Müller et al. (2021 [76]).

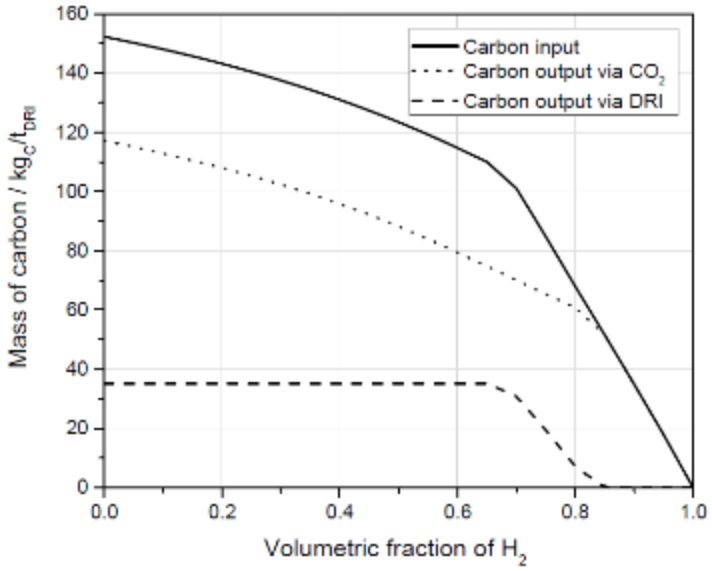


Figure 65: Input and output mass of carbon into the DRP per ton of DRI [136].

For manufacturers, it is interesting to have an operating range enabling the production of DRI with a constant carbon content, since this makes it possible to make the process flexible (in particular in terms of the functionalities of the electrolyser) while avoiding downstream control operations insofar as the composition of the DRI is known. A further advantage is improved conditions of storage and transport since, with its high carbon content, DRI is less subject to self-ignition (so called "pyrophoric" substance) and therefore does not require briquetting [76].

3.4.1.2.1. CO_2 Capture in the DRI-EAF Process

As indicated in part 3.4.1.2, when the DRI-EAF process operates on natural gas, part of the CO_2 is selectively removed from the reduction gases circuit. This flow of CO_2 is in a highly concentrated form, since it is produced using solvent capture technology. It may therefore be considered ready for transport and storage if this technological option is adopted. According to K. Benavides et al. (2022) [137], this option would add 160 kWh/t_{steel} of electricity consumption as compared with a case without CCS, i.e. 133 kWh/t_{DRI}. This value was adopted in the modelling A capture rate of 100% was assumed for "selective" CO_2, while a capture rate of 90% was assumed for "non-selective" CO_2 (i.e. equivalent to a flow from conventional combustion). The investment cost of the capture unit was taken to be equal to USD 127.91/t_{steel}.year on the basis of K. Benavides et al. (2022) [137] i.e. around EUR 107/t_{steel}.year[39] or EUR 89/t_{DRI}.year. The assumptions used to model CO_2 capture are summarised in Table 23.

Additional electricity consumption	Steam production	20.7 kWh_e/t_{HRC}
	CO_2 capture	50.8 kWh_e/t_{HRC}
	CO_2 compression	101.1 kWh_e/t_{HRC}
	Total	172.6 kWh_e/t_{HRC}
Additional heat consumption	Capture cost increase	3.03 GJ/tCO_2
		3,767 MJ/t_{HRC}
	Boiler efficiency	89.2%
	Capture rate	90%

Table 23: Assumptions connected with the modelling of CO_2 capture in DRI-EAF

3.4.1.3. Towards a 100% Hydrogen Process

A number of scientific papers focus on the study of a DRI-EAF process operating on 100% hydrogen (in the rest of the report, this route will be abbreviated H_2-DRI-EAF). This is the case in particular of V. Vogl et al. (2018) [138] whose process diagram is shown in Figure 66. In 2017, ArcelorMittal mothballed a plant using a CIRCORED-type process based on fluidised bed reactors, which had been built to operate with 100% H_2. This was due to technical and financial issues which resulted in the plant never being able to operate with 100% H_2[139].

However, experimental tests nevertheless show that between 700 and 900°C, the kinetics of reduction of iron oxides with 100% H_2 are faster than with a conventional syngas (mixture of CO and H_2) due to the good diffusivity of H_2 within the pellets as compared with CO. This higher reaction speed with 100% H_2 is synonymous with increased productivity. Compared with mixed CH_4/H_2 operation, operation with 100% H_2 would theoretically make it possible to opt for a more compact shaft furnace architecture, thus reducing the investment cost (CAPEX) and heat losses through the surfaces [131]. In addition, in a 100% H_2 process, the reduction gas loop would be shorter, and partial methane reforming and therefore oxygen injection would no longer be necessary [135]. In addition to better reactivity, hydrogen as a reducing agent has other advantages over CO, such as lower viscosity, better diffusion capacity, better thermal conductivity and absence of pollutant reaction products [47].

[39] Assumed exchange rate: EUR 1 = USD 1.2

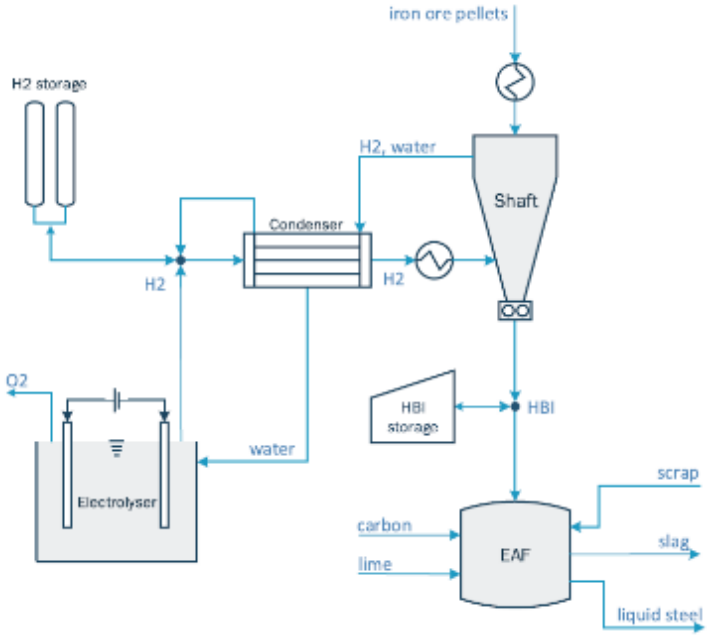


Figure 66: Proposed process design for hydrogen direct reduction (H-DR) process [138].

However, the use of 100% hydrogen poses a number of technical challenges connected with the characteristics of its reaction with iron oxides. As it happens, in the final stage of reduction of wüstite (FeO) to iron (Fe), the use of hydrogen is more effective than carbon monoxide at high temperatures (> 825°C) and inversely. In order be effective, an H_2 reduction process necessarily has to operate at higher temperatures than with carbon monoxide [140]. In fact, the reduction of iron ore with hydrogen is an endothermic reaction, unlike reduction using carbon, which means that the process has to be supplied with energy continuously throughout the process[139]. It is therefore not surprising to find studies which conclude that energy consumption is greater in the H_2-DRI-EAF route as compared with the BF-BOF route: this is the case in the study by A. Bhasker et al. (2020) [131], which estimates the energy consumption of the H_2-DRI-EAF route at 3.72 MWh/$t_{liquid\ steel}$ as compared with 3.48 MWh/$t_{liquid\ steel}$ for the BF-BOF route.

Furthermore, insofar as iron ore reduction takes place in the solid state in the H_2-DRI-EAF route, the porosity and size of the pellets are highly important parameters, since the reduction gases have be able to diffuse within the pellets' porous structure in order to thoroughly react with the iron oxides. The steam formed as a result of the reaction then has to be able to escape from the structure. At high temperatures, the rate of the chemical reaction is higher than the mass flow through the pellets, making this parameter the limiting factor in the reaction. The rate of reaction with pure H_2 is greater than with traditional syngas (composed of CO and H_2) at a temperature of between 700 and 900°C. Above 900°C, sintering phenomena occur on the outer walls of the pellets, thus reducing permeability and the rate of diffusion and reaction [135]. For this reason the reaction temperature is set at around 800°C, with heat supplied, by an electric heater, for example.

Finally, since the reaction occurs at a temperature above 570°C, wüstite (FeO) is formed, which has not entirely reacted when it leaves the shaft furnace. In the analysis by A. Bhasker et al. (2020) [131], the percentage of metallic iron (Fe) leaving the shaft furnace is assumed to be 94%, the remainder being wüstite (FeO), which needs to be deoxidised. This reaction takes place in the electric arc furnace, by addition of carbon and oxygen to form CO, which reacts with the wüstite (FeO) to produce metallic iron (Fe) and carbon dioxide. For this reason, residual CO_2 emissions still remain in a H_2-DRI-EAF process as theorised by A. Bhasker et al. (2020) [131]. In the absence of carbon as a reducing agent in the H_2-DRI-EAF process (i.e. with a process operating with 100% H_2), the technical challenge largely resides in melting the DRI in the electric arc furnace, and in practice hydrogen does not cover 100% of the reduction of iron oxides. The addition of carbon also serves to produce iron carbide (FeC) for adjustment of the composition of the steel, and CO serves in the formation of a foamy slag, which is essential for the operation of the electric arc furnace to stabilise it and extend the life of the graphite electrodes and refractories. The presence of carbon in the DRI at the time of melting provides a heat input (by oxidation of the carbon), thus contributing to melting the metal [131], [139], [141]. The carbon input may also come from the introduction of scrap metal into the electric arc furnace [141]. In standard operation, the chemical energy produced by oxidation of the carbon present in the metallic charge represents between 20 and 30% of the total heat input in the electric arc furnace [141].

Focus on the HYBRIT Project

HYBRIT (Hydrogen Breakthrough Iron-making) is an industrial-scale project designed to study and produce steel from decarbonated hydrogen. The project, for which the pilot project is based in Luleå, Sweden, is the result of cooperation between the LKAB mining company, the SSAB steel company and Vattenfal, the country's main energy supplier. HYBRIT was officially launched in February 2018 with the decision to build an initial pilot project, and has now almost become a symbol for the advancement of research on the decarbonisation of steel [142]. In August 2021, the consortium announced that it had obtained the world's first steel plate produced with 100% hydrogen in its industrial pilot project, which would be delivered to the Volvo Group [143].

3.4.1.4. The DRI-Melter-BOF route

One of the disadvantages of the DRI-EAF process is the higher price of pellets compared with BF quality ore (around 10 to 20% on the market, depending on the economic situation [144]). Indeed, the DRI-EAF route requires metallic inputs with a higher iron content (over 65%) than the BF route. The technical constraint does not lie in the production of DRI in the DRP reactor, which in practice can tolerate a charge containing less than 65% iron, but rather in the melting of the DRI in an EAF. Mastering the quantity and quality of the slag formed in an electric arc furnace is an essential parameter in melting the DRI, and an insufficient iron content in the DRI indirectly generates more slag, which complicates metallurgical operations in the electric arc furnace.

New technical solutions are emerging in the sector in order to incorporate lower quality ores in DRI production. Indeed, another possible configuration consists in the addition of a stage of melting the DRI in a special furnace before charging the molten metal into the oxygen converter (this production route is referred to as "DRI-Melter-BOF"). The DRI-Melter unit imitates, so to speak, the production of hot metal in a blast furnace, which means that the metal can then be processed in an oxygen converter. This configuration is being studied by a number of steel companies, including the Thyssenkrupp group, ArcelorMittal and BlueScope. Two principal technologies are envisaged for the DRI melting stage: the Submerged Arc Furnace (SAF) and the Open Slag Bath Furnace (OSBF).

An SAF furnace (see Figure 67) is a special type of electric furnace. It is particularly well-suited to the production of ferro-alloys (Fe-Mn, Fe-Si, etc.) due to better temperature control [145], as well as to the extraction of certain non-ferrous metals (zinc, lead, copper, etc.) [146]. In this type of furnace, the electrode is immersed in the bath and the metal is melted continuously, unlike an electric arc furnace, which operates in batches. Electricity is converted into heat through the resistance of the materials, which are then melted [146].

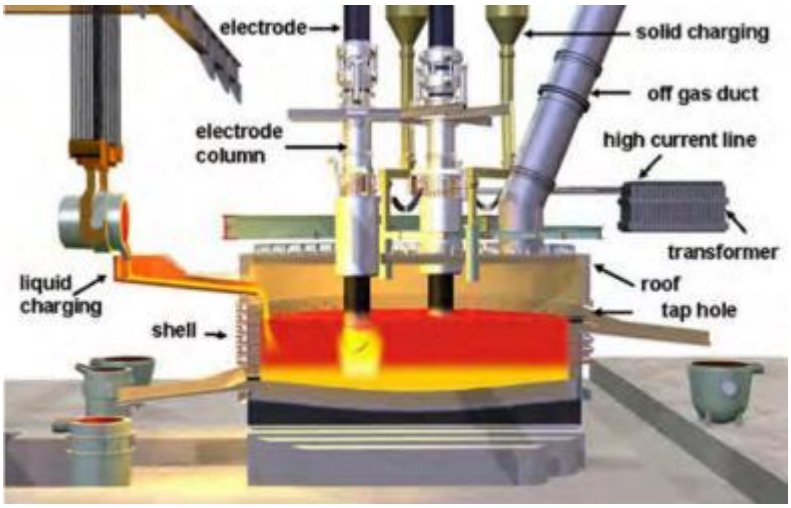


Figure 67: Main components of a submerged arc furnace[146].

An OSBF, on which the Italian group TENOVA is working in particular (see Figure 68), operates in a very similar way. The main difference lies in the position of the electrode: in an SAF furnace, the electrode is immersed in the molten bath, whereas in an OSBF, the electrode is at the top and generates a brush arc [18]. According to P. Cavaliere et al. (2022) [133], unlike an SAF, the charge contained in an OBSF has no influence on the electric current because the electrode is not immersed, resulting in better operational control of the process. For this reason, ore fines can also be consumed by this type of furnace. However, because of its "open arc" configuration, an OBSF generates more heat loss through the roof and more rapid deterioration of the refractories, which has to be reduced by means of a cooling system. An OBSF would also reduce operating costs as compared with an electric arc furnace. In the first place, the use of 'Soderberg' type electrodes in an OSBF would have a lower cost price than conventional graphite electrodes. Furthermore, the refractories in an OSBF operating in a stable and

continuous manner can be changed every 5 to 7 years, as compared with an EAF which typically requires maintenance operations about every two weeks [133].

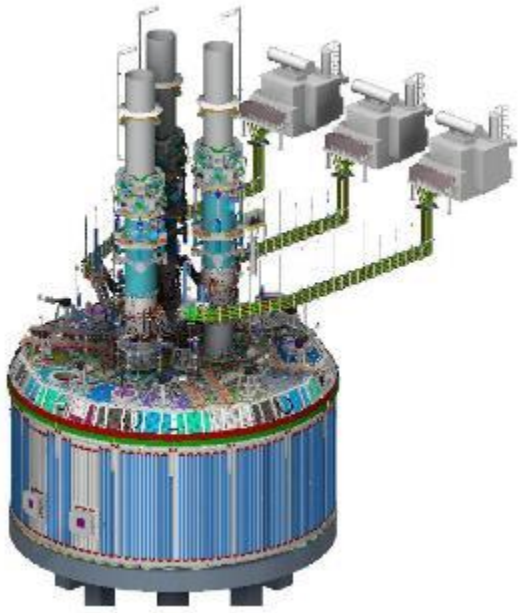


Figure 68: Layout of a OSBF furnace developed by TENOVA[133].

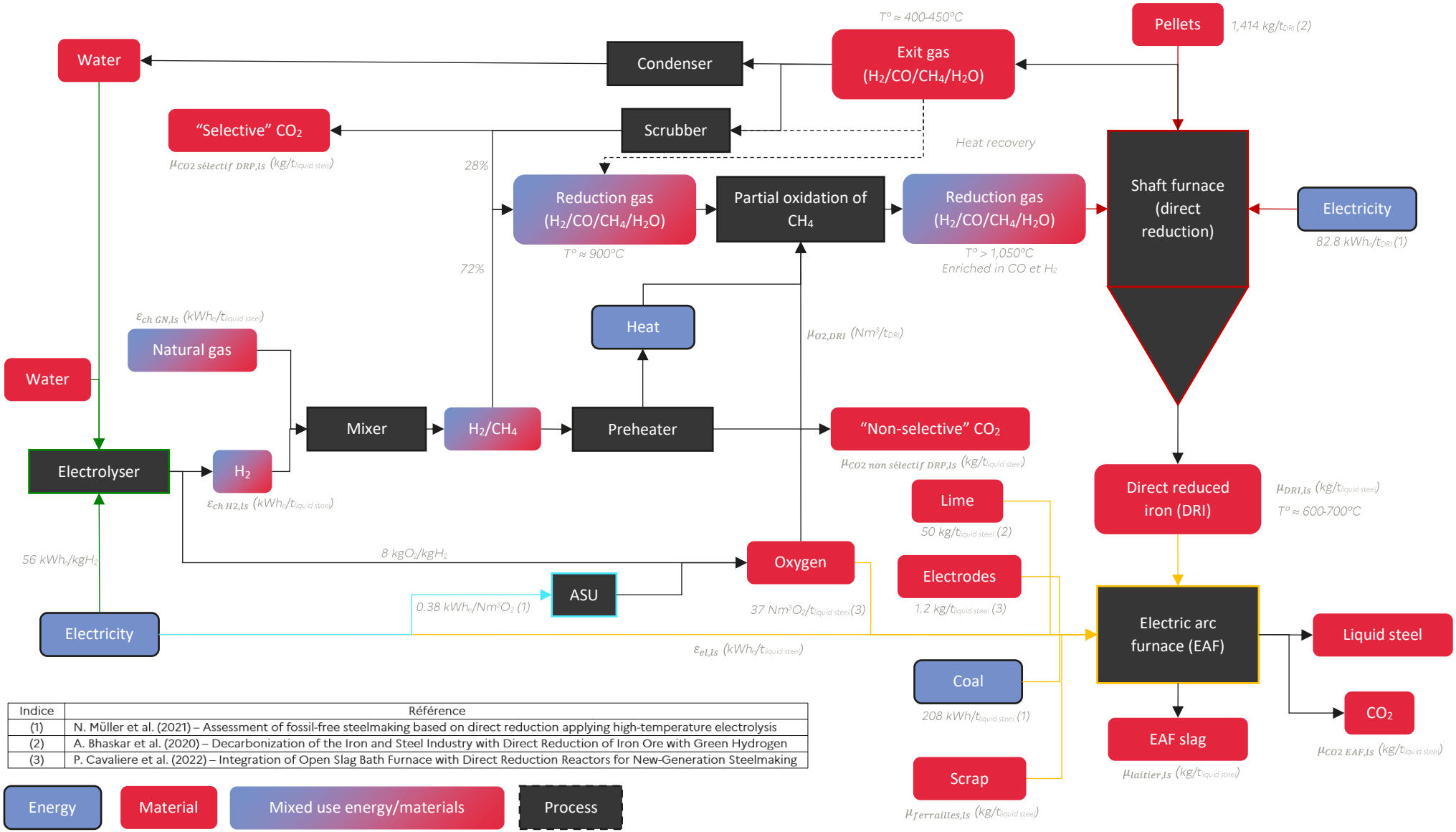
3.4.2. Modelling the DRI-EAF route

In the modelling, because the DRI-EAF process is fundamentally different from conventional processes, it is treated as a reference plant rather than as a decarbonisation lever to be activated on an existing plant. In the start year, the model indeed assumes an existing plant, though with zero production and therefore zero emissions and energy consumption. In order to activate it from a certain year onwards, production simply has to be increased in a more or less progressive manner, mirroring a reduction in the production of the other plants that the process is intended to replace.

Figure 69 provides a detailed view of the DRI-EAF reference plant (REF3) process, as modelled on the basis of an Energiron/HYL type technology (see part 3.4). The plant was designed in order to operate with a hybrid hydrogen/natural gas system, which can be controlled by the user via the percentage by volume of hydrogen ($\%_{vol}H_2$). The hydrogen injection rate can be set at any level from 0% (in case of 100% natural gas operation) to 100%. It is also possible to control the proportion of scrap (as compared with the proportion of DRI) placed in the electric arc furnace. The operating parameters for the plant (oxygen consumption, specific emissions, etc.) are to a large extent dependent on these two variables, for which reason Figure 69 does not show all of the numerical values. For example, the production of slag in the electric arc furnace tends to increase when the proportion of DRI is increased, since the proportion of gangue contained in DRI[40] is higher than in scrap. Similarly, oxygen consumption tends to decrease as the volume of hydrogen increases, since there is less need for partial oxidation of CH_4. The process stops with the production of liquid steel, since the next stage of continuous casting and hot rolling is assumed to be strictly identical to the integrated blast furnace plant (REF1 plant, see Figure 33).

The functions governing the operation of the DRI-EAF process (presented in Figure 70, Figure 71, Figure 72, Figure 73, Figure 74 and Figure 75) were principally modelled on the basis of the work of N. Müller et al. (2021) [76], N. Müller et al. (2018) [136] and K. Rechberger et al. (2020) [134]). Most of the results of N. Müller et al. (2021) [76] only being presented in graphical form, the functions were reproduced by graphical interpretation followed by superimposition of a trend curve, a six degree polynomial in most cases, in order to ensure the most accurate and faithful possible reproduction. The other fixed numerical assumptions (such as the specific electricity consumption of the direct reduction furnace) were taken on the basis of N. Müller et al. (2021) [76], A. Bhaskar et al. (2020) [131] and P. Cavaliere et al. (2022) [133]).

[40] Gangue refers to the whole of the components of an ore that are of no value, and whose elimination is in general desired. In the case of iron ore, this includes, for example, silica (SiO2), alumina (Al2O3) and phosphorus (P).



Indice	Référence
(1)	N. Müller et al. (2021) – Assessment of fossil-free steelmaking based on direct reduction applying high-temperature electrolysis
(2)	A. Bhaskar et al. (2020) – Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen
(3)	P. Cavaliere et al. (2022) – Integration of Open Slag Bath Furnace with Direct Reduction Reactors for New-Generation Steelmaking

Figure 69: Reference plant REF3 DRI-EAF - Process diagram.

The total energy consumption of the DRP changes insofar as hydrogen replaces natural gas. To be specific, it tends to decrease, as illustrated in Figure 70. This may appear paradoxical insofar as the reduction of iron oxides with hydrogen is endothermic and therefore needs to be supplied with more energy as compared with reduction with carbon, which for its part is exothermic. However, the chemical energy in the form of CH_4 and H_2 that fuels the DRP also makes up for the heat loss in order to capture CO_2 from the exit gases at the scrubber (see Figure 69). When hydrogen replaces CH_4, there is less and less CO_2 to be removed from the reduction gas loop, and therefore the need for chemical energy for the DRP tends to decrease. As it happens, the latter effect preponderates over the endothermic nature of hydrogen reduction, and for this reason the total chemical energy consumption of the DRP decreases with the injection of hydrogen.

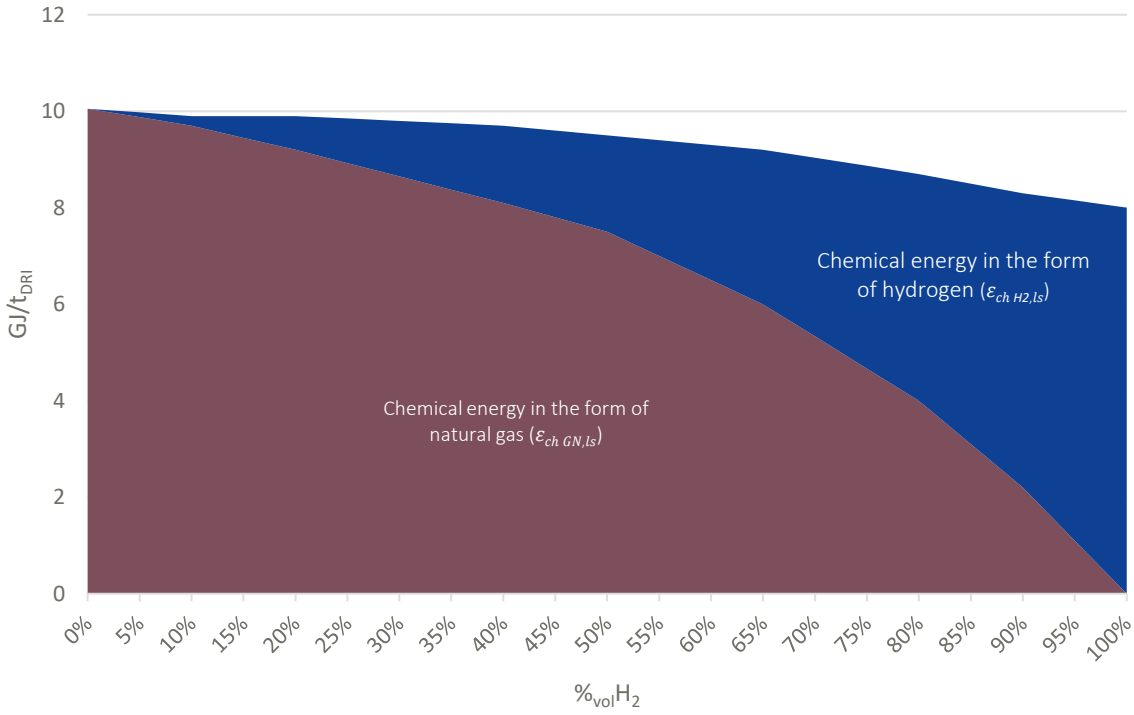


Figure 70: Reference plant REF3 DRI-EAF - DRP energy consumption as a function of $\%_{vol}H_2$ (graph reproduced from N. Müller et al. (2021 [76]).

The DRI-EAF plant model distinguishes between three sources of emissions: CO_2 generated by the so called 'selective' direct reduction furnace ($\mu_{CO2\ sélectif\ DRP,ls}$), 'non-selective' CO_2 ($\mu_{CO2\ non\ sélectif\ DRP,ls}$) and emissions from the electric arc furnace ($\mu_{CO2\ EAF,ls}$). The 'selective' CO_2 actually comes from the washing of the exit gas before it can be reused as a reduction gas in a form of loop. 'Selective' CO_2 is unique in that it is in a highly concentrated form, since it is produced using solvent capture technology. This flow may therefore be considered ready for transport and storage if this technological option is adopted [137], [147]. For its part, 'non-selective' CO_2 is produced from the thermal energy required for the reforming of natural gas in the reduction gas loop. As a simple product of combustion, this flow of CO_2 has no particular suitability for transport and storage. For this purpose, a capture stage would have to be applied to it beforehand. Lastly, the electric arc furnace is also a source of CO_2 emissions due to the presence of combustion of the carbon contained in DRI and coal.

In order to estimate the respective weight of each of the sources of emissions, the results of K. Rechberger et al. (2020) [134] were used in order to model the emissions connected with the direct reduction furnace, which are given in $kgCO_2/t_{DRI}$. In the case of operation with 100% DRI, these emissions were converted into $kgCO_2/t_{liquid\ steel}$ on the basis of a specific consumption of 1,200 $kg_{DRI}/t_{liquid\ steel}$ taken from N. Müller et al. (2021) [76]). These specific DRP emissions were then distributed between 40% for 'selective' CO_2 and 60% for 'non-selective' CO_2. This 40%/60% division is taken from N. Müller et al. (2021) [76] for operation with 100% natural gas, but the ratio was assumed to be constant whatever the rate of hydrogen injection $\%_{vol}H_2$. Specific emissions from the electric arc furnace were estimated by subtraction of the total emissions (provided by N. Müller et al. (2021) [76]) and of the specific emissions from the DRP. Total emissions from the DRI-EAF plant are indeed therefore exactly equal to the data provided by N. Müller et al. (2021) [76], only the distribution of these emissions was partially estimated using the results of K. Rechberger et al. (2020) [134].

Figure 71 thus presents the changes in these three sources of CO_2 emissions as a function of the hydrogen injection rate $\%_{vol}H_2$. As the hydrogen replaces the CH4, there is less and less CO2 present in the exit gases and therefore less to be selectively removed, until it finally disappears when the reduction gases loop is supplied solely with hydrogen. The same applies to 'non-selective' CO2, which decreases as the quantity of CH4 to be oxidised is reduced. In order to understand the

changes in emissions from the electric arc furnace, it is first necessary to specify that the plant was modelled according to a so called 'conventional' mode of operation. This concept, used N. Müller et al. (2021) [76] refers to a mode of operation in which the amount of additional carbon entering the electric arc furnace (specifically in the form of coal) is maintained constant for practical and economic reasons. The other mode, referred to as 'thermodynamic', is for its part designed to operate under conditions that minimise CO2 emissions, which in practical terms means optimisation of the quantity of coal according to the percentage of hydrogen and the percentage of carbon in the DRI. In addition to simplifying the modelling, the 'conventional' mode would extend the lifespan of the EAF and reduce the costs associated with energy consumption for melting the DRI. With this in mind, it is therefore natural to observe that emissions from the electric arc furnace are more or less constant even when the percentage of hydrogen is 100%: coal remains necessary in order to provide thermal energy to the DRI, to foam the slag, to reduce the remaining iron oxides (and therefore improve metal yield) and lastly to carburise the steel.

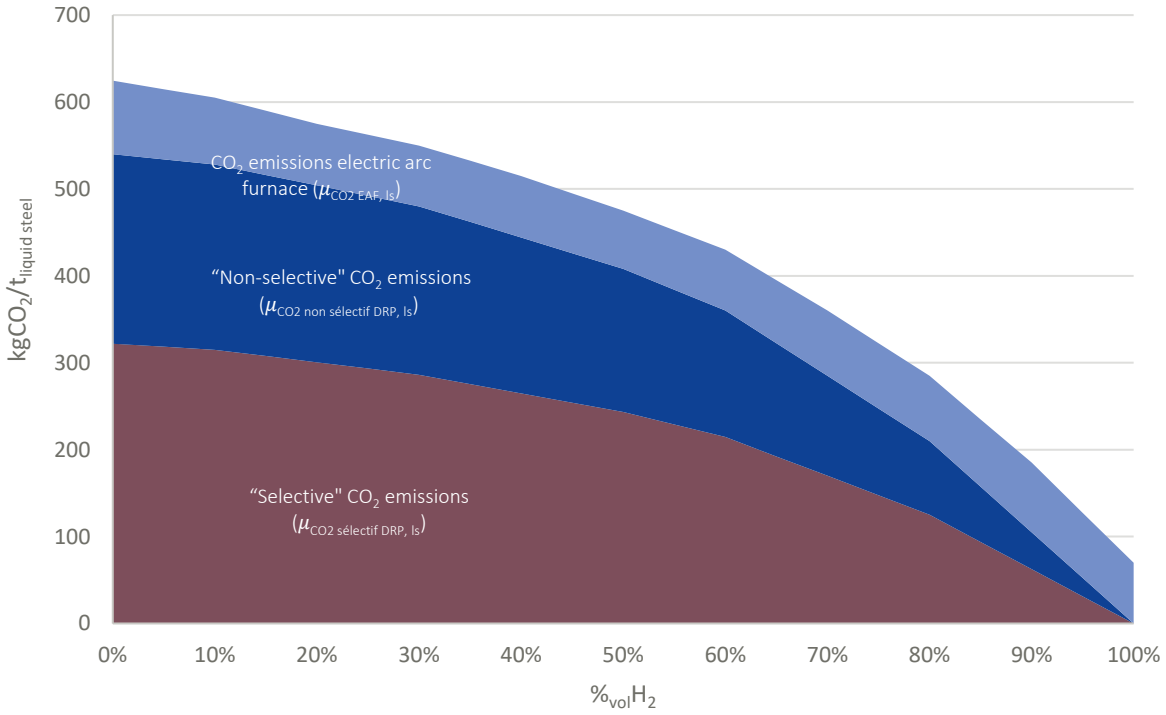


Figure 71: Reference plant REF3 DRI-EAF - CO_2 emissions as a function of $\%_{vol}H_2$ (fixed rate of DRI of 100%).

The specific electricity consumption of the electric arc furnace also varies according to three parameters: the quantity of DRI consumed (in relation to the quantity of scrap), the $\%x_c$ carbon content in the DRI, which depends on the $\%_{vol}H_2$ rate of hydrogen injection, and whether the DRI is charged hot at 600-700°C (HDRI / Hot DRI) or cold (CDRI / Cold DRI). Slag production also depends on the quantity of DRI consumed and the $\%x_c$ carbon content of the DRI. Figure 72 reproduced from N. Müller et al. (2021) [76] presents the changes in specific electricity consumption and slag production by the EAF according to these parameters. The following variations can be observed:

- The higher the $\%x_c$ carbon content in the DRI, the more the electricity consumption of the EAF $\varepsilon_{el,ls}$ is reduced: combustion of the carbon contained in the DRI makes it possible to supply thermal energy to the charge and therefore, so to speak, to replace electrical energy.
- The feeding of hot DRI (HDRI) reduces the electricity consumption $\varepsilon_{el,ls}$ as compared with cold DRI (CDRI): the heat contained in the DRI represents correspondingly less energy to be supplied in the form of electricity.
- Except in the case of HDRI and x_c = 3.5%, the electricity consumption of the EAF $\varepsilon_{el,ls}$ tends to increase as the proportion of DRI increases as compared with the quantity of scrap: this effect is connected with a higher proportion of gangue (fraction not containing iron, of no economic value) in DRI than in scrap. When the proportion of DRI increases, there is at the same time a corresponding increase in the amount of additional material to be heated "unnecessarily" or which, in other words, does not contribute to steel production In the case of HDRI and x_c = 3.5%, the double energy input from the hot DRI and the carbon it contains offsets this effect.
- The quantity of slag produced $\mu_{slag,ls}$ increases when the proportion of DRI increases: as with electricity consumption, DRI contains a larger proportion of gangue than scrap, which needs to be removed in the form of slag.

- The quantity of slag produced $\mu_{slag,ls}$ increases as the carbon content %x_c increases: the higher the carbon content of DRI, the more needs to be removed by means of oxygen injection. However, oxygen not only has the effect of oxidising the carbon, but also reacts with other metallic elements, including iron. Thus, as the oxygen injection increases, a greater proportion of iron is lost in the form of FeO iron oxides in the slag. It is also for this reason that the ferric yield is lower when the carbon content of the DRI is higher.

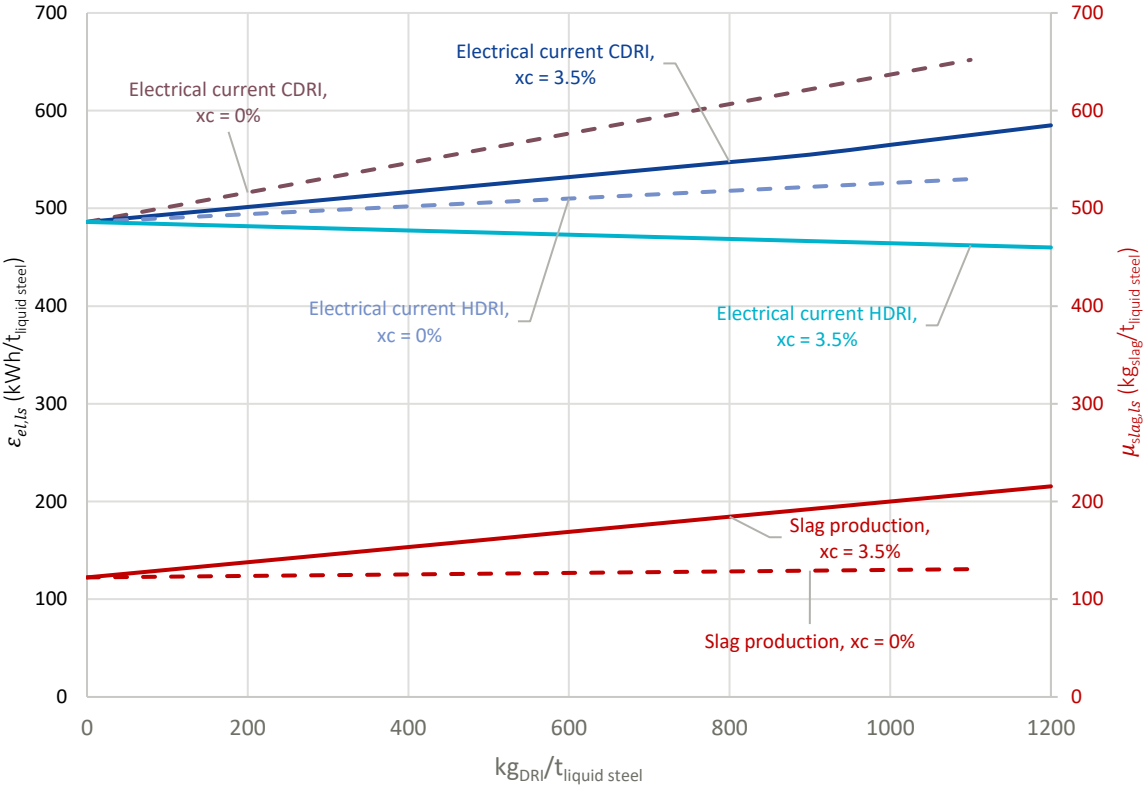


Figure 72: Reference plant REF3 DRI-EAF - Electricity consumption $\varepsilon_{el,ls}$ and slag production $\mu_{slag,ls}$ of the EAF according to the quantity of DRI (graph reproduced from N. Müller et al. (2021 [76]).

Indeed, concerning changes in carbon content in the DRI, the latter was modelled as a function per piece on the basis of the results of N. Müller et al. (2018) [136]. As presented in Figure 73, the carbon content in DRI remains constant at 3.5% up to a hydrogen content of 70% by volume, and then declines rapidly to zero at a hydrogen content of 90%.

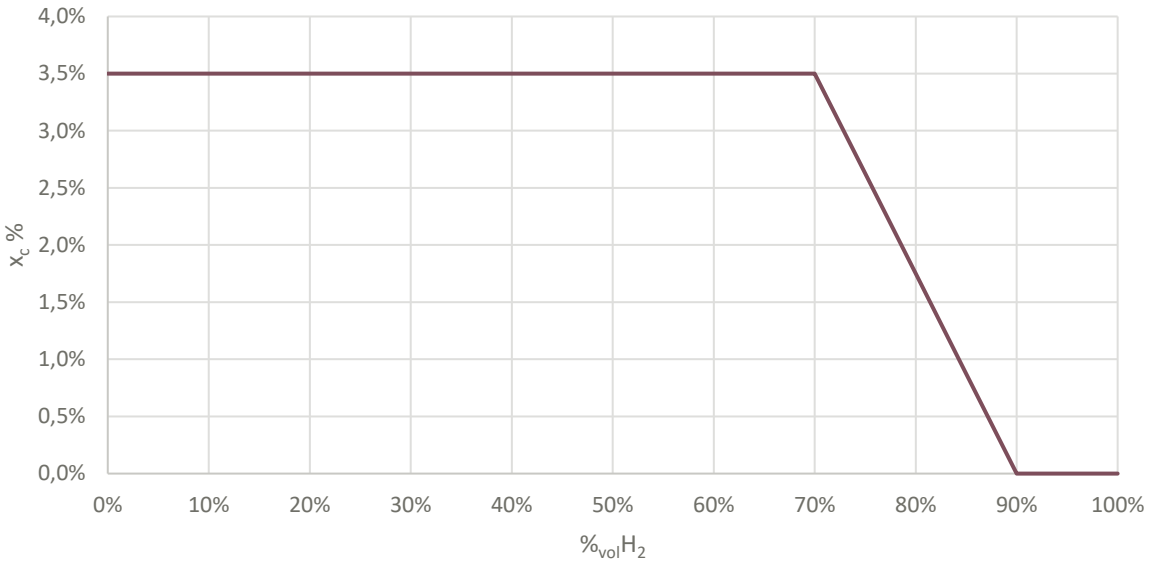


Figure 73: Reference plant REF3 DRI-EAF - Carbon content in DRI as a function of $\%_{vol}H_2$ (graph reproduced from N. Müller et al. (2018 [136]).

The specific oxygen consumption in the DRP for the partial oxidation of CH_4 varies according to the rate of hydrogen injection $\%_{vol}H_2$. N. Müller et al. (2021) [76] give a value of 60 Nm^3O_2/t_{DRI} for operation with 100% natural gas. By simplification, it was assumed that the DRP oxygen requirement varies in a linear manner with the $\%_{vol}H_2$ hydrogen injection rate and that consumption would be zero for operation with 100% H_2 (see Figure 74). Consumption of oxygen by the EAF was assumed to be constant and taken as equal to 37 $Nm^3/t_{liquid\ steel}$ on the basis of P. Cavaliere et al. (2022) [133]). Moreover, the oxygen co-produced by electrolysis of water is consumed in priority, and supplemented by an air separation unit (ASU). Surplus oxygen is assumed to be sold to neighbouring industrial consumers at a price of EUR 60.8/tO_2 (assumption taken from V. Vogl et al. (2018) [138], i.e. around EUR 87/kNm^3 assuming a density of 1.43 kg/Nm^3 for the oxygen.

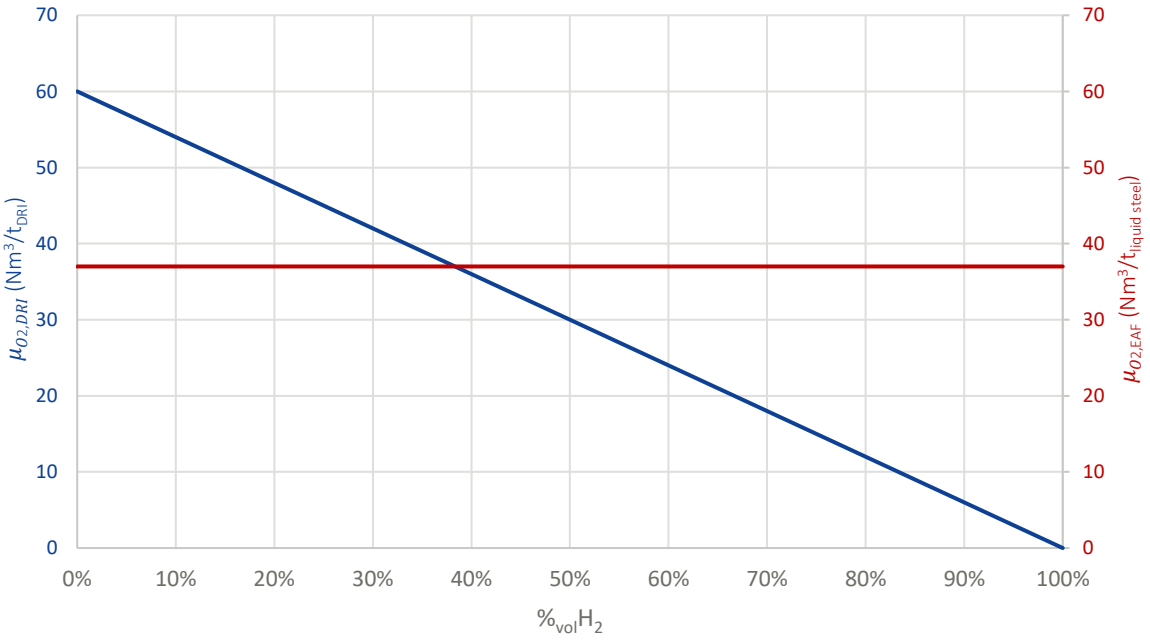


Figure 74: Reference plant REF3 DRI-EAF - Specific oxygen consumption of DRP and EAF according to $\%_{vol}H_2$.

Specific consumption (in kg/$t_{liquid\ steel}$) of DRI and scrap depends on the % of scrap charged in the EAF and also on the carbon content of the DRI, for the same reasons given above. In a case with 100% scrap, the necessary charge was taken to be equal to 1,050 kg/$t_{liquid\ steel}$ (assumption made on the basis of L. Yang et al. (2017 [96]). In the case of 0% scrap (and therefore 100% DRI), N. Müller et al. (2021) [76] enable specific DRI consumption to be estimated at 1,200 kg/$t_{liquid\ steel}$ in a case where the carbon content in the DRI is 3.5%, and 1,100 kg/$t_{liquid\ steel}$ in a case where the carbon content in the DRI is 0%. Between these values, linear change was assumed (see Figure 75).

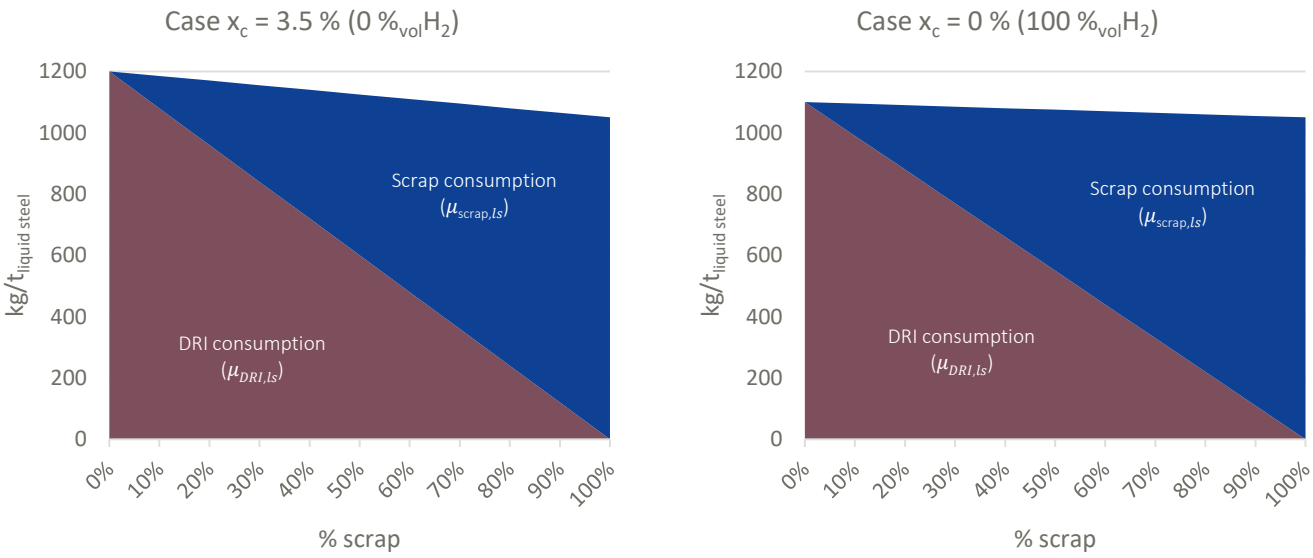


Figure 75: Reference plant REF3 DRI-EAF - Specific consumption of DRI and scrap by the EAF according to % scrap in the case x_c = 3.5% (left) and in the case x_c = 0% (right).

It was assumed in the modelling that in the case of production of HBI for external sale or export, a briquetting system would be required for the DRI exiting the DRP. On the basis of L. Hooey et al. (2014) [148], it was assumed that a system of this kind would result in additional electricity consumption of 100 kWh/t_{HBI}.

On the basis of E. Jacobasch et al. (2021) [149], the investment cost assumption was set at EUR 303/t_{DRI}.year for a DRP reactor and at EUR 240/$t_{liquid\ steel}$.year for a new electric arc furnace. This source was favoured over others because it appeared closer to the investment totals actually observed in new industrial projects. In addition to this investment total, an interest rate of 7% was set.

3.5. New Steelmaking Processes

3.5.1. Smelting (HIsarna)

HIsarna is a smelting reduction process without any coke or sinter production stage. The raw materials (coal, iron ore, lime, etc.) may be injected directly into the reactor, in which the temperature is higher than the melting temperature of the iron, thus maintaining it in a liquid state. At the top of the reactor (the cyclone), the iron ore injected is immediately partially reduced, by around 10-20%, by means of the reduction gases and the turbulent environment inside (see Figure 76). Once it has fallen to the bottom of the reactor, the liquid iron is reduced by the carbon contained in the powdered coal [31].

If implemented on an industrial scale, the HIsarna process would theoretically make it possible to reduce CO_2 emissions and energy consumption by around 20% as compared with conventional blast furnaces, thanks to the elimination of coking and sintering [150]. Furthermore, the process is capable of incorporating scrap and biomass in partial replacement of iron ore and coal, thus enabling reduction of CO_2 emissions by at least 50% as compared with conventional production. Trials using around 35% scrap metal and 40% biomass have already been successfully completed [151]. The process also presents the advantage of being capable of removing up to 90% of the phosphorus contained in the ore via the slag. In theory, the reactor would therefore be capable of operating with iron ore with a higher phosphorus content than would normally be accepted in a blast furnace [31]. Lastly, the process moreover generates a highly concentrated stream of CO_2 exiting the reactor, making it compatible with carbon capture and storage [151].

A pilot project was put in place in 2011 at the Tata Steel site in IJmuiden, the only integrated steelworks in the Netherlands. The pilot project was successfully conducted and proved the possibility of producing hot metal for several hours. A new industrial-scale pilot project with a capacity 10 times greater than the first is to be constructed in Jamshedpur, India, at an estimated investment cost of EUR 300 M [31]. The technology is now 100% owned by the Tata Steel group, and the project is now also looking into the possibility of recovering and recycling the zinc contained in galvanised scrap [151].

This technology was not modelled in the decarbonisation trajectory since it was considered unlikely in France and because another solution with CO_2 capture (CCS in TGR-BF) was already taken into account.

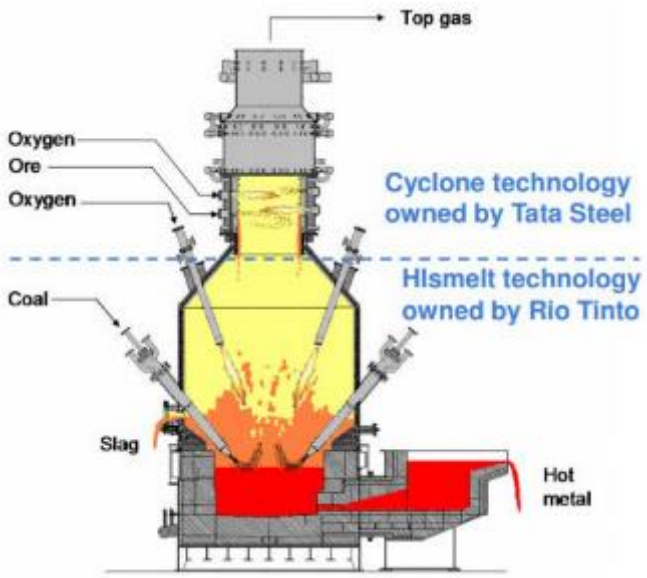


Figure 76: Simplified schematic of the HIsarna process with CCS [31].

3.5.2. Direct Electrolysis of Iron

Apart from hydrogen and the DRI-EAF route for decarbonisation of primary steel production, there is also the direct electrolysis of iron route. As with other metals such as aluminium and lithium, the principle consists in placing the ore in a solution (an electrolyte) and passing an electric current through it in order to reduce the iron oxides. The reaction produces metallic iron at the cathode and oxygen at the anode. Until now, this process had been ruled out for economic reasons, and the principal technical difficulty encountered concerns the selection of the materials composing the electrodes. Indeed, these materials need to be able to withstand temperature conditions of above 1,500°C without corroding on contact with the chemical species present in the electrolyte [147]. Today, two principal avenues are being explored.

3.5.2.1. Electrolysis in an Alkaline medium

The ULCOWIN and ULCOLYSIS processes are based on the electrochemical reduction of iron oxides. In the ULCOWIN process, the iron ore is dissolved in an electrolytic sodium hydroxide solution (NaOH) at a temperature of 110°C (see Figure 77). In this configuration, the reduced iron is obtained in a solid state and therefore has to be subsequently melted in an electric arc furnace [75]. With this system, 99.98% pure iron has been obtained, but with a very low rate of production of around 5 kg/day. In order to overcome this difficulty, in the ULCOLYSIS process, the iron is dissolved in an electrolytic solution containing molten oxides at a temperature of 1600 °C [31]. To be charged into the electrolytic bath, the raw materials first need to be finely ground and the gangue removed by leaching with an alkaline solution. The solution thus enriched with iron oxides is circulated in the electrochemical cell. During the decomposition, the iron is deposited in solid form at the cathode. It is collected periodically and then melted in an electric furnace, potentially mixed with scrap [152].

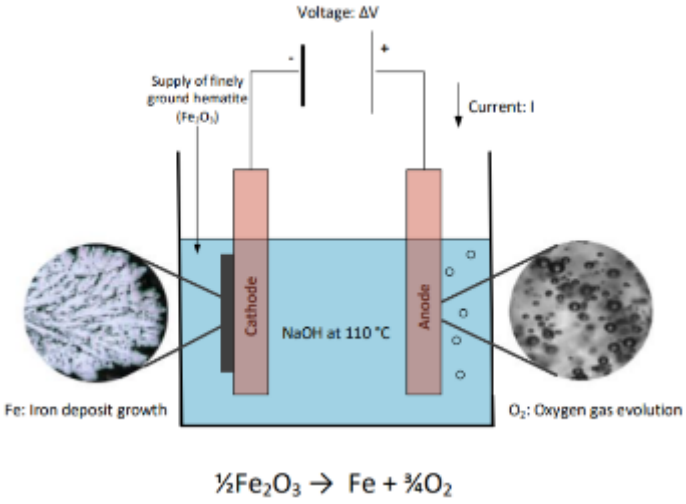


Figure 77: Basic schematic of iron ore electrolysis [31].

The SIDERWIN project led by ArcelorMittal has received funding from the European Horizon 2020 fund. The technology has been developed since 2004 and the objective, through the ULCOS project, is to bring it up to TRL 6 in 2022 by means of a demonstration [75]. Before 2023, it was apparently acknowledged that the technology would not reach industrial maturity (TRL 9) before 2040 [153]. As compared with the blast furnace route, direct iron electrolysis as developed by SIDERWIN would make it possible to reduce CO_2 emissions by 87% and energy consumption by 31% [154].

The experimental results presented in March 2023 [155] show that Faraday efficiency of 90% can be achieved for electrolysis of haematite (Fe_2O_3). It is also possible to use ore with a high concentration of magnetite (Fe3O4), which suggests that magnetite-rich metallurgical residues (such as bauxite residues) could be used as an input for electrolysis. However, the presence of non-conductive impurities (principally aluminium, magnesium and titanium) tends to slow down the reaction and reduce the Faraday efficiency. Thus, in spite of the technical feasibility of using alternative raw materials, the Faraday yields are relatively low: 30-50% for bauxite residues, 10-40% for ferruginous sludge from nickel metallurgy, 20-30% for slag from copper and ferronickel production. The only exception appears to be mill scale, for which electrolysis has a Faraday efficiency of 92% to 97%. This is due to its high concentration of iron oxides and low proportion of impurities. The tests also demonstrated that the electrolysis could operate in a variable manner and therefore adapt to the intermittent nature of renewable energies. According to M. Barberousse et al. (2020) [152], 92% of the electrical power consumed for electrolysis alone can be made available (not 100% since certain auxiliaries need to be able to remain in operation). By way of comparison, this value is typically between 8% and 75% for other industrial processes.

In the same presentation [155], the SIDERWIN consortium announced that the technology would be made available on an industrial scale by 2030 (see Figure 78). On the basis of this timetable, it was assumed in the modelling that this technology would be available by 2030.

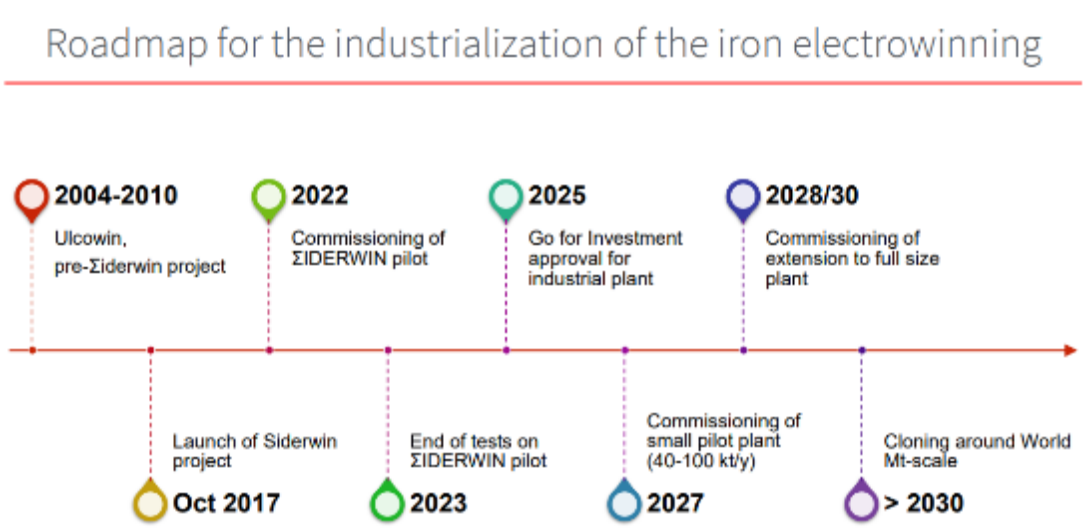


Figure 78: Estimated development schedule for the SIDERWIN project in March 2023 [155].

According to M. Barberousse et al. (2020) [152], the specific electricity consumption of the SIDERWIN electrolysis process is 2,720 kWh/t_{iron} (i.e. 2,693 kWh/$t_{crude\ steel}$), to which must be added 66 kWh/t_{iron} (i.e. 65 kWh/$t_{crude\ steel}$) for ore crushing and 325 kWh/t_{iron} (i.e. 322 kWh/$t_{crude\ steel}$) for leaching. Lastly, the required consumption needs to be added for the melting of solid iron in an electric arc furnace, i.e. around 450 kWh/$t_{crude\ steel}$. These values were adopted in the modelling. Moreover, the electrical power was estimated at 280 MW/Mt_{steel}.year for electrolysis, crushing and leaching.

The investment cost for a new direct electrolysis plant is estimated at around EUR 500 M for a production capacity of 1 Mt/year, which represents around a quarter of the investment cost of an equivalent blast furnace solution [75]. This is an estimate of the cost for an initial industrial unit, which also includes the cost of the electric arc furnace (EUR 184 M). The cost of the electrolysis unit alone can therefore be estimated at EUR 316 M for a capacity of 1 Mt/year.

3.5.2.2. Molten Oxide Electrolysis (MOE)

In molten oxide electrolysis (MOE), iron oxides are dissolved at around 1,600°C in a mixture of oxides such as calcium oxide (lime, CaO) or silicon oxide (silica, SiO_2). As it is above melting point, the iron is obtained in a liquid state in this process (see Figure 79). Boston Metal, which was founded in 2013, is currently working on its development and has announced that the technology will be deployed commercially by 2026. It is important to note that this timetable is particularly ambitious since, apart from the company's announcements, it is estimated that the technology will not reach TRL 9 until 2050 [153]. Moreover, in January 2023, the ArcelorMittal group announced that it had invested USD 36 million in Boston Metal through its XCarb® innovation fund [156].

Iridium-based anodes appear to be a promising solution for this process [147]. Specific electricity consumption has been estimated at 4,100 kWh/$t_{crude\ steel}$ while, for its part, the theoretical minimum is estimated at 2,780 kWh/t_{steel} [147]. The developed technology would also be capable of operating with any grade of iron ore. Although it is estimated that the R&D costs required to achieve TRL 8 would be in the region of EUR 1 billion [75], no investment costs have been identified for this technology at this stage. This is the principal reason why alkaline electrolysis (see part 3.5.2.1) was selected for the modelling of direct iron electrolysis technology, even though Boston Metal's announcements imply that molten oxide electrolysis (MOE) technology will be available earlier. It is also interesting to note that Boston Metal is planning a modular form of operation, enabling it to have installed capacities ranging from several thousand to several million tonnes of steel per year.

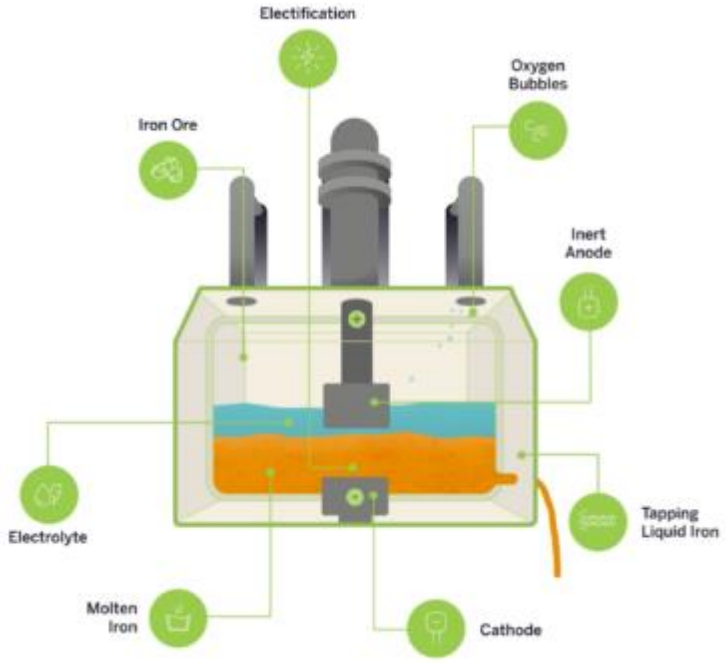


Figure 79: Molten oxide electrolysis process diagram (source: Boston Metal [157]).

3.5.2.3. ELECTRA Process

The Colorado-based company ELECTRA, which was founded in 2020, is working on a new direct iron electrolysis process capable of operating at 60°C, i.e. a much lower temperature as compared with the two preceding projects, thereby reducing energy consumption. In the concept developed by Boston Metal, the temperature has to be maintained at 1,600°C without any halt in the process, which would involve the risk of solidification of the molten metal, halting production for several months. The fact that the ELECTRA process (like the SIDERWIN process) operates at a low temperature provides it with increased flexibility engaging in stop-and-go production, therefore enabling it to consume electricity when prices are low. Furthermore, the company has announced that it will be able to consume any quality type of iron ore. ELECTRA has not released any further details on how the process works, but has announced commercial production by 2026 [158], [159].

3.6. Primary Processing

3.6.1. Primary Processing

Once the liquid steel has been obtained and brought to the desired grade (i.e. the right composition), it undergoes a series of mechanical and thermal processing stages. Apart from a few slight differences, the subsequent stages are similar for all of the three main steel production routes (the blast furnace, electrical and DRI-EAF routes).

3.6.1.1. Continuous Casting and Continuous Rolling Mill

The continuous casting phase corresponds to the shaping of the steel and involves several stages and facilities. Slabs (for the blast furnace sector) and blooms (for the electrical sector) are semi-finished products obtained directly after the pouring of ‘unkilled’ steel into ingot moulds (see Figure 80). The steel is cooled and solidifies, forming its own mould throughout its casting, guided by a series of rollers, until it reaches a horizontal position. Slabs and blooms are obtained by cutting the continuous strip. To start a casting sequence, an metal dummy bar is first introduced into the ingot mould. As it cools around the part, the steel anchors itself to the dummy, which can then be pulled and recovered after cutting at the end of the roller tunnel.

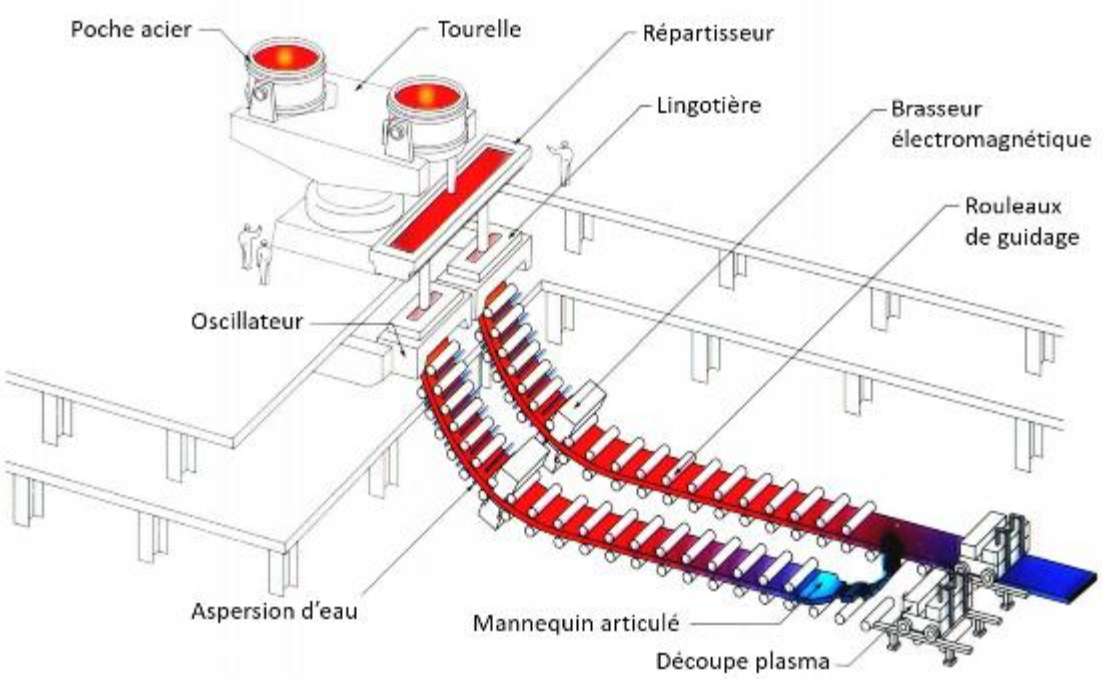


Figure 80: Continuous casting process diagram (reproduced from R. Guthrie & M. Isac (2022) [160]).

Next, the slabs and blooms are placed in a reheating furnace, preferably when they are hot, in order to limit heat loss. When the semi-finished products have reached the desired temperature, which depends on the grade and rolling format, they are de-scaled with high-pressure water jets in order to remove the layer of oxide formed during reheating, and then go through a series of rolling stages until the desired dimensions are obtained. In the case of production of plates, strips and sheets, the slabs are in general rolled into coils (known as 'hot rolled coils') before shipment. Blooms are in general formed directly into beams, tubes and bars. An additional stage of cold rolling and coating with a protective surface layer of zinc or tin may be conducted in order to obtain the desired final thickness, and direct protection of the sheets.

3.6.2. Modelling of Primary Processing

The modelling of primary processing is already included in the modelling of the reference plants (see part 3.2.2.5 for the blast furnace sector and part 3.3.2 for the electrical sector). The modelling of primary processing for the DRI-EAF reference plant is in fact the same as for the blast furnace reference plant.

3.6.3. Primary Processing Decarbonisation Technologies

3.6.3.1. Regenerative Burners

Regenerative burners can also be applied in reheating furnaces for semi-finished products and heat treatment furnaces (see part 3.3.3.2.5). For these stages, it was assumed that installation of regenerative burners would reduce specific consumption of natural gas by 40% as compared with cold air burners.

3.6.3.2. Oxy-Fuel Burners

Oxy-fuel burners can also be applied in reheating furnaces for semi-finished products and heat treatment furnaces (see part 3.3.3.2.6). For these stages, it was assumed that installation of oxy-fuel burners would reduce specific consumption of natural gas by 35% as compared with cold air burners.

Between 2005 and 2007, the installation of oxy-fuel burners in the pit furnaces at the Ascométal Fos-sur-Mer site reportedly reduced specific energy consumption and NOx emissions by 40% for this part of the process. The Ascométal Les Dunes site reportedly did the same between 2007 and 2008 in four of its pit furnaces [114].

3.6.3.3. Hot Charging

According to M. Samanian et al. [161], the energy required for the reheating of semi-finished products when the charge is at ambient temperature is 1170 kJ/kg. This is reduced to 680 kJ/kg of energy when the products are hot charged (at a temperature of 660°C), i.e. a reduction of around 40% in energy consumption. Although this might be considered a technique already applicable to existing plants, the energy saved by hot charging demonstrates the value of optimising the whole of the production chain, so that the melting, casting and final shaping of the steel are completed on a single site. Since this is more an operational method than a technology, and given that many steelworks already use it, it was not modelled in the

decarbonisation trajectories. Unless the plant has logistical constraints (e.g. rolling stage conducted on another site) or a production schedule necessitating temporary storage (and therefore cooling) of semi-finished products, hot charging is systematically used. This report simply mentions the benefits and potential gains it may represent.

3.6.3.4. Total or Partial Electrification of Rolling Processes

Hot rolling requires temperatures to be raised to close to 1,300°C, whereas current electrification techniques allow maximum temperatures of around 1,000°C. However, the introduction of hybrid furnaces would make it possible to limit the use of fossil fuels and go beyond the limits of electricity. Semi-finished product reheating furnaces can be staggered with set temperatures for the successive burners, thus making it possible for the products to be heated progressively and in a controlled manner. It is therefore technically possible to electrify the initial gas burners, for which the set temperature is the lowest, up to around 1000-1100°C. Hybridisation of a thermal application in this manner also gives manufacturers greater flexibility and enables them to partially guard against supply risks for one of the two energy carriers. This economic equation may prove advantageous insofar as electricity is generally more efficient than combustion of natural gas for the heating of semi-finished products, which tends to override the excess cost of electricity. Furthermore, it is conceivable for manufacturers to draw extra income through a flexibility contract with the grid operator: the manufacturer is paid for load shedding, temporarily reducing their consumption from the grid at certain times of peak demand, which provides additional stability for the operator.

3.6.3.5. Direct Combustion of Hydrogen

Direct combustion of hydrogen may also be applied to reheating furnaces for semi-finished products (see part 3.3.3.3.4).

3.6.3.6. CO_2 Capture from Rolling

Because of its heat requirements for the reheating of semi-finished products, hot rolling constitutes a small proportion of CO_2 emissions from a steelworks and, as with other industrial processes, it is possible to capture this CO_2. For manufacturers, this abatement solution is attractive since it may be technically complicated and expensive to electrify this process. However, the CO_2 from this process has a relatively low concentration: around 10% according to J.K. Pandit et al. (2020) [162], 4.6% according to IEAGHG (2013) [57] and 6.7% in the study by F. Zhang et al. (2018) [163]).

The modelling of CO_2 capture from reheating furnaces is based on the work of F. Zhang et al. (2018) [163], which studies a post-combustion capture system using solvents, which is standard for such low concentrations of CO_2. The study identifies a high potential for recovery of waste heat from the rolling stage (heat contained in the combustion gases at around 650°C and heat from the slabs). This heat can be recovered in order to meet a significant proportion of the heat required for regeneration of the amine solvent. With a capture rate of 90%, the energy requirement for the system is 3.67 GJ/tCO_2. The CO_2 thus captured has a concentration of 98.4%. In order to comply with requirements for transport of CO_2 by ship (which requires a concentration of over 99.9%), it was assumed that a final stage of purification by cryogenic distillation would be used. Thus, on the basis of the IEAGHG study (2013) [57], it was assumed that the additional electricity consumption would be 170 kWh/tCO_2 for cryogenic capture and 195 kWh/tCO_2 for its compression to 110 bars, i.e. a total electrical consumption of 365 kWh/tCO_2. On the basis of the results of A. Haglund (2020) [164], an investment cost of USD 186/t$CO_{2\ captured}$.year (or EUR 155/t$CO_{2\ captured}$.year[41]) for the capture technology was adopted.

F. Zhang et al. (2018) [163] specify that the waste heat from the slabs may not be sufficient to fulfil this energy requirement when the quantity of slabs stored and undergoing cooling decreases. In this case, the capture system requires additional external heat input and the study concludes that if coke oven gas is used to make up this shortfall, this would indirectly lead to the emission of 26.5% of the CO_2 captured (i.e. 0.265 kgCO_2 for each tonne of CO_2 captured), which remains relatively limited. However, the study does not specify the annual frequency with which this external extra heat contribution would be required. By way of simplification, it was therefore assumed that the heat requirements for the capture system can be met entirely by recovery of waste heat. Although this assumption may appear ambitious, it is important to note that CO_2 capture at the rolling mill is not to be introduced before 2030-2040 in the foresight exercise, thus leaving time for improvement of the techniques. In this respect, the DMX project at the ArcelorMittal Dunkirk site is a demonstration studying a solvent whose regeneration would lead to energy consumption of around 2.3 to 2.9 GJ/tCO_2, i.e. around 30% less than the adopted assumption of 3.67 GJ/tCO_2. **It should be noted that only blast furnace sites are assumed to be concerned by CO_2 capture technology for rolling mills in the decarbonisation trajectories. Electric arc furnace sites were ruled out without close examination because they individually represent too small a volume of emissions, and the majority are not favourably located for access to a storage area.**

The deployment of capture in hot rolling is controlled in the model by a rate of penetration of between 0% and 100% and defined by the variable $penetration\_CCS\_rolling$.

[41] Assumed exchange rate: EUR 1 = USD 1.2

Commodity	Unit	Original value /t_{coil}	New value /t_{coil}
CO2	*tCO2*	*Carbon accounting*	$SELF + 0{,}9 \cdot penetration\_CCS\_rolling$
/ tCO2 captured	*tCO2*	-	$- 0{,}9 \cdot penetration\_CCS\_rolling$

Table 24: Effect of CO_2 capture on rolling in the input-output modelling of continuous casting and hot rolling.

Commodity	*Unit*	*Original value / $t_{CO2\ captured}$*	*New value / $t_{CO2\ captured}$*
Electricity	kWh	-	$-365 \cdot penetration\_CCS\_rolling$

Table 25: Input-output modelling of CO_2 capture in rolling mill[42].

3.7. Assessment of Decarbonisation Technologies

3.7.1. Literature Review of Investment Costs in the Primary Sector

Table 26 below summarises the total investment costs for decarbonisation technologies in the primary sector (blast furnace and DRI). This overview of the literature on the subject enables us to compare sources and obtain realistic orders of magnitude for investment totals. The cost assumptions ultimately used in the modelling for each decarbonisation technology are set out in each relevant sub-section.

Technology	Description	Total investment cost	Unit investment cost	Sources
TGR-BF	TGR-BF: recirculation of top gases in the blast furnace (see part 3.2.3.3.4).	EUR 100 M (capacity of 2 $Mt_{hot\ metal}$.year)	EUR 50/$t_{hot\ metal}$.	N. Müller et al. (2012) [105]
		EUR 220 M (capacity of 2 $Mt_{hot\ metal}$.year)	EUR 110/$t_{hot\ metal}$.year	M. de Santis et al. (2021) [75]
New electric arc furnace	No precise description.	EUR 368 M (capacity of 2 $Mt_{hot\ metal}$.year)	184 EUR/$t_{liquid\ steel}$.year	A. Krüger et al. (2020) [165]
		EUR 186 M (capacity of 2 $Mt_{liquid\ steel}$.year)	USD 111.43/t_{steel}.year ≈ EUR 93/t_{steel}.year	S. Baig (2016) [166]
		EUR 442 M (capacity of 2 $Mt_{liquid\ steel}$.year)	USD 265.79/$t_{liquid\ steel}$.year ≈ EUR 221/$t_{liquid\ steel}$	M. Son et al. (2020) [167]
		EUR 266 M (capacity of 2 $Mt_{liquid\ steel}$.year)	USD 160/$t_{liquid\ steel}$.year ≈ EUR 133/$t_{liquid\ steel}$	V. Vogl et al. (2018) [138]
	Total investment cost for an electric arc furnace, including the cost of building and commissioning the industrial facility.	EUR 480 M (capacity of 2 $Mt_{liquid\ steel}$.year)	EUR 240/$t_{liquid\ steel}$.year	E. Jacobasch et al. (2021) [149]
DRI – MIDREX	No precise description.	EUR 240 M (capacity of 1 Mt_{DRI}.year)	EUR 240/t_{DRI}.year	A. Krüger et al. (2020) [165]
		EUR 250 M (capacity of 1 Mt_{DRI}.year)	EUR 250/t_{DRI}.year	N. Pardo et al. (2012) [105]

[42] Electricity consumption for 1 (positive) tonne of captured CO_2 is negative since the flow of captured CO_2 conventionally takes a negative value, given that it is an outflow and not an inflow. In practice, therefore, the quantity of electricity consumed is indeed positive for -1 t of captured CO_2.

		EUR 164 M (capacity of 1 Mt_{DRI}.year)	USD 196.33/t_{steel}.year ≈ EUR 164/t_{steel}.year[43]	S. Baig (2016) [166]
DRI - HYL	No precise description.	EUR 350 M (capacity of 2 Mt_{DRI}/ year)	EUR 175/t_{DRI}.year	N. Pardo et al. (2012) [105]
	Total investment cost for a direct reduction furnace, including the cost of building and commissioning the industrial facility.	EUR 606 M (capacity of 2 Mt_{DRI}/ year)	EUR 303/t_{DRI}.year	E. Jacobasch et al. (2021) [149]
DRI - EAF integrated plant	New greenfield plant with flexible use of natural gas and hydrogen.	EUR 10,000 M (capacity of 7.5 Mt_{steel}.year)	EUR 1,333/t_{steel}.year	JRC (2018) [139]
	Cost based on the MIDREX natural gas process. V. Vogl et al. (2018) [138] assume that this cost is the same for a plant running on H_2.	EUR 828 M (capacity of 2 Mt_{steel}.year)	230 (DRI) + 184 (EAF) = EUR 414/t_{steel}.an	M. Wörtler et al. (2013) [168]
H_2 electrolyser	Alkaline electrolysis (AEL) including equipment, stacks, and AC/DC converter.	-	EUR 800/kW in 2020 EUR 580/kW in 2030	A. Krüger et al. (2020) [165]
		-	EUR 848/kW in 2020 EUR 383/kW in 2050	E. Jacobasch et al. (2021) [149]
	PEM electrolysis (PEMEL) including equipment, stacks, and AC/DC converter.	-	EUR 1287/kW in 2020 EUR 296/kW in 2050	E. Jacobasch et al. (2021) [149]
	Solid oxide electrolysis (SOEL), which includes equipment, stacks, AC/DC converter, heat exchangers and condensers.	-	EUR 2,000/kW in 2020 EUR 1,000/kW in 2030	A. Krüger et al. (2020) [165]
		-	EUR 1906/kW in 2020 EUR 257/kW in 2050	E. Jacobasch et al. (2021) [149]
H_2 injection in BF	Adaptation of injection tuyères to shaft, electrolyser.	EUR 150 M (capacity of 2 $Mt_{hot\ metal}$/ year)	EUR 75/$t_{hot\ metal}$.year	M. de Santis et al. (2021) [75]
NG injection in BF	Adaptation of injection tuyères to shaft.	EUR 10 M (capacity of 2 $Mt_{hot\ metal}$/ year)	EUR 5/$t_{hot\ metal}$.year	M. de Santis et al. (2021) [75]
Preheating of scrap	Use of waste heat from the electric arc furnace to preheat scrap.	USD 3.2 M ≈ EUR 2.7 M (capacity of 0.5 Mt_{steel}/ year)	EUR 5.3/t_{steel}.year	EPA (2012) [106]
CCS	No precise description.	EUR 107 M (capacity of 1 $Mt_{hot\ metal}$/ year)	EUR 107/$t_{hot\ metal}$.year	N. Pardo et al. (2012) [105]
	CO_2 capture and compression. MDEA/Pz solvent post-combustion capture technology with OBF and TGR.	EUR 579 M (capacity of 4 Mt_{steel}/ year)	EUR 137/t_{steel}.year	L. Hooey et al. (2013) [169]
	CO_2 capture and compression. Post-combustion capture technology (capture of CO_2 from the coking, Cowper stoves, lime kiln and steam production plant).	USD 242 (thermal power station and steam production) + 917 (capture equipment) M = USD 1,159 M ≈ EUR 966 M	EUR 248/t_{steel}.year	IEAGHG (2013) [57]

[43] Assumed exchange rate: EUR 1 = USD 1.2

		(capacity of 3.9 $Mt_{hot\ iron}$/year)		
	CO_2 capture and compression. Post-combustion capture technology with OBF and MDEA solvent.	USD 306 (thermal power station, steam production and ASU) + 578 (capture equipment) M = USD 884 M ≈ EUR 737 M (capacity of 3.9 $Mt_{hot\ iron}$/year)	EUR 189/t_{steel}.year	IEAGHG (2013) [57]
	CO_2 capture and compression in TGR-BF. Additional investment to be made once the TGR-BF has been installed.	EUR 160 M (capacity of 4 $Mt_{hot\ metal}$.year)	EUR 40/$t_{hot\ metal}$.year	M. de Santis et al. (2021) [75]

Table 26: Comparison of investment costs for decarbonisation levers in the primary sector.

3.7.2. Assessment of Technical and Economic Data for the Electrical Sector

Table 27 below summarises the whole of the technical and economic assumptions used to model the decarbonisation technologies for the electrical sector, as well as the associated sources.

	Stage of process	Source of energy / process emissions	Assumed impact	Assumed CAPEX	Sources
Processing and cleaning of scrap	Electric arc furnace	Electricity	- 50 kWh/$t_{liquid\ steel}$	EUR 1,250/kt_{steel}	ADEME assumptions on the basis of interviews and confidential sources
Digitalisation	Electric arc furnace	Electricity	- 15 kWh/$t_{liquid\ steel}$	EUR 1,670/kt_{steel}	ADEME assumptions on the basis of confidential sources
Electromagnetic Stirring	Electric arc furnace	Total energy	- 4 %	EUR 2,000/kt_{steel}	Confidential sources ABB review 3/2015 [103]
		Graphite electrode	- 5 %		
Preheating of scrap	Electric arc furnace	Electricity	- 25 kWh/$t_{liquid\ steel}$	EUR 4,600/kt_{steel}	Confidential sources N. Pardo et al. (2012) [105] EPA (2012) [106]
		Graphite electrode	-40%		
Improved Sealing of the Electric Furnace	Electric arc furnace	Electricity	- 20 kWh/$t_{liquid\ steel}$	EUR 1,500/kt_{steel}	ADEME assumptions on the basis of confidential sources
Regenerative Burners	Reheating furnace	Natural gas	-40%	EUR 8,300/kt_{steel}	ADEME assumptions on the basis of confidential sources
	Heat treatments	Natural gas	-40%		
Oxy-Fuel burners	Preheating of ladles	Natural gas	- 35 %	EUR 5,600/kt_{steel}	N. Pardo et al. (2012) [105] J. von Schéele (2010) [114]
	Reheating furnace	Natural gas	- 35 %		
	Heat treatments	Natural gas	- 35 %		
Direct Current Electric Arc Furnace	Electric arc furnace	Electricity	- 70 kWh/$t_{liquid\ steel}$	EUR 5,170/kt_{steel}	Confidential sources E. Worrel et al. (2009) [111]
	Electric arc furnace	Graphite electrode	- 50 %		
Induction furnaces		Natural gas	- 100 %		

	Reheating furnace	Electricity	+ 450 kWh/t	EUR 590/MWh of natural gas saved	ADEME assumptions on the basis of confidential sources
	Heat treatments	Natural gas	- 100 %		
		Electricity	+ 225 kWh/t		
Vacuum pumps for VOD	Secondary Steelmaking	Natural gas	- 40 kWh/$t_{liquid\ steel}$	EUR 11,200/kt_{steel}	ADEME assumptions on the basis of confidential sources
		Electricity	+ 2 kWh/$t_{liquid\ steel}$		
Direct combustion of hydrogen in replacement of natural gas	Preheating of ladles	Natural gas	- 100 %	-	ADEME assumptions on the basis of interviews and confidential sources
	Reheating furnace	Natural gas	- 100 %		
	Heat treatments	Natural gas	- 100 %		
	Whole plant	Electricity	Hydrogen production by electrolysis: 56 kWh_e/kg_{H2}		
Recarbonation of slags	Capture and use	Total direct emissions	53 $kgCO_2/t_{slag}$	-	S. Kombathula (2020) [123]
Change of reducing agent	Electric arc furnace	Anthracite, coke and other sources of carbon	30% substitution max., 50% biogenic carbon	-	Confidential sources S. Devasahayam et al. (2019) [127] E. Worrel et al. (2010) [111]

Table 27: Summary of the technical and economic assumptions for decarbonisation levers in the electrical sector.

Table 28 below presents the impact of decarbonisation technologies in the electrical sector on electricity consumption and CO_2 emissions at site level. Unlike the previous table, this is more in the nature of a table of results by decarbonisation lever.

Technology	*Methods*	*Description*	e⁻	CO_2
Energy efficiency	Regenerative Burners	Heat recovery from combustion gases to preheat air and fuel	-	- 19%
	Oxy-Fuel burners	Burner running on pure oxygen instead of air, reducing NOx emissions and fuel consumption		- 4%
	Electromagnetic Stirring	Creation of a convection movement in the molten steel bath to accelerate melting and reduce consumption of electrodes	- 3 %	- 3 %
	Scrap cleaning	Removal of impurities from scrap to reduce heat loss	- 6%	-
	Preheating of scrap	Heating of scrap to reduce melting time	- 3%	
	Sealing of the furnace	Reduction of heat losses and parasitic reactions	- 2%	
	Digitalisation of the process	Digital optimisation of the process	- 2%	
Electrification	Electrical resistance	Use of electric resistors rather than natural gas furnaces for the reheating of semi-finished products	**+ 31%**	- 48%
	Electrolytic hydrogen	Combustion of hydrogen rather than natural gas for the reheating of semi-finished products	**+ 57%**	
	Induction Furnace	Heating of metal products by induction for heat treatments during rolling (IFA sector)	**+ 22%**	- 21%
	Vacuum pumps	Electrification of vacuum production, operating via natural gas, in VOD decarburisation systems for stainless steel (IFA sector)	**+ 0.2%**	- 3%
Substitution of waste plastics for coal		Recovery of waste plastics, which have higher calorific value and reducing power than coal	-	- 19 %

Recarbonation of slags	Capture of CO_2 and reaction with slag minerals to form solid carbonates		**- 4%**

Table 28: Impact of decarbonisation levers in the electrical sector on electricity consumption and CO_2 emissions.

3.8. Cost of Steel Production

The breakdown of production costs differs according to the production route. Recycled steel is highly dependent on the cost of scrap, and to a lesser extent, on the price of energy. For primary steel, the main costs are material inputs such as coal and iron ore.

A JRC study published in 2020 [170] covering 153 steel production sites in the European Union and ten other countries outside the EU made it possible to characterise average production costs for the steel industry. Figure 81 presents the average steel production costs for the European Union of 27 Member States (EU27) in 2019 for the blast furnace (BF-BOF) and electric arc furnace (EAF) sectors, with the production of hot rolled coils and rods as proxies.. The costs are broken down into five categories:

- **Raw materials** constitute by far the biggest item of expenditure (between 60 and 70%). This item includes the purchase of iron ore, metallurgical coal, injection coal, injection natural gas, lime, scrap, additive metals and ferro-alloys.
- The **"energy"** item, which covers the purchase of electricity and natural gas.
- The **"labour"** item.
- The **"credits"** item represents the potential savings made, for example by means of the recycling of scrap and the production of energy on site.
- The **"other"** item includes the purchase of other consumables such as fluxing agents, refractories and electrodes, as well as costs connected with capital depreciation and the cost of carbon.

Overall, production costs for European steelmakers in 2019 are estimated at between EUR 450 and EUR 500/t_{steel} without any significant distinction between production sectors. It should be noted, however, that these figures only reflect the European context, and the situation may prove to be very different in other regions of the world, particularly where there is a large difference in cost between electricity and coal.

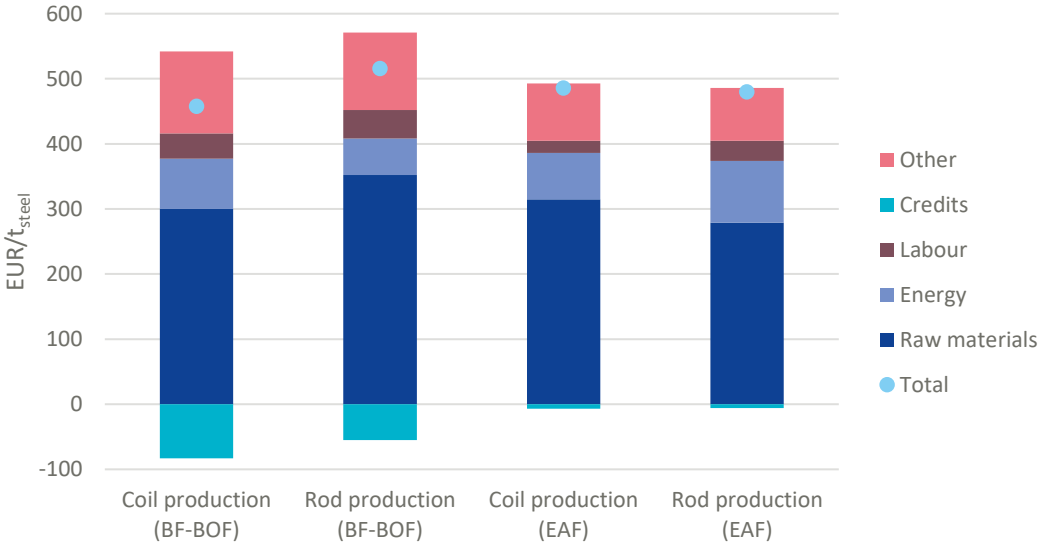


Figure 81: Average production costs for steel coils and rod in the EU27 in 2019 [170].

In comparison with other countries outside of the European Union, such as China, Russia and Brazil, production costs in the EU27 are often higher. Generally speaking, the cost of labour and raw materials are the two items that most affect the competitiveness of the European steel industry as compared with other regions of the world [170]. This was also revealed by a report published in 2022 [171] whose conclusions are illustrated in Figure 82. The latter shows the spectacular rise in the average production cost of steel in 2021 in all of the major producing countries (in the order of 50%) as a result of the rise in energy prices that year, as well as the gap in production costs between countries. In 2021, the difference between the two extremes (which are found to be India / Russia and Germany within the sample of countries selected) was 46% for the blast furnace sector and 36% for the electrical sector.

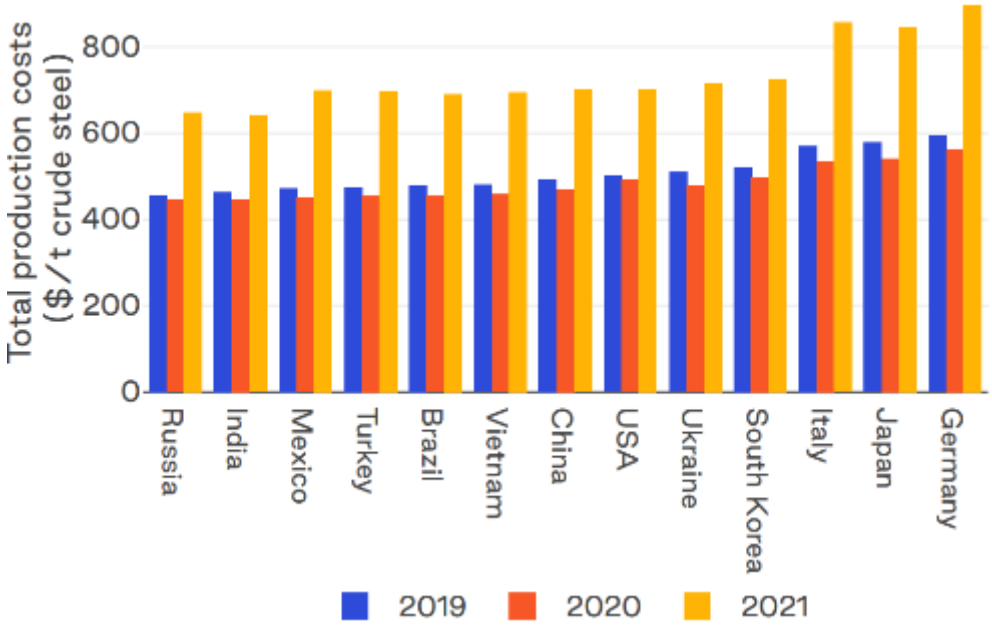


Figure 82: Average cost of steel production in various countries, 2019-2021 [171].

In the modelling of the French steel industry, production costs in the pig iron sector were constructed on the basis of:

- Specific consumption of energy and material inputs from the reference plants.
- Assumed purchase prices for all commodities (coal, iron ore, etc.)
- Assumed selling prices for co-products such as granulated blast furnace slag, steelworks slag, and tars and benzol produced in the coking plant.
- A downward trajectory for free allowances allocated under the EU ETS.
- Assumptions concerning fixed operating costs (labour, maintenance, management, etc.)
- An assumption concerning the amount of depreciation which is reflected in the cost of production and depends upon past investments ("CAPEX depreciation" item).

For the years 2015-2021, the purchase price of commodities was calculated on the basis of the market values and quantities imported into France available via customs data[44]. Similarly, the selling price of co-products (tar, benzol and slags) was calculated on the basis of market values and quantities exported from France. The estimated price values are consistent with other data available in the literature [57], [133], [137], [138], [149], [172]. In addition to these purchases, assumptions were made concerning the cost of transport of iron ore (principally from Brazil and Canada) and different types of coal on the basis of IEAGHG (2013) [57]. Lastly, assumptions concerning other fixed and variable costs (labour, consumables, maintenance, etc.) were also made on the basis of IEAGHG (2013) [57]. The cost of CO_2, for its part, was reconstructed on the basis of the average price of CO_2 within the EU ETS and the proportion of emissions covered by free allowances for companies within the pig iron sector in France. It is therefore assumed that all missing allowances required to cover emissions are purchased within the EU ETS.

[44] Data accessible via the Trade Map website: https://www.trademap.org/Index.aspx

Category	Item	Unit	2015	2016	2017	2018	2019	2020	2021	Description/source
Raw materials and energy	Iron ore	EUR/t	49	51	72	72	90	94	145	Average import price, customs codes 260111 and 260112
	Transport of ore	EUR/t	15	15	15	15	15	15	15	ADEME assumptions on the basis of IEAGHG (2013) [57]
	Coal[45]	EUR/t	88	84	128	129	140	102	126	Average import price, customs code 2701
	Metallurgical coal	EUR/t	100	104	207	183	187	129	145	Average import price, customs code 27011210
	Anthracite	EUR/t	107	105	147	144	153	143	149	Average import price, customs code 270111
	Transport of coal	EUR/t	25	25	25	25	25	25	25	Assumptions on the basis of IEAGHG (2013) [57]
	Limestone	EUR/t	22	24	22	21	18	21	23	Average import price, customs code 252100
	Lime	EUR/t	88	89	87	92	93	89	95	Average import price, customs code 2522
	Calcined dolomite	EUR/t	131	134	131	141	163	175	204	Average import price, customs code 251820
	FeMnC	EUR/t	889	832	1356	1195	1133	933	1357	Average import price, customs codes 720211 and 720219
	FeSi-75	EUR/t	1164	970	1162	1412	1121	1030	1457	Average import price, customs code 720221
	Aluminium	EUR/t	2807	2144	2473	2601	2410	2173	3212	Average import price, customs code 7605
	Scrap	EUR/t	225	225	250	325	250	250	400	Estimate on the basis of S&P Global [173] and Steelonthenet [174]
	Natural gas	EUR/MWh	30	30	30	30	30	30	30	ADEME assumptions on the basis of P. Cavaliere et al. (2022) [133], K. Benavides et al. (2022) [137]
	Grid electricity	EUR/MWh	60	60	60	60	60	60	60	
	Heating oil	EUR/MWh	70	70	70	70	70	70	70	
Other variable costs	Consumables and other utilities (refractories, electrodes, water, etc.)	EUR/t_{steel}	9	9	9	9	9	9	9	Assumptions on the basis of IEAGHG (2013) [57]
	Miscellaneous costs (logistics, engineering, waste treatment, etc.)	EUR/t_{steel}	14	14	14	14	14	14	14	
Cost of carbon	Price of CO_2 on the EU ETS market	EUR/tCO_2	6	5	5	15	24	24	55	Estimate on the basis of Carbon Price Viewer [175]
	% of emissions covered by free allowances	%	84%	83%	73%	76%	75%	94%	84%	Estimate on the basis of EU Transaction Log database [176]
	Cost of CO_2 in the production cost	EUR/t_{steel}	2	2	3	7	11	3	17	Calculation on the basis of previous data and specific emissions from the reference plant
Fixed costs	Maintenance costs	EUR/t_{steel}.year	26	26	26	26	26	26	26	Assumptions on the basis of IEAGHG (2013) [57]
	Labour	EUR/t_{steel}.year	38	38	38	38	38	38	38	
	Sub-contracting and management costs	EUR/t_{steel}.year	14	14	14	14	14	14	14	
	Amortised CAPEX	EUR/t_{steel}.year	30	30	30	30	30	30	30	
Sale of co-products	Tars	EUR/t	217	166	262	422	292	191	349	Average export price, customs code 2706
	BTX	EUR/t	467	364	483	500	406	280	515	Average export price, customs code 2707
	Granulated slag	EUR/t	13	13	19	26	48	51	39	Average export price, customs code 261800
	Other slags	EUR/t	6	10	20	30	22	15	16	Average export price, customs code 2619

Table 29: Summary of cost assumptions in current EUR for the construction of production costs for the pig iron sector.

The final reconstruction of the production cost as modelled for the pig iron sector between 2015 and 2021 is presented in Figure 83. This cost is expressed in euros per tonne of hot rolled coil (HRC). The total production cost (around 500 - 600 EUR/t_{HRC}) is consistent with the values presented in Figure 81 from JRC (2020) [170]. Broken down in this way, Figure 83 provides an overview of the weight of raw materials in the cost of production, in particular iron ore and coal. It also shows the sharp rise in costs in 2021 as a result of the supply constraints that marked the post-Covid period, in line with Figure 82.

[45] Assumption: quality of coal used for sintering

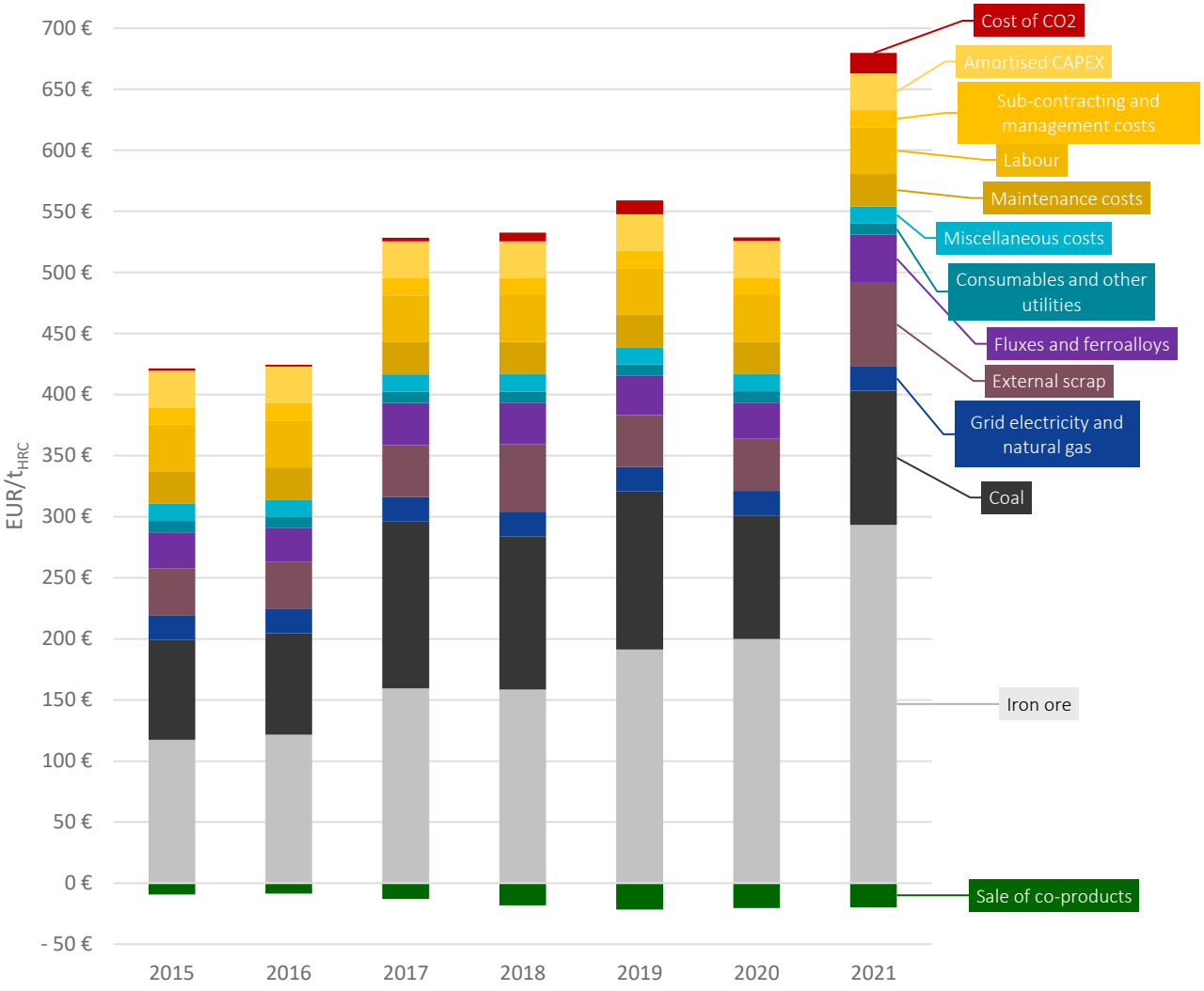


Figure 83: Reference plant REF1 Integrated blast furnace site - Reconstructed production cost between 2015 and 2021.

For the DRI-EAF sector, the production cost was calculated on the basis of the specific energy and material input consumption of the dedicated reference plant and the purchase prices of the various commodities. Assumptions for labour, maintenance and other variable and fixed costs were made on the basis of V. Vogl et al. (2018) [138], K. Benavides et al. (2022) [137] and E. Jacobasch et al. (2021) [149]). Moreover, the maintenance cost is estimated at 3% of the initial CAPEX, i.e. around EUR 18/t_{steel}.year (for an investment cost of EUR 604/t_{steel}.year for a DRI-EAF unit). Amortised CAPEX is calculated on the basis of a lifespan of 25 years and an interest rate of 7%, i.e. EUR 52/t_{steel}.year. Subcontracting and management costs, as well as other variable costs, were taken as equal to those for the pig iron sector.

4. Three contrasting scenarios to illustrate the challenges of far-reaching decarbonisation of the steel industry by 2050

The worlds in which the scenarios are projected vary, and the underlying assumptions concerning domestic demand and international trade differ quite significantly. These elements are respectively grouped in sub-sections 4.1 and 4.2. Sub-sections 4.3, 4.4 and 4.5 present the results from the scenarios concerning changes in production, the level of emissions reduction achieved in 2050 and the associated investment requirements.

4.1. Transition world

As with any foresight exercise, the work on decarbonisation of the steel industry by 2050 involves a very high degree of uncertainty, due in particular to the difficulty of forecasting changes in the economic, social, technological and regulatory situation over such a long time horizon. This observation led to the proposal, common to the different Sectoral Transition Plans, to integrate decarbonisation of an industrial sector into several deliberately contrasting scenarios in order to cover a relatively broad spectrum of possible changes in the sector.

Among the structural uncertainty factors for decarbonisation of the steel industry (see Text Box 1 in section 1.5.2), **access to competitive low-carbon electricity appears to be a decisive factor in the deployment of decarbonisation technologies in France**[46]. Apart from the energy mix specific to each country, which is relatively dependent on the availability of fossil and renewable resources within its territory, the involvement of public authorities in industrial policy plays a decisive role in access to competitive low-carbon electricity, and more generally in whether or not production capacity is maintained in the country. Although, historically, France's choice of an energy mix dominated by nuclear-generated electricity has enabled manufacturers to benefit from a relatively competitive price, this advantage needs to be reconsidered in the medium and long term, in the light of the sharp increase in renewable electricity production capacity worldwide and the resulting possible reorganisation of industrial value chains. The contrast between the scenarios is thus illustrated as follows:

- In a context where international trade is neither hindered by trade barriers, nor disrupted by the consequences of global warming on supply chains, comparative advantages fully assert themselves. **The "Reduced Competitiveness"** scenario thus highlights the comparative advantages of Australia, South Africa and Brazil in the production of low-carbon hydrogen, DRI and steel: i.e. plentiful renewable resources and a subsoil rich in iron ore. In order to guarantee the supply of steel for sectors considered strategic, a minimum of steel production capacity in France is maintained and the cost of access to low-carbon, competitive electricity is relatively limited.
- In **the "Hydrogen Bet" scenario**, plans for investment in DRI-EAF processes led by the majority of the big steel groups are supported and continue to receive financial backing through investment subsidies and a price of electricity that is sufficiently competitive to guarantee the maintenance of European production capacity. At the same time, European and French manufacturers benefit from the increase in import transaction costs created by the deployment of the Carbon Border Adjustment Mechanism (CBAM - see Text Box 4)[47], from the public authorities' will to maintain the historical industrial sector through the promotion of 'Made in Europe' and 'Made in France', and from an increase in the cost of international transport in order to face up to the consequences of climate change. These three elements are at the root of the structural trend towards the regionalisation of trade flows.
- **The "Sobriety and Diversification" scenario** is based upon an international context in which value chains are being drastically reshaped as a result of significantly increasing transport costs, and a strong will on the part of public authorities to relocate and maintain industrial activities as close as possible to the place of consumption. In a situation of this kind, the incentive for new industrial entrants from outside of the EU to enter the European market with more or less processed steel products is relatively weak. As in the "Hydrogen Bet" scenario, and in an even more preponderant manner here, the weight of the need for low-carbon, competitive electricity for industry is reduced.

[46] More generally, this factor appears to be of structural importance for the decarbonisation and relocation of certain economic activities back to France, particularly those which are most energy-intensive.

[47] The transaction costs are here borne by importers and correspond to administrative costs, in particular those associated with data collection and with bringing economic actors into line with European authorities' requirements with regard to the importing of products and materials coming under the CBAM.

Text Box 4: The Carbon Border Adjustment Mechanism (CBAM)

In a situation of increasing climate action at the European level, the Carbon Border Adjustment Mechanism (CBAM[48]) is a regulatory instrument with the primary objective of subjecting products imported into European customs territory to carbon pricing equivalent to that applied to industrial products within the framework of the EU ETS. The steel, aluminium, cement, ammonia, hydrogen and electricity generation industries are the sectors most exposed to international competition, for which the mechanism came into force in October 2023, for a test phase. By gradually replacing the existing system of allocation of free allowances (the total disappearance of free allowances is scheduled for 2034), the CBAM is aimed at fighting against the risk of carbon leakage, while promoting internalisation of the price of CO2 within international value chains. In particular, this new set-up should make it possible to stimulate the deployment of decarbonisation technologies and promote the incorporation of recovered raw materials into consumer products and goods. Furthermore, the auctioning of more allowances would enable the EU and national governments to obtain significant, vital funds to devote to climate policies, in particular to leading-edge industrial technologies, which will probably require substantial financial support (the CBAM is expected to generate between €10 and €14 billion in revenue per year from 2030, to the benefit of the European budget). Nevertheless, the terms of application of the CBAM, such as the inclusion of indirect emissions and its extension to a greater number of sectors, still remain to be clarified in coming years in order to maximise the system's effectiveness[49].

Changes in domestic demand for steel in the consumer sectors constitute a second structural uncertainty factor. In view of the multitude of outlets for steel, requirements are likely to remain at a relatively high level between now and 2050. Nevertheless, the weight of the various sectors in the steel production chain differs and could lead to variable production prospects depending on whether the output originates from blast furnaces or historic electric arc furnaces. The ADEME Transition(s) 2050 scenarios highlight the role of sufficiency and changes in consumer behaviour in different scenarios, as well as the potential consequences of regulatory changes in sectors such as building and civil engineering and packaging. The transition worlds initiated with the preceding uncertainty factor may be associated with the framework of the different Transition(s) 2050 scenarios, and in particular the place of sufficiency policies and changes in consumption behaviour. The *Reduced Competitiveness* scenario is thus similar to the S4 "Restoration Gamble" scenario, the *Hydrogen Bet* scenario to the S3 "Green Technologies" scenario and the *Sobriety and Diversification* scenario to the S2 "Regional Cooperation" scenario[50].

Generally speaking, the contrast between the scenarios can be observed in Table 30:

	By 2050	Reduced competitiveness	Hydrogen bet	Sobriety and diversification
Industrial policy	Re-industrialisation of "downstream" activities	★☆☆☆☆	★★☆☆☆	★★★★★
	Effect of CBAM on reduction of import/export flows	★☆☆☆☆	★☆☆☆☆	★★★★★
	Development of the H2 sector	★☆☆☆☆	★★★★★	★★★★★
Technology	Deployment of DRI in replacement of blast furnaces	★☆☆☆☆	★★★★★	★★★★★
	Deployment of direct iron electrolysis	★☆☆☆☆	★☆☆☆☆	★★★★★
	Deployment of CCS	★★★☆☆	★☆☆☆☆	★★★★★
Domestic demand	Reduction in the pace of construction of new buildings (residential)	★☆☆☆☆	★★☆☆☆	★★★★★
	Mobility needs	★★★★☆	★★★☆☆	★★★★★
	Shift towards "low-impact" modes of mobility	★☆☆☆☆	★★☆☆☆	★★★★★
	Deployment of renewable energies	★★★☆☆	★★★★☆	★★★★★
Circular economy	Mobilisation of national sources of scrap	★☆☆☆☆	★★★☆☆	★★★★★

Table 30: Illustration of the contrast between scenarios

Despite their contrasts, these three scenarios share similarities illustrating trends in the development of the steel industry:

- **Incremental decarbonisation of blast furnaces** until the establishment of DRI-EAF route facilities: increase in the proportion of scrap in oxygen converters (from 17% to 28% on average in 2026) and recirculation of coke oven gases from 2024;

[48] Also known under its French name "MACF" or *Mécanisme d'Ajustement Carbone aux Frontières*

[49] Further information is available in the policy paper: « Analyse des différentes modalités d'application du Mécanisme d'Ajustement Carbone aux Frontières de l'Union Européenne », Oliver Sartor and Sylvain Sourisseau, 2022.
For further information, visit the dedicated website: https://www.ademe.fr/en/futures-in-transition/

- **Development of the DRI-EAF route**: construction of direct reduction furnaces (DRP) and electric arc furnaces in 2027 and 2035 to replace closed blast furnaces;
- **Progressive closure of blast furnaces**: principally by 2027 [51] and subsequently by 2035 (except in Sobriety and Diversification, in which one blast furnace out of the six is maintained);
- **Capture and geological storage of CO_2 emissions** from hot rolling from 2036;
- Improvement of the **energy efficiency** of existing electric arc furnaces.

4.2. Principal Market Assumptions

4.2.1. Domestic Demand

The principal assumptions are listed in Table 31. They come from two principal sources: the Sectoral Transition Plan for the cement industry (1) and Transition(s) 2050 (2). Other assumptions are arbitrarily taken into account in the modelling, with the sole aim of reflecting a context of transition by 2050 (3). Moreover, the values are given for the year 2050, and therefore obscure relatively different dynamics of change between the scenarios. By way of example, the investment in renovation in the building sector is most pronounced between 2025 and 2035 for the *Sobriety and Diversification* scenario, before slowing down by 2050. A dynamic of this kind was also adopted for the *Reduced Competitiveness* scenario, but to a lesser extent. On the other hand, the deployment of renewable energies, principally completed in the decade 2022-2030, concerns all 3 scenarios (*i.e.* with the same targets as in the French Multi-Annual Energy Programme[52]). The differences can be seen in 2050, according to the place of renewable energies in the energy mix taken into account in the Transition(s) 2050 scenarios.

[51] This is an accelerated timetable compared with the roadmap for the Mining and Metallurgy sector, where ArcelorMittal plans to progressively replace three of its five blast furnaces between 2027 and 2030 with three electric arc furnaces and a direct reduction plant (DRP) with a capacity of 2.5 Mt.

[52] Further information available : https://www.ecologie.gouv.fr/programmations-pluriannuelles-lenergie-ppe

Parameter (unit/year)	Value in 2015	Value in 2050 (change as compared with 2015)			Sources
		Sobriety and Diversification	Hydrogen Bet	Reduced Competitiveness	
BUILDING AND CIVIL ENGINEERING					
Individual houses - IH and collective housing - CH (number of new buildings)	338,719	66,400 (-80%)	220,587 (-35%)	179,661(-47 %)	(1) (2)
Tertiary, industrial and agricultural (thousands of m² built)	21,750	11,825 (-46 %)	19,180 (-13%)	19,278 (-11 %)	(1) (2)
Non-LEB renovation - "piecemeal" (individual houses (IH), collective housing (CH) and tertiary sector)	3,556,550	1,618,103 (-54 %)	3,556,550 (constant)	2,127,930 (-40 %)	(1) (2)
LEB renovation	16,100	473,350 (x 28)	82,083 (x 5)	188,100 (x 12)	(1) (2)
Market share of wood in IH construction (%)	10%	40%	15%	14%	(1) (2)
Motorways (km)	89	0	0	0	(1) (2)
Communal roads	7,000	500	7,000 (constant)	7,000 (constant)	(1) (2)
High-speed rail (LGV)	45	0	66 (+50%)	66 (+50%)	(1) (2)
Tramway (km)	45	0	66 (+50%)	66 (+50%)	(1) (2)
TRANSPORT					
Total distance travelled by bike (Gkm passengers)	6	18 (x 3)	34 (x 4.7)	16 (x 3)	(2)
Total distance travelled by train (Gkm passengers)	105	126 (+20%)	161 (+56%)	162 (+56%)	(2)
Total distance travelled by car (Gkm passengers)	724	745 (+3%)	767 (+8%)	970 (+34%)	(2)
New vehicles (number of sales in thousands)	1,777	1,357 (-24 %)	2,277 (+28 %)	3,550 (x 2)	(2)
Proportion of electric vehicles sold (%)	0%	99%			(2)
ENERGY					
Installed offshore wind power capacity (MW/year)	0	1,155	2311	2311	(2) (3)
Installed land-based wind power capacity (MW/year)	1,156	2,141 (+85 %)	1,962 (+70 %)	2,319 (x 2)	(2) (3)
Installed ground-based photovoltaic power capacity (MW/year)	577	2,294 (x 4)	3,059 (x 5)	3,250 (x 6)	(2) (3)
Installed roof-based photovoltaic power capacity (MW/year)	381	1,180 (x 3)	2,832 (x 6)	2,832 (x 6)	(2) (3)
CAPITAL GOODS AND CONSUMER GOODS					
Mechanical/Motor generators (% change in per capita consumption)	0%	-5%			(2)
Consumer electronics (change in per capita equipment rate)	0%	+221%			(2)
Household electric lighting (change in per capita equipment rate)	0%	+34%			(2)
PACKAGING					
Change in consumption of steel packaging (%)	0%	+7%	+17%	+28%	(2)
Rate of reuse of steel packaging (%)	37%	60%	50%	40%	(2)

Table 31: Principal assumptions adopted for modelling the demand for steel in France up to 2050

4.2.2. International Trade:

As outlined in sub-section 4.1 concerning the "access to competitive low-carbon electricity" uncertainty factor, developments in international trade differ markedly from one scenario to another.

The assumptions were not derived from sources in the existing literature and do not constitute forecasts. Indeed, there are numerous uncertainties concerning changes in import and export flows within the 2030 and 2050 time frames, and the forecasting of these trends would require specific modelling work. In the absence of work of this kind, the rates of import and export were set arbitrarily on the basis of the the changes in flows over the 2014-2019 period for each of the three sectors. The rates are above all intended is to reflect the configuration of international trade as outlined in each of the three transitional worlds.

		Imports				Exports			
		Import rate		Change as compared with 2022 (e)		Export rate		Change as compared with 2022 (e)	
		2030	2050	2030	2050	2030	2050	2030	2050
Hydrogen bet	Flat steel products	65%	65%	-4%	-7%	68%	70%	+12%	+22%
	Long carbon steel products	54%	52%	-5%	-14%	48%	47%	+1%	0%
	Stainless and high alloy steels	77%	75%	+5%	+12%	65%	66%	+13%	+31%
Reduced Competitiveness	Flat steel products	65%	78%	+1%	+20%	68%	58%	+14%	-54%
	Long carbon steel products	62%	64%	+12%	+2%	44%	40%	-26%	-47%
	Stainless and high alloy steels	69%	61%	+4%	+9%	61%	57%	+4%	-14%
Sobriety and diversification	Flat steel products	60%	50%	-17%	-40%	60%	50%	-13%	-42%
	Long carbon steel products	45%	35%	-28%	-58%	62%	64%	-18%	-43%
	Stainless and high alloy steels	69%	61%	-12%	-19%	61%	57%	+16%	+26%

With regard to the *Sobriety and Diversification* scenario, relocation of trade flows back to a regional scale is assumed. This configuration results from three factors:

- The application of the CBAM at the borders of member countries of the European Economic Area (EEA)[53] does not lead to significant decarbonisation of industries in third countries, resulting in an excess cost that is sufficiently large to induce importers and manufacturing exporters to concentrate the bulk of trade in major regional centres;
- The rise in transport costs connected with the increase in the price of energies and insurance to cope with climatic vagaries and therefore potential pressures affecting logistics;
- A will on the part of countries to limit the length of value chains in order to reduce dependency on changes in the geopolitical context and contain supply risks with regard to strategic materials, including certain alloys.

With regard to the *Reduced Competitiveness* scenario, the transitional world in which French steel manufacturers are assumed to operate implies the development of trade flows on a global scale and reveals the low competitiveness of French manufacturers in this international competition. This configuration results from three factors:

- Flexibility in the modes of application of the CBAM, combined with major diplomatic work in relations with countries that were initially reticent with regard to a system of this kind, makes it possible to significantly

[53] It was assumed that the EEA member countries, as well as Switzerland and Great Britain, are included in the geographical area covered by the CBAM due to the integration of their respective carbon markets.

decarbonise international energy mixes and industrial processes through the harmonisation of carbon pricing, thereby reducing de facto the risk of carbon leakage;

- Decarbonisation of the transport sector facilitates the expansion of trade, the character of which depends solely on countries' comparative advantages, excluding "carbon dumping" [54];

With regard the *Hydrogen Bet* scenario, the assumptions adopted illustrate the trends outlined in the other two transition worlds, but in a more moderate way. The scenario thus reflects changes tending towards the regionalisation of trade throughout the world. The introduction of the CBAM has the intended effect: third countries are incentivised to introduce carbon pricing mechanisms, and global steel production progressively becomes decarbonised. However, Europe takes advantage of its technological lead (particularly DRI-H_2) as compared with third countries to remain competitive in the face of imports.

Moreover, heterogeneous dynamics affecting international trade due to the influence of products downstream from the sector were also taken into account. More specifically, the *Hydrogen Bet* scenario includes measured reindustrialisation of certain strategic activities such as the production of wind turbines and photovoltaic panels. This dynamic is much more extensive and ambitious in the *Sobriety and Diversification* scenario, and absent in the *Reduced Competitiveness* scenario.

4.3. The "Hydrogen Bet" Scenario: Increased Production due to the Use of Competitively-Priced Electrolytic Hydrogen

4.3.1. Increased Production due to investment in Relocation of Industry back to France and Stable Demand

In this scenario, French steel consumption increases by 2% between 2022 and 2050. This is due in particular to the growth of electricity consumption, which quadruples the demand for steel for the energy sector (wind power and photovoltaics in particular). However, this increase is limited by a fall in demand for the construction industry, where the need for thermal retrofitting (x4) is largely offset by a 35% fall in new buildings. Trade in steel trade remains concentrated in the EU (in line with current trends), in a context of technological collaboration and collective transition to the DRP-H_2 / EAF route. In 2050, imports have been reduced by 6% and exports have increased by 18% as compared with 2015, reducing the steel trade deficit (the difference between tonnes of steel imported and exported) that had developed between 2014 and 2019. Moreover, a drive to relocate production of wind turbines (30% in France) and photovoltaic panels (10% in France) back to France has made it possible for a large proportion of the increase in demand from the energy sector to be catered for by French steelmakers. In Figure 84, this corresponds to the increase in indirect steel imports (i.e. imports of manufactured products containing steel), stimulated by the strong demand for energy equipment, but on a scale that is limited by the investment made in relocation of production back to France. **As a result, French steel production increases by 11% between 2022 and 2050.**

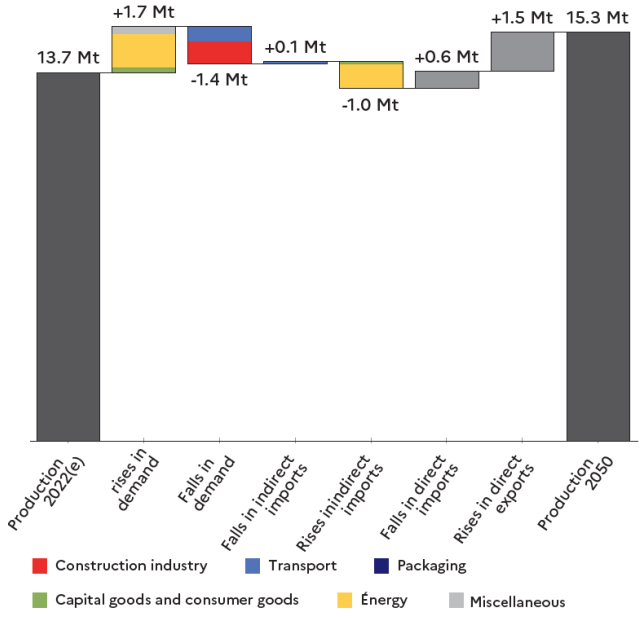


Figure 84: Hydrogen Bet Scenario - Breakdown of changes in steel production between 2022 and 2050

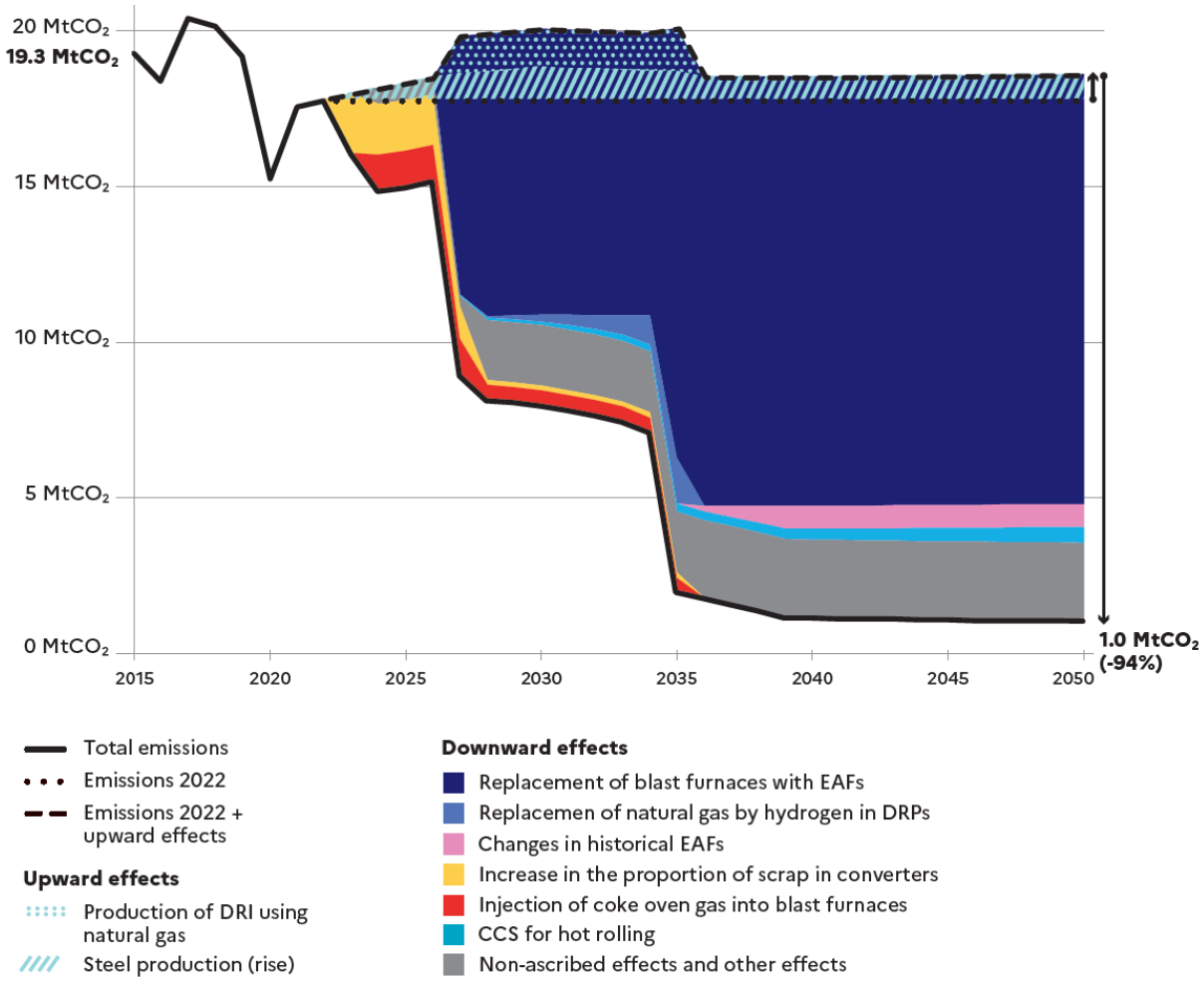
[54] Harmonisation of carbon pricing eliminates any relocation of industry that might occur for climatic reasons, but does not prevent other forms of dumping connected with other environmental externalities and labour costs.

However, this aggregate trend in consumption obscures a number of differences between steel products. While the consumption of flat steel products from the primary sector (blast furnaces and DRI-EAF) has contracted by 4% by 2050, it has increased by 12% for products from the historical electrical sector, principally due to the significant needs in the energy sector. Stainless steel and high alloy products are the principal beneficiaries of these future needs on the domestic market, and moreover on the export market, on which volumes have increased by 31%, as compared with 22% for flat steel products. Assuming a downward trend in imports as a result of the beneficial ambition for French industry of relocating industry back to France, production levels increase by 14% and 31% respectively for flat products and for stainless steel and high alloy products. On the other hand, the less favourable export dynamic for long carbon steel products, does not enable this traditional sector to increase its level of production, whose outlets have diversified to compensate for the downturn in the building and civil engineering sector. In 2050, the level of production has therefore stabilised as compared with the level estimated in 2022.

4.3.2. An Ambitious Transition to Hydrogen-based Direct Reduction to Replace Blast Furnaces

In this scenario, the whole of French blast furnaces are shut down by 2035. Electric arc furnaces (EAF) are built at equal capacity to replace them (11 Mt), since production levels remain stable over the long term. These furnaces transform scrap and direct reduced iron (DRI) into steel, whether or not it is produced on site. In total, **due to the competitiveness of the supply of hydrogen in France, three direct reduction furnaces (DRP) are opened in 2026, 2027 and 2035 producing 6.8 Mt of DRI or HBI in 2050.** The first initially runs on natural gas, which is progressively replaced with hydrogen by 2035. The other two are, from the outset, run on hydrogen. These DRPs have the theoretical capacity to cover almost all of France's DRI and HBI requirements, so as to maintain an almost even HBI trade balance, with a view to national sovereignty.
In addition, favourable conditions of access to low-carbon electricity enable the existing EAF sector to become more electrified. They develop the recarbonation of slags from 2031, and also replace coal with up to 50% waste plastics by 2043.

The scenario achieves a 95% reduction in annual direct emissions from the French steel industry by 2039, as compared with 2015 (Figure 85). In cumulative total, 144 $MtCO_2$ are emitted between 2023 and 2050, i.e. 71% less than if emissions had remained constant at their 2022 level. Of these cumulative reductions in emissions totalling 386 $MtCO_2$, three quarters (292 $MtCO_2$) are attributable to the replacement of blast furnaces by electric arc furnaces. Nevertheless, this transition is accompanied by the cumulative emission of 11 $MtCO_2$ due to the production of DRI using natural gas until 2035. By comparison, other technological changes have little impact on this reduction in emissions. Increasing the proportion of scrap and the injection of coke oven gas nevertheless make it possible to reduce cumulative emissions by around 17 $MtCO_2$ between the present and the complete closure of the blast furnaces in 2035.



Key for interpretation: *By 2040, the changes having taken place since 2022 have resulted in a cumulative net reduction in annual emissions as compared with 2022, due to significant downward effects (-17 $MtCO_2$/year), inherited principally from the replacement of blast furnaces by EAFs (completed in 2035) [55], which greatly outweigh the upward effect (+0.7 MtCO2/year) due to successive changes in production.*

Figure 85. Hydrogen Bet scenario - Breakdown of changes in annual CO_2 emissions between 2022 and 2050

The investments undertaken amount to 13 billion euros, principally for the DRI-EAF route. The construction of DRPs and electric arc furnaces, in 2027 and 2035, accounts for three quarters of the 6.3 billion euros invested between the present and 2050 (Figure 86). To this total, must be added 6.6 billion euros of external investment for the construction and replacement of the electrolysers to produce hydrogen in order to fuel the DRPs. For its part, the decarbonisation of existing electric arc furnaces, between 2026 and 2050, represents 1.3 billion euros, that is to say a fifth of total non-electrolysis investments, principally due to the development of induction furnaces.

[55] Among these downward effects, the non-ascribed effects are inherited from the effects of the increase in the proportion of scrap in converters and from the injection of coke oven gas, which are rendered obsolete when the blast furnaces are closed.

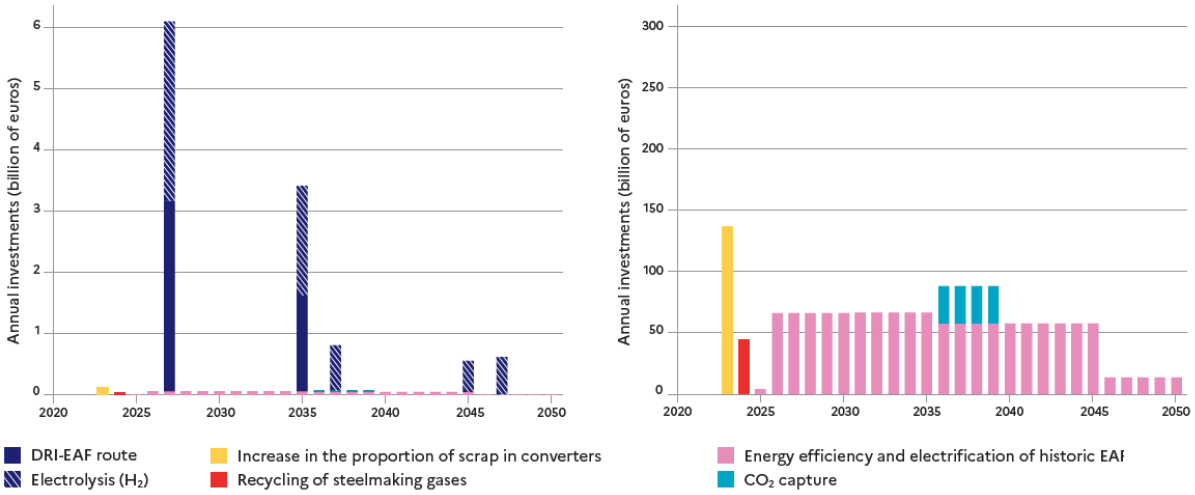


Figure 86. Hydrogen Bet Scenario - Annual investment timelines, all investments combined (left) and non-DRI-EAF route investments (right)

Conditions for success

The success of the *Hydrogen Bet* scenario depends on a number of assumptions and conditions.

- It requires access to **low-carbon hydrogen at a competitive cost**, which means securance of the supply of low-carbon electricity and adaptation of the electrical power system to meet a fivefold increase in demand (see section 3.3).
- It requires long-term securance of **sources of scrap** in order to withstand sharply increased demand.
- It assumes sufficient availability of **water resources** for water electrolysis, which could be restricted in a situation of global warming.
- Finally, the DRI-EAF route requires a supply of **high-quality iron ore**[56].

For further details:

- The DRP-H_2 / EAF route is particularly electricity-intensive, but is capable of providing opportunities for voluntary contributions to load-shedding without halting production. Indeed, certain DRPs are capable of operating with a flexible mix of hydrogen or (bio)methane, enabling consumption of (bio)methane during hours of peak demand for electricity.
- The use of hydrogen storage in salt caverns would also enable the provision of electrical flexibility for many hours. This could be the case at Fos-sur-Mer due to its proximity to the potential storage site at Manosque, but the use of this site could come into competition with other uses, such as e-fuel production.
- Lastly, the consumption of hydrogen whose production does not involve use of the local electrical power system would make it possible to reduce the load on the grid. The solutions that can be mobilised include the importation of hydrogen via hydrogen pipelines, the production of low-carbon hydrogen using processes other than electrolysis (e.g. plasma pyrolysis of methane), and the exploitation of geologic hydrogen deposits.

4.4. "Reduced Competitiveness" scenario: in the face of the lack of competitiveness of energy prices in France, decarbonisation of the steel industry is based on the relocation of production abroad and CO2 capture, rather than the excessively expensive use of hydrogen.

4.4.1. A marked decline in production due to relocation of industry abroad, despite increased consumption

In this scenario, French steel consumption increases by 6% between 2022 and 2050. It envisages an intensification of current consumption patterns and therefore an increased demand for steel, notably for transport and packaging (+13%), despite a decline in the building and civil engineering industry (-17%). Moreover, this increase in consumption is greater for products from the historical electrical sector (+11%) than for flat products from the primary sector (+3%).

The competitiveness of the European steel industry is eroded in the face of competitors outside the EU that adopt the DRP-H_2 / EAF route, benefiting from low-cost renewable electricity and iron deposits. In 2050, steel imports have increased by 12% and exports have fallen by 49% as compared with 2022, intensifying the deterioration in the trade balance for steel

[56] The use of Submerged Arc Furnaces (SAF) would enable this limit to be exceeded, but they are less mature and have not been modelled.

(difference between tonnes of steel imported and exported) observed in France between 2014 and 2019. Moreover, rising demand for energy equipment does not benefit French steelmakers, since for the most part it continues to be imported. In Figure 87, this corresponds to the rise in indirect steel imports (i.e. imports of manufactured products containing steel), stimulated by the high level of demand for energy equipment. French steel production is severely affected by these problems of competitiveness, so much so that capacities are closed down.

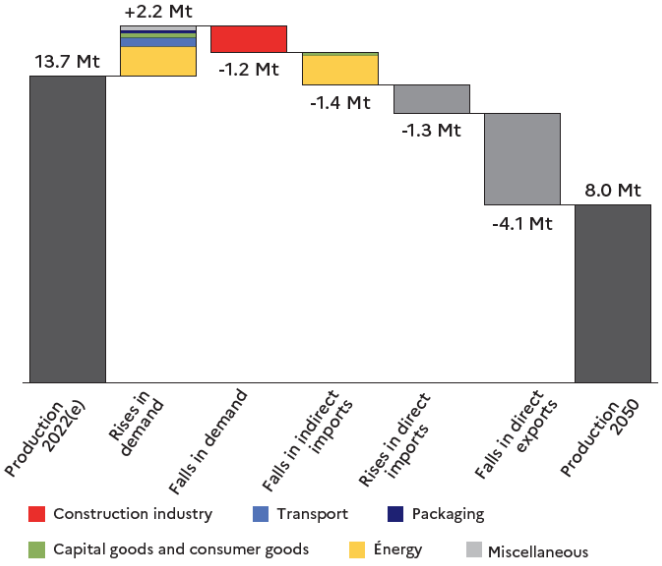


Figure 87. Reduced Competitiveness scenario - Breakdown of changes in steel production between 2022 and 2050

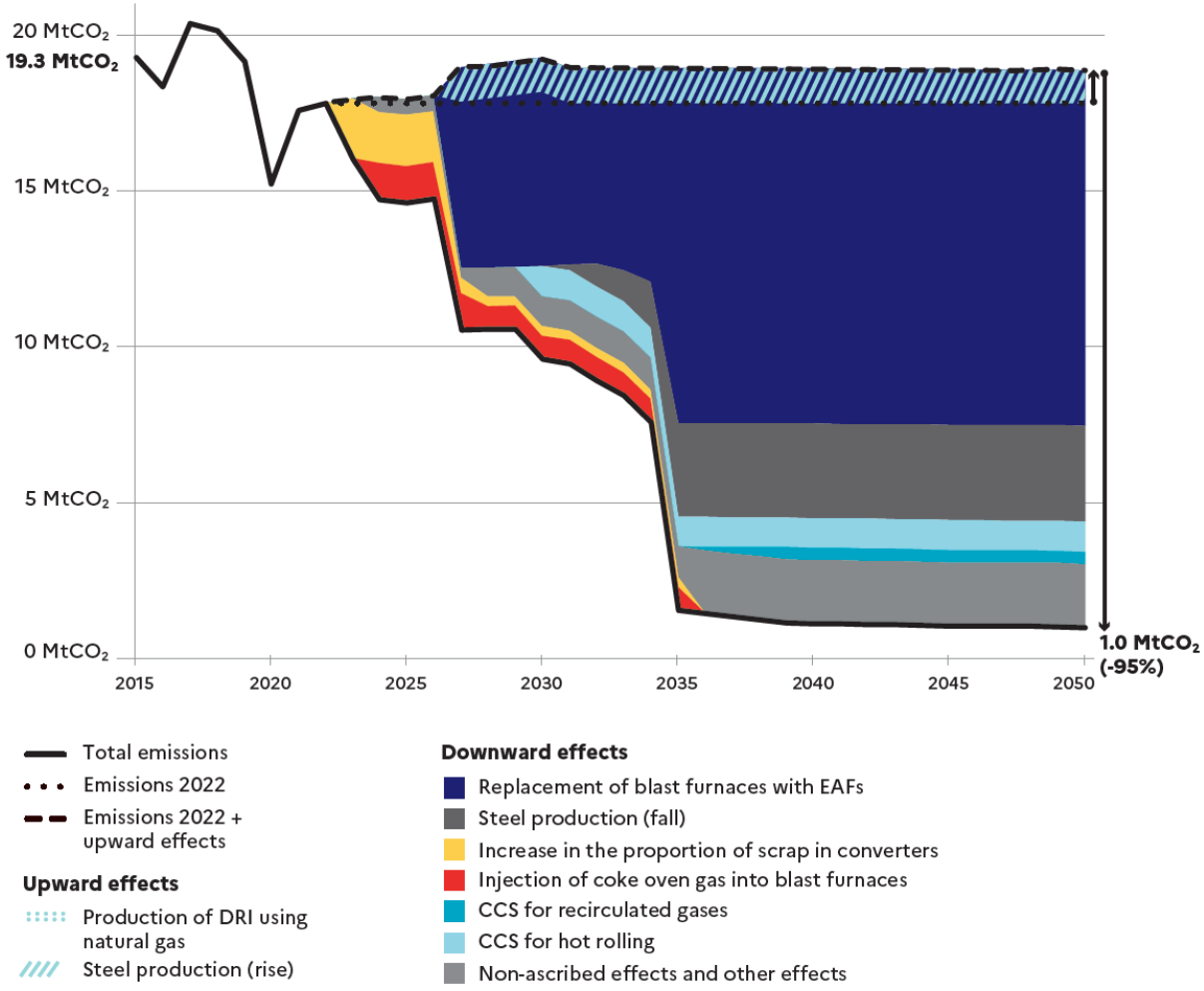
Beyond this general observation, it should be emphasised that, on the basis of the trends observed between 2014 and 2019, the deterioration in competitiveness is less marked for stainless steel and high alloy products than for long carbon steel and flat products, due to their positioning on more specific markets for which the price criterion carries relatively less weight. By way of example, export volumes are assumed to have been reduced by around 50% for long carbon steel and flat products, as compared with 14% for stainless steel and high alloy products. **Ultimately, outputs of primary steel, long steel products, and stainless and high-alloy steels thus respectively fall by 48%, 34% and 5%.**

4.4.2. A technological transition from blast furnaces to electric arc furnaces, incorporating limited national DRI production based on the use of natural gas and CO_2 sequestration

In this scenario, the DRP-H_2 / EAF route is compromised due to the lack of competitiveness of low-carbon hydrogen in France. **Blast furnaces are thus replaced by electric-arc furnaces**, which make it possible to exploit sources of scrap, and also use imported HBI, in order to meet the relatively restrictive requirements of the primary sector's clients with regard to the virgin iron content of the steel (30% incorporated scrap).

DRI is nevertheless produced in France, with a view to mastery of the value chain, in particular in view of the strategic uses of steel (e.g. energy system, defence etc.). However, economic conditions do not allow it to be run on hydrogen: it therefore remains fuelled by natural gas. To guarantee its decarbonisation, a CO_2 capture plant is set up by 2030, and the CO_2 is transported for geological storage in the North Sea. Existing electric arc furnaces, for their part, show little decarbonisation, apart from the energy efficiency gains common to all scenarios. Nevertheless, by 2035, 30% of coal consumption has been replaced by plastic waste.

The changes in emissions from the French steel industry are similar to those of the *Hydrogen Bet* scenario. **Annual direct emissions have been halved by 2030 and reduced by 95% by 2050 as compared with 2015** (see Figure 88). In cumulative total, 155 MtCO2 are emitted between 2023 and 2050, that is to say 69% less than if emissions had remained constant at 2022 levels. Of these cumulative reductions in emissions (totalling 372 MtCO2), two thirds (235 MtCO2) are attributable to the replacement of blast furnaces by electric arc furnaces, as a result of the development of the DRI-EAF route. The choice of natural gas-based reduction results in the production of around 1 $MtCO_2$/year, which is, for the most part, captured and stored. Nevertheless, in contrast to the *Hydrogen Bet* scenario, a significant proportion (14%) of the emission reductions is connected with the relocation of production abroad, which saves around 3 $MtCO_2$/year within French territory.



Key for interpretation: *In 2040, the whole the changes having taken place since 2022 have resulted in a cumulative increase in annual emissions of 1.1 $MtCO_2$/year as compared with 2022 (due to the production of DRI using natural gas [57]) and a cumulative decrease of -18 $MtCO_2$/year (including in particular CO_2 capture in the DRP)* [58].

Figure 88. Reduced Competitiveness scenario - Breakdown of changes in annual CO_2 emissions in cumulative effect between 2022 and 2050

In this scenario investments of 2.6 billion euros are mobilised between the present and 2050, which is relatively little as compared with the other scenarios, due to a fall in production capacity and weaker technological development. The construction of the DRP and EAFs in 2027 (1.9 billion euros) accounts for three quarters of this amount (see Figure 89). For its part, the development of CO_2 capture, in particular in the DRP, represents 265 million euros of investment (10% of the total).

[57] This increase in emissions is for the most part theoretical since, of this production of 1.1 $MtCO_2$/year, 0.96 $MtCO_2$/year is in practice captured.

[58] Among these downward effects, the non-ascribed effects are inherited from the effects of the increase in the proportion of scrap in converters and from the injection of coke oven gas, which are rendered obsolete when the blast furnaces are closed.

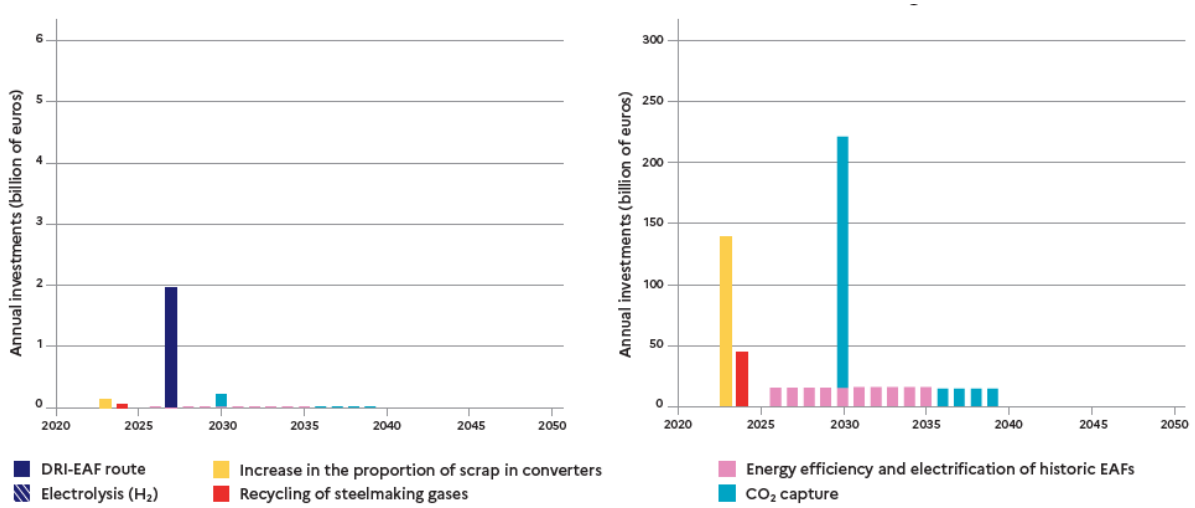


Figure 89. Reduced Competitiveness Scenario - Annual investment timelines, all investments combined (left) and non-DRI-EAF route investments (right)

Conditions for success

The success of the *Reduced Competitiveness* scenario depends on a number of assumptions and conditions.

- It makes it necessary to guarantee **free trade** on the basis of relations of **trust** between importing and exporting countries. Indeed, this scenario follows a logic of regional specialisation, in which countries with cheap, low-carbon energy become the primary producers and exporters, while other countries, including France, become importers, relinquishing part of their sovereignty.
- For the same reasons, it presupposes that steel-producing countries successfully complete their ecological transition (low-carbon electricity production, infrastructures, etc.), **at the risk of importing steel with a higher carbon footprint** than domestic production.
- It also relies largely on CO_2 capture and storage, whereas alternative technologies could make it possible not to produce CO_2.

For further details:

In order to aim at negative net emissions, the DRP, whose emissions are captured and stored, could incorporate a fraction of biomethane. In the event of CO_2 leaks occurring at any point within the capture, transport and storage infrastructures, this would moreover make it possible, to delay, if not cancel out the re-emission of the captured biogenic carbon, well beyond the restoration time of the removed biomass. However, this integration has to comply with the prioritisation of uses of biomass, whose availability is limited.

4.5. "Sobriety and Diversification" scenario: multiple technological routes accompanied by sobriety measures

4.5.1. A fall in production connected with real estate sufficiency, despite a net investment in relocation of certain economic activities in France

In this scenario, **French steel consumption falls by 20% between 2022 and 2050, due to a rapid expansion of sufficiency, particularly land sufficiency** (connected with the *No Net Land Take* target). Demand for steel in the building and civil engineering industry and the transport industry is thus halved as a result of a fivefold reduction in new buildings and changes in mobility. However, this downturn is partly offset by increased demand for steel for the deployment of renewable energies (x3) (Figure 90).

Steel imports and exports between France and other countries contract by about a third, and the trade balance for steel becomes even again by 2050, due to a will to relocate production back to France and increased transport costs. Any remaining trade takes place at the European level. Moreover, major investment in relocating the production of wind turbines (75% in France) and photovoltaic panels (40% in France) back to France, makes it possible for a large proportion of the increase in demand from the energy sector to be catered for by French steelmakers, particularly in the stainless steel and high alloy sector. In Figure 90, this corresponds to the rise in indirect steel imports (i.e. imports of manufactured products containing steel), stimulated by the high level of demand for energy equipment, but on a scale that is greatly limited by the investment made in relocation of production back to France.

Sufficiency measures thus lead to a decline of 20% in French production of primary steels and long steel products, but industrialisation of the manufacture of renewable energy generation equipment in France boosts the output of stainless steel and high alloy products by 43%.

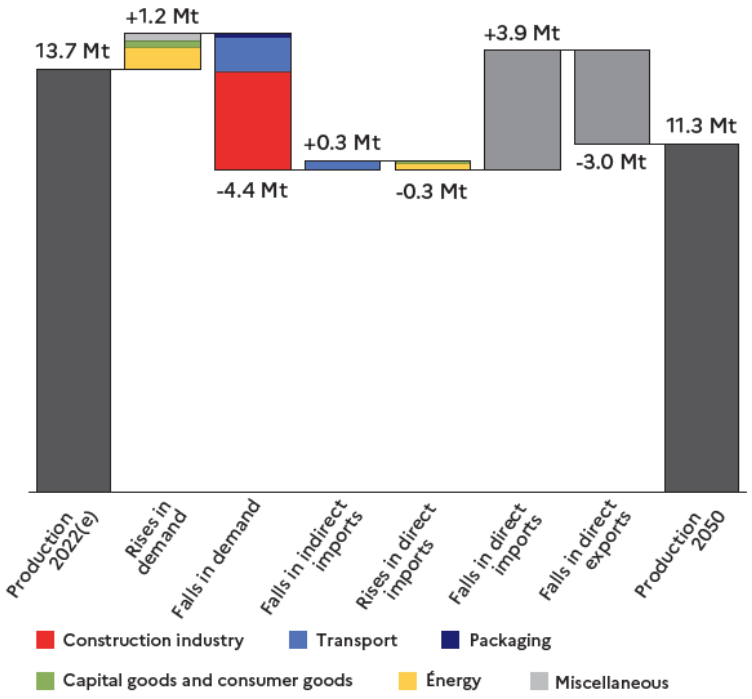


Figure 90. Sobriety and Diversification scenario - Breakdown of changes in steel production between 2022 and 2050

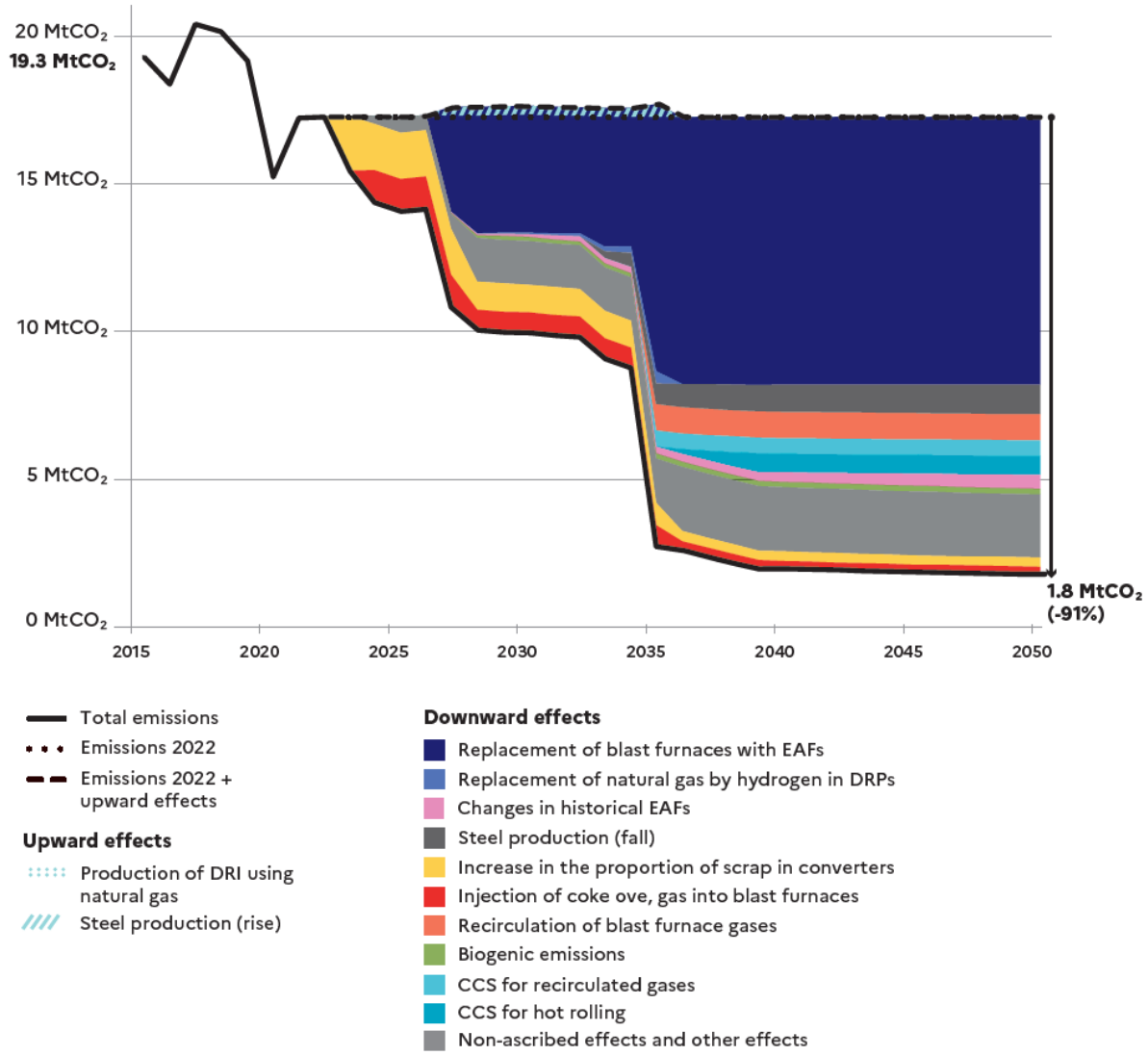
4.5.2. Diversified technological decarbonisation with the maintenance of a blast furnace, hydrogen-based direct reduction, and iron electrolysis.

The technological routes are diversified in such a manner as to anticipate their risks and therefore maximise the chances of the successful completion of decarbonisation of the steel industry. In the first place, a part of the blast furnace facilities is maintained, with a production capacity of 2 Mt of pig iron, and is decarbonised to the extent of 61% by means of a slight increase in the proportion of scrap used[59], the replacement of 15% of the coal injected into the blast furnace with biochar (2029) and the injection of coke oven gas (2024), followed by the recirculation of blast furnace gas with separate CO_2 capture and storage (2035). At the same time, the DRI-EAF route is progressively developed, in 2026 and then in 2035, through the opening of 6.4 Mt of electric arc furnace capacity, which is partly supplied with DRI *via* the construction of 2.9 Mt of DRP reactor capacity. Furthermore, existing electric arc furnaces are decarbonised via improvement their energy efficiency, their electrification and the total replacement of fossil coal consumption by 2043 with a mix comprising 50% waste plastics and 50% biochar. Existing electric arc furnaces also use virgin iron, in the form of HBI (8% by 2050), and iron produced by electrolysis (17%). Lastly, a number of small direct iron electrolysis facilities are opened between 2033 and 2045, cumulatively reaching a capacity of 0.75 Mt. This makes it possible to avoid constraints with regard to sources of scrap (in terms of quantity and quality) and potentially to diversify outlets by entering markets requiring the highest grades of steel. As considered in this scenario, iron electrolysis is therefore a lever not for decarbonisation (which could have been applied to replace blast furnaces) but for mastering the quality of steel in the electrical sector. This technology is therefore not shown in Figure 91, which only presents direct emissions from the steel industry (excluding, in particular, those associated with electricity consumption).

Annual direct emissions from the French steel industry have been halved by 2030 and reduced 91% by 2050 as compared with 2015 (see Figure 91). In cumulative total, 169 $MtCO_2$ are emitted between 2023 and 2050, that is to say 65% less than if emissions had remained constant at 2022 levels. *Sobriety and Diversification* therefore has slightly higher emissions than the other scenarios, due to the perpetuation of a blast furnace, but still exceed the SNBC 2 target for industry (-81% annual emissions). Of the 318 $MtCO_2$ of cumulative emissions reductions, 56% (235 $MtCO_2$) remains attributable to the replacement of blast furnaces by electric arc furnaces, due to the development of the DRI-EAF route, which saves 9 $MtCO_2$/year by 2050. The recirculation of blast furnace gas and CO_2 capture and storage represent 10% of these reductions, saving around 2

[59] The proportion of scrap in the converter is not maximised in order to promote the use of newly-built electric arc furnaces and maintain a sufficient rate of use (>80%) for the remaining blast furnace.

$MtCO_2$)/year for the remaining blast furnace route facilities. Lastly, the contribution of sufficiency measures in this scenario (reduced production) amounts to 5% of emissions reductions, saving around 1 $MtCO_2$/year.



Key for interpretation: *By 2040, the whole of the changes having taken place since 2022 have resulted in a cumulative reduction of 15 $MtCO_2$/year in annual emissions as compared with 2022, principally due to the replacement of blast furnaces by electric arc furnaces*[60].

Figure 91. Sobriety and diversification scenario - Breakdown of changes in annual CO_2 emissions in cumulative effect between 2022 and 2050

This scenario requires a total investment of 7 billion euros. Due to more moderate development of the DRI-EAF route, the 2.4 billion euros that it requires (DRP and EAF) only represent half of the 4.5 billion euros invested in the steel industry, with the addition, however, of 2.5 billion euros for the construction and replacement of electrolysers by energy players. For its part, the decarbonisation of existing electric arc furnaces between 2026 and 2050 represents 29% of investments in the steel industry, principally due to the development of induction furnaces. By comparison, the rest of the decarbonisation of the primary route and the development of direct iron electrolysis only represent 12% and 5%, respectively, of investment in the steel industry.

[60] Among these downward effects, the non-ascribed effects are inherited from the effects of the increase in the proportion of scrap in converters and from the injection of coke oven gas, which are rendered obsolete when the blast furnaces are closed. Biogenic emissions correspond to emissions connected with the incorporation of biochar.

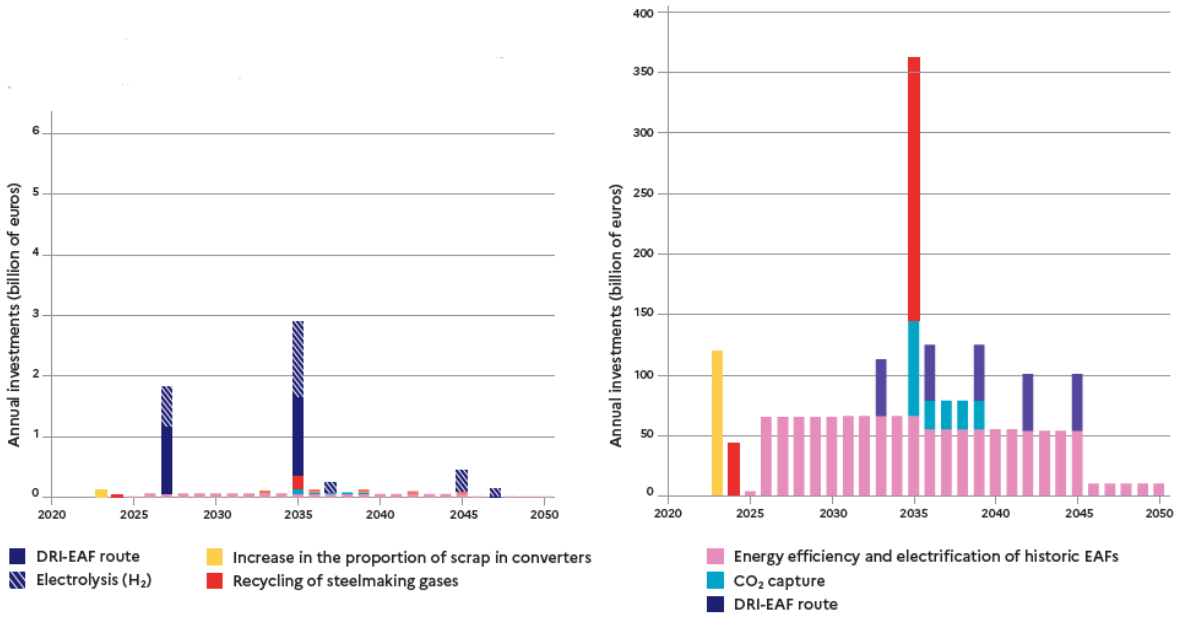


Figure 92. Sobriety and Diversification scenario - Annual investment timelines, all investments combined (left) and non-DRI-EAF route investments (right)

Conditions for success

The success of the *Sobriety and Diversification* scenario depends on a number of assumptions and conditions.

- It presupposes significant **sufficiency** measures, particularly with regard to land, involving optimised use of existing buildings (e.g. mobilisation of vacant housing).
- It is based on the successful development of a larger number of non-mature technologies than in the other scenarios, such as direct iron electrolysis.

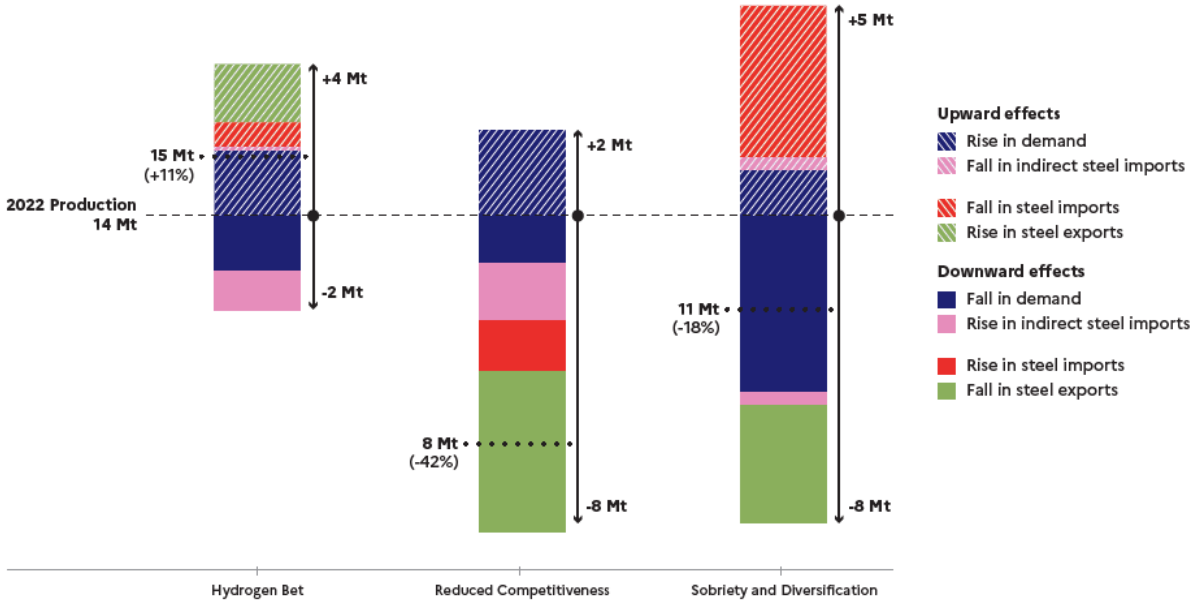
For further details

- In order to maximise the decarbonisation of the steel industry, all blast furnaces could be closed, as in the other scenarios, and replaced by plants based on iron reduction using hydrogen or (bio)gas coupled with CCS, or direct iron electrolysis.
- At the same time, more ambitious development of direct iron electrolysis could have been considered, going beyond a simple additional supply of virgin iron for existing electric arc furnaces. Indeed, the modular nature of these facilities would make it possible to decentralise the primary sector throughout the country, thus dividing the load on the power grid and the pressures on water resources, while reinforcing capacity for adaptation to climate risks. The interruptibility of these facilities would also make it possible to even out the load on the electrical power system.

5. Comparative Analyses of Prospects for Decarbonisation of the Steel Industry

5.1. Production

Steel production increases in the *Hydrogen Bet* scenario alone (+11% between 2022 and 2050), thanks to generally stable demand and investment in relocation of production back to France. Conversely, production declines the most in the *Reduced Competitiveness* scenario (-42%), due to relocation of the steel industry abroad (increase in imports and decrease in exports), despite a rise in consumption. In the *Sobriety and Diversification* scenario, production is reduced by 18% as a result of sufficiency measures, but significant investment in relocation of production back to France makes it possible to limit the effects thereof on production.



Key for interpretation: *In the Reduced Competitiveness scenario, the sectors making the greatest use of steel are responsible for 2Mt of growth in annual demand for steel between 2022 and 2050 (in blue hatching), which is partially offset by a decline in demand in the other sectors (in blue). The increase of this demand leads to a rise in imports of steel (in red) and manufactured products containing steel (indirect steel imports, in pink), depending on the international trade assumptions, which also cause a fall in steel exports (in green). On balance, steel production falls from 14 Mt in 2022 (broken line) to 14 + 2 – 8 = 8 Mt in 2050 (dotted line), that is to say a fall of 42%.*

Figure 93: Breakdown of changes in annual steel production between 2022 and 2050 according to the effects of demand and international trade, by scenario

5.2. Cumulative Emissions

All of the scenarios exceed the SNBC 2 target of reduction of annual direct emissions by 81% between 2015 and 2050: they are reduced by 95% in the *Hydrogen Bet* and *Reduced Competitiveness* scenarios, and by 91% in the *Sobriety and Diversification* scenario. In all of the scenarios, the closure of blast furnaces and their replacement by DRI-EAF plants is the principal contributor to the reduction in emissions, cumulatively saving from 177 $MtCO_2$ to 285 $MtCO_2$ between 2023 and 2050, according to the scenarios (Figure 94)[61]. The retainment of a blast furnace explains the lesser reduction of emissions in *Sobriety and Diversification*. CO_2 capture and storage is also a lever common to all of the scenarios, in varying proportions: it saves 10 $MtCO_2$ (3% of the downward effects) in the *Hydrogen Bet*, 25 $MtCO_2$ (6%) in the *Reduced Competitiveness*, and 17 $MtCO_2$ (6%) in the *Sobriety and Diversification* scenarios. Lastly, production levels have an appreciable effect on emissions. Production increases in *Hydrogen Bet*, leading to the emission of an additional 22 $MtCO_2$ between 2023 and 2050. Its decline, due to relocation of industry abroad, in *Reduced Competitiveness*, saves 50 $MtCO_2$ within national territory. Similarly, the effect of sufficiency on production in *Sobriety and Diversification* saves 15 $MtCO_2$.

[61] Including emissions connected with the use of natural gas in DRP.

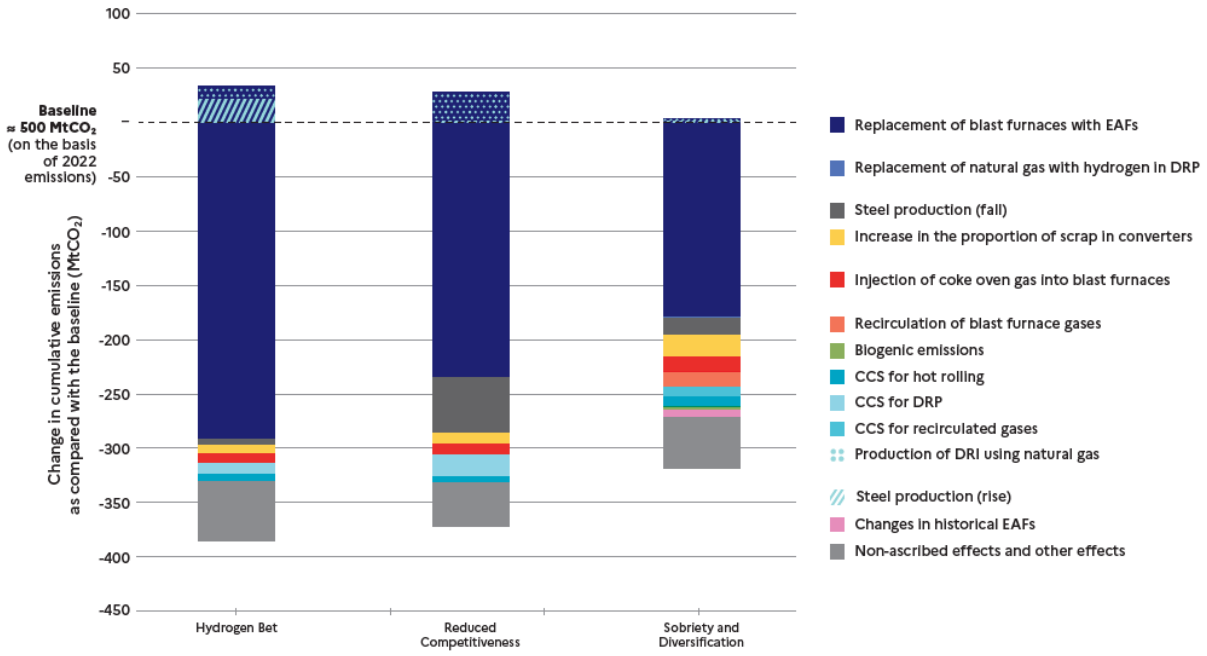


Figure 94: Breakdown of cumulative totals of emissions saved and added between 2023 and 2050, by effect and by scenario[62]

5.3. Investments

The transition to the DRI-EAF route is the most expensive change for decarbonisation of the steel industry, all the more so if investments connected with hydrogen production by electrolysis (hatched in Figure 95) are taken into account. The transition from electric arc furnaces is also particularly costly, due to the installation of induction furnaces. As a result, ***Hydrogen Bet*** **is the scenario calling for the largest investments (12.9 billion euros between 2023 and 2050), of which half are connected with the construction and replacement of electrolysers.** *Sobriety and diversification* calls for lower levels of investment (7 billion euros), of which a third is connected with electrolysis. Lastly, R*educed Competitiveness* requires relatively small investments compared with the other two scenarios, as it does not opt for electrification, either for the DRI-EAF route (reduction by natural gas), or for the decarbonisation of existing electric arc furnaces.

[62] Among the downward effects, the non-ascribed effects are inherited from the effects of the increase in the proportion of scrap in converters and from the injection of coke oven gas, which are rendered obsolete when the blast furnaces are closed.

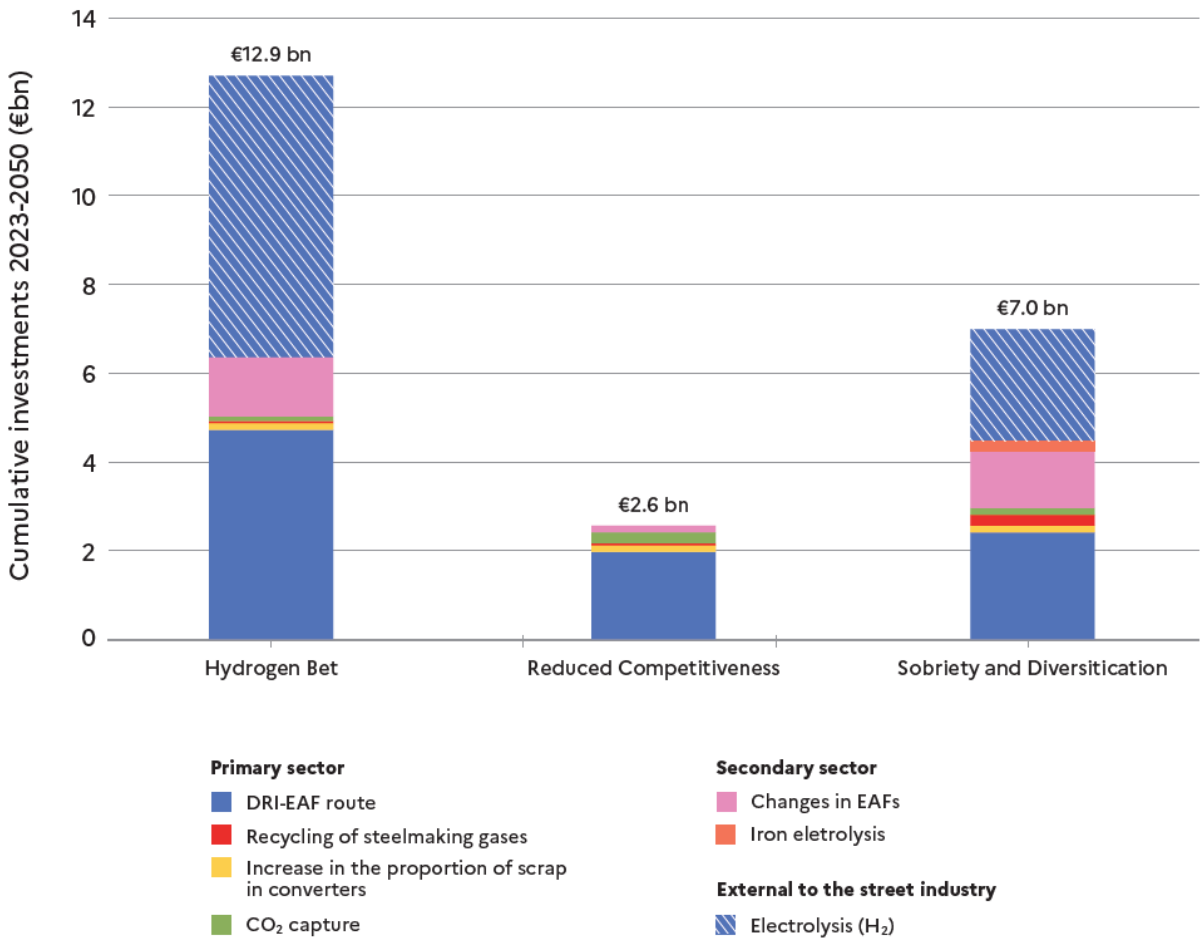


Figure 95: Cumulative investments between 2023 and 2050 in the three scenarios

5.4. Energy

In all scenarios, closure of blast furnaces and transition to the DRI-EAF route lead to the massive replacement of coal by hydrogen or natural gas (in the *Reduced Competitiveness* scenario) in the steel industry's energy mix, although a proportion remains in the *Sobriety and Diversification* scenario with the retainment of one blast furnace (see Figure 96). Due to the production of hydrogen by electrolysis, **the drawing of electricity from the grid for the steel industry is quintupled in *Hydrogen Bet*** (36 TWh in 2050, as compared with 7 TWh in 2022) **and tripled in *Sobriety and Diversification*** (23 TWh in 2050), which benefits from the effects of sufficiency and the maintenance of one blast furnace. Electricity supply is therefore a key constraint in these scenarios, and all the more so in the context of massive electrification connected with the ecological transition. Due to these constraints a transition to direct reduction using natural gas is considered in the *Reduced Competitiveness* scenario, which results in the tripling of mains gas consumption between 2022 and 2050, but a reduction in electricity consumption (-5% between 2022 and 2050)[63].

[63] Consumption of natural gas also increases in the Hydrogen Bet scenario (+33%). Indeed, the transition to the DRI-EAF route deprives rolling mills of access to steelmaking gases, which are replaced by natural gas.

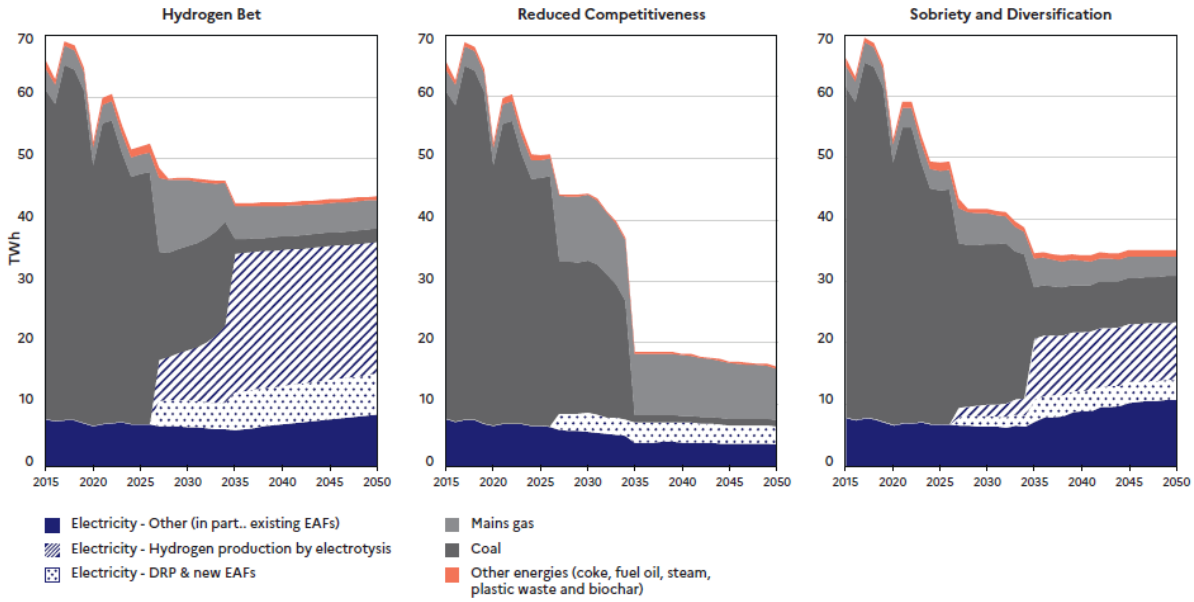


Figure 96. Changes in energy consumption in the three scenarios between 2015 and 2050

5.5. Scrap

The supply of scrap represents the second major constraint to decarbonisation of the steel industry. In *Hydrogen Bet*, consumption of external scrap[64] has grown by 59% by 2050 as compared with 2022 (Figure 97). This increase is driven by the primary sector, where the proportion of scrap is 40% in 2035, as compared with 15% today, so much so that the share of external scrap consumed by the primary sector rises from 10% to 40% between the present and 2035, revealing new competition with the secondary sector. In *Sobriety and Diversification*, scrap consumption also rises sharply between the present and 2030 (+53% as compared with 2022), due to greater incorporation of scrap (50% from 2040), but the sufficiency measures make it possible to limit the increase to +21% in 2050. Conversely, the quantity of scrap consumed in *Reduced Competitiveness* falls by 15% as compared with 2022, due to the relocation of production abroad and a low level of incorporation of scrap into primary steel (30%). France's scrap metal reserves should be sufficient, but trade in scrap, for its part, needs be adapted to these requirements. Today, more than half of France's scrap is exported, due to excessively low quality and the overly high cost of re-sorting and decontamination, while a part of requirements is imported[65]. If this export rate were to be maintained (in the absence of the establishment of protectionist export measures), **the French steel industry would have to import 3.6 times more scrap in the *Hydrogen Bet* scenario (4.3 Mt in 2050), as compared with today, and 2 times more in the *Sobriety and Diversification* scenario.** In contrast, in the *Reduced Competitiveness* scenario, almost no imports would be required from 2040 onwards.

[64] As opposed to internal scrap, which corresponds to the recovery of production scrap (pre-consumer waste), external scrap is collected and recycled (post-consumer) steel waste.

[65] See ADEME, Pierrick DRAPEAU, Louis OLLION, and Guillaume BOUYER. 2023. *Étude du potentiel de recyclage de l'acier, de l'aluminium et du cuivre en France* [Study of the potential for recycling steel, aluminium and copper in France]. 206 pages.

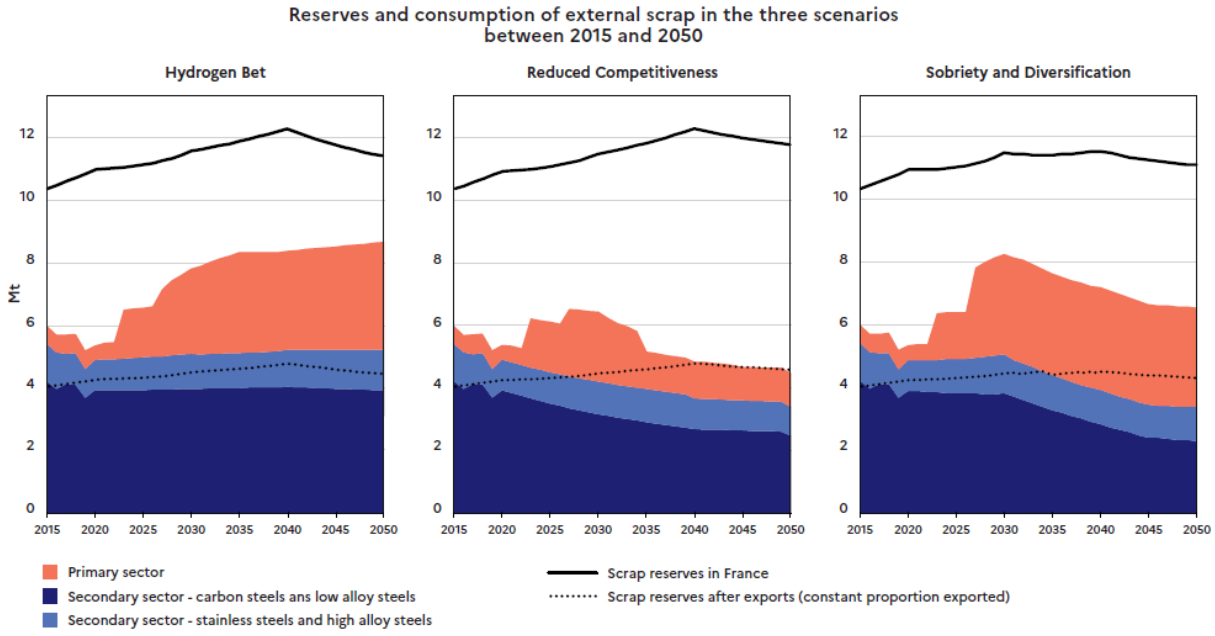


Figure 97. Reserves and consumption of external scrap in the three scenarios between 2015 and 2050

5.6. Value Chains

Historically, steelworks have been established close to iron ore and coal resources. Due to the drying up of these resources, steelmaking sites in Europe gradually moved closer to port areas in order to be able to take delivery of raw materials from foreign countries. The climate imperatives that increasingly weigh upon the industry have henceforth paved the way for a potential new reorganisation of the steel value chain. The ecological transition of the steel industry is reshaping the international steel value chain, notably by introducing HBI as an intermediate processed material. Like the production of ammonia and efuels, the production of direct reduced iron (HBI) – and even direct steel production – makes it possible to take advantage, by means of exports, of the favourable conditions for hydrogen production specific to certain countries (e.g.: availability of energies produced by means of wind or photovoltaics).

A certain number of institutional and academic studies consider that it would be relevant from a technical and economic point of view to separate the stage of production of primary iron in the form of DRI or HBI (the most high-emission and energy-intensive forms) from the steel preparation and processing stage (cf. Text Box 5). This arrangement is illustrated in *Reduced Competitiveness*, in which the majority of the steel is directly imported, as is a large proportion of the HBI (Figure 98).

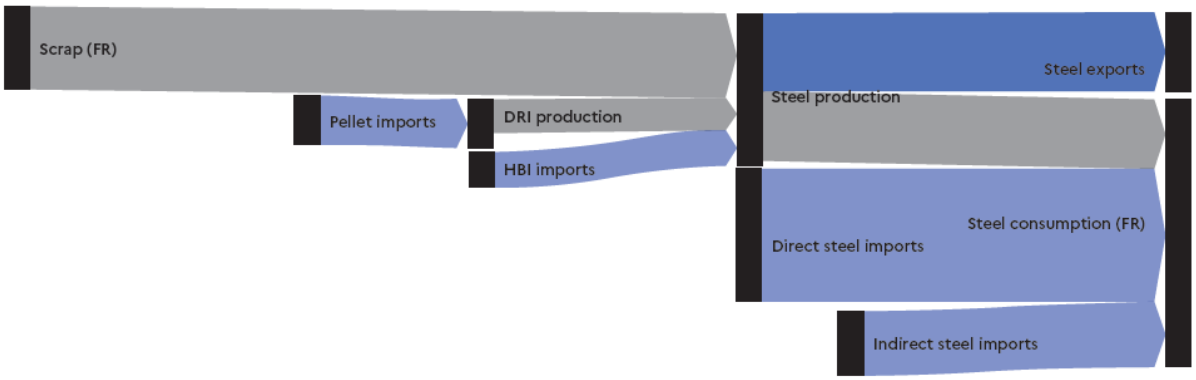


Figure 98. Reduced Competitiveness scenario - Steel value chain in 2050

Text Box 5: An internationalised value chain?

Historically, steelworks have been established close to iron ore and coal resources. Due to the drying up of these resources, steelmaking sites in Europe gradually moved closer to port areas in order to be able to take delivery of raw materials from foreign countries. The climate imperatives that increasingly weigh upon the industry have henceforth paved the way for a potential new reorganisation of the steel value chain. In order to decarbonise, it is widely accepted in the scientific literature that the primary sector will need sources of decarbonised energy at a competitive price and good quality iron ore for the production of DRI. Certain regions of the world have comparative advantages of this kind as, for example, in the cases of Brazil, South Africa and Australia. More and more institutional and academic studies thus support the idea that it would be relevant from a technical and economic point of view to separate the stage of production of primary iron in the form of DRI or HBI (the most high-emission and energy-intensive forms) from the steel preparation and processing stage. A foresight study conducted in 2022 by the Shell corporation illustrates, as an example, a configuration of the value chain of this kind for the period up to 2050. It is important to note that under these new conditions, Europe (with the possible exception of Sweden) would become an importing region for direct reduced iron and would "content" itself with producing steel from HBI and scrap."

One technical and economic study compares 12 typologies of steel export value chains between Australia (producer country) and Japan (consumer country) [177]. According to the authors, export of energy and mineral resources for steel production in the consumer country would be less efficient in terms of energy consumption than a scenario in which primary steel production were located close to the mining of mineral resources and to the generation of renewable energy. Moreover, the average cost of steel would be 45% higher in the first normal case, as compared with 32% in the second.

The technical and economic relevance of five different steel value chains in Europe has also been studied, with the cases of Germany, Spain and Finland [178]. On the basis of the observation that access to inexpensive, decarbonised electricity is the primary competitive factor in the production of low-carbon steel, the production of hydrogen by electrolysis is studied in two locations with conducive abundance of solar energy: Morocco in North Africa and the Atacama Desert in Chile. Among the possible configurations for a decarbonised steel value chain in Europe: low-carbon hydrogen can be exported directly to Europe by pipeline (in the case of Morocco) or by ship in liquefied form (in the case of Chile); hydrogen can be used locally to produce low-carbon DRI, which would then be transported to Europe in the form of HBI for the production of steel, or indeed crude steel could be produced entirely in Morocco or Chile, and European countries would “content” themselves with directly importing it. These configurations are compared with a fully integrated value chain at the European level, from the production of hydrogen from a mix of solar PV/wind renewable energies to the production of crude steel, including the DRI stage. The results of this analysis appear more nuanced than in the study by A. Devlin & A. Yang (2022) [177] or what might be suggested by Shell's foresight vision (2022) [179]. Indeed, G. Lopez et al. (2023) [178] conclude that an integrated decarbonised steel value chain would be capable of being competitive in the face of imports, particularly in countries where the cost of renewable electricity is already low and would be further reduced in the future (as in the case of solar energy in Spain). Of the three European countries studied, Spain indeed appears to be the most economically conducive to a complete H_2-DRI-EAF chain, despite its geographical proximity to Morocco, giving it the benefit of lower hydrogen transport costs. In the most unfavourable case, direct import of crude steel to Spain from Morocco in 2030, would have a cost price representing only 96% of the cost of the same steel produced entirely in Spain. By 2050, this ratio would be 100%, in other words, the two cost prices would be strictly identical. In the case of Germany, the import of HBI or direct import of crude steel from Morocco are the most economically attractive configurations: the final cost price of the steel represents between 85% and 90% of the cost of the same steel produced by an integrated H_2-DRI-EAF chain in Germany. It is also a less costly option than importing hydrogen, whether from Morocco or Chile. The case of Finland is even more marked since all configurations with imports (hydrogen, HBI or crude steel) compete economically with local production which, according to G. Lopez et al. (2023) [178], would imply that Finland seems doomed to become an importer of at least one component of the steel value chain in the future. In addition to the economic relevance that separation of the steel value chain might have, G. Lopez et al. (2023) [178] also see it as an opportunity for the establishment of new trade relations with certain countries in the Global South. Historically, imports of raw materials or minimally processed products from these countries was favoured, but the decarbonisation of certain value chains, including steel, is henceforth an opportunity for several emerging countries to accelerate their development and the transition to decarbonised energies. This is the case for example not only in North Africa, but also in South Africa.

H. Trollip et al. (2022) [180] have indeed studied the case of DRI production from low-carbon hydrogen in South Africa for export to Europe. The article highlights the potential benefits that both regions could derive from a configuration of the value chain of this kind. For Europe, this would make it possible to reduce the levelled costs of production of decarbonised steel, and moreover to make decarbonised electricity more freely available for other uses. For South Africa, the development of this industry would contribute to the country's economic stability by means of diversification of sources of income and improvement of public finances, but it would also provide an opportunity for the transition to a decarbonised economy.

Conversely, as explained in sub-section 4.2, the *Hydrogen Bet* scenario illustrates a configuration in which the public authorities play a decisive role in the reorganisation of value chains by means of support based upon access to low-carbon, competitive electricity, and more generally through policies for maintaining historical and strategic industrial sectors in the country. The involvement of the public authorities in this scenario is part of a structural trend towards the regionalisation of trade flows, in particular in order to limit the vulnerability of industrial sectors to the consequences of global warming on supply chains. As shown in Figure 99, the supply of iron in the form of DRI is thus almost entirely produced in France, enabling the creation of an industrial sector and several hundred jobs in industrial areas undergoing redevelopment in order to meet the challenges of the transition[66]. Only the fixed dependence on pellets from the historical suppliers of iron ores is maintained. Moreover, trade in steel products and scrap is maintained, with European countries in particular.

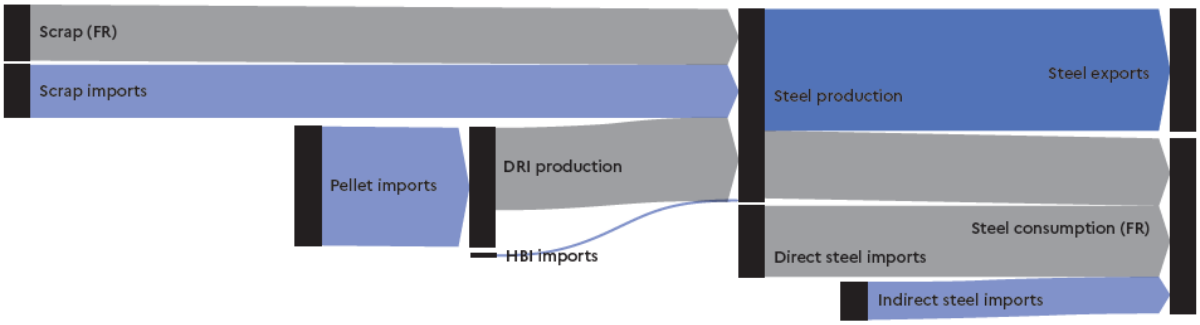


Figure 99: Hydrogen Bet scenario - Steel value chain in 2050

The *Sobriety and Diversification* scenario is also in line with the relocation of flows back to France recalled in *Hydrogen Bet*. On the other hand, it tends to highlight a more diversified strategy in terms of decarbonisation technologies, in particular with a greater proportion of recycling, in order to limit dependence on imports of iron ore to feed the blast furnace (after sintering), iron electrolysis, and pellets for the production of DRI in the country[67] (Figure 100).

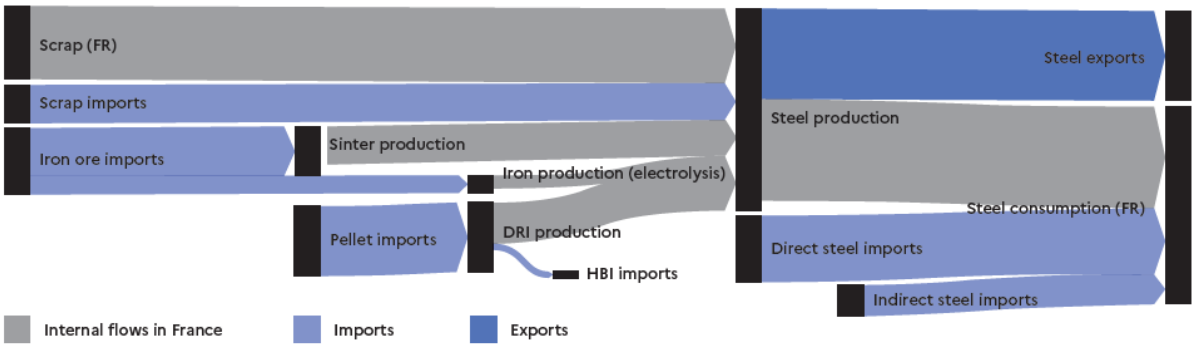


Figure 100: Sobriety and Diversification scenario - Steel value chain in 2050

5.7. Cost of Production

On the basis of a reconstruction of production costs and price trends between 2015 and 2022 (cf. section 3.8), the proportion represented by the purchase of iron ore in the production cost of primary steel[68] is on average 40%, as compared with 31% for coal. However, these average values nevertheless obscure significant variations between years with the rise in the prices of energy inputs and raw materials, and the deployment of new decarbonisation technologies.

[66] DRI is produced by processing pellets, which are imported since they are often produced near the iron ore mine. Emissions connected with pelletisation (a process similar to sintering) are therefore not included in the territorial inventory.

[67] By way of simplification, it is here assumed that DRI/HBI produced in France is consumed in France in priority. In addition, the direct reduced iron produced can be consumed on site or sold elsewhere in France; for this reason purchases of HBI appear in Figure **Erreur ! Document principal seulement.** for *Sobriety and diversification*, even though exports predominate in the trade balance.

[68] Scope of analysis: sites operating the blast furnace and DRI-EAF routes, excluding electrolysers and facilities producing HBI for external use only.

On the basis of the technological pathways modelled in the three scenarios, Figure 101 illustrates changes in production costs at constant prices[69]. A number of observations can thus be made:

- **Energy costs are doubled, in the *Hydrogen Bet* and *Sobriety and Diversification* scenarios**, due to the transition from coal to electricity and hydrogen. On the other hand, in *Reduced Competitiveness*, they are reduced by 30% due to the improved efficiency of iron ore reduction using natural gas and the low price of gas.
- The **cost of ferrous inputs also doubles between the present and 2050 in the *Hydrogen Bet* and *Reduced Competitiveness* scenarios, and increases by 50% in *Sobriety and Diversification*, due to the incorporation of pellets, scrap and HBI**, which are more costly than iron ore.

At constant prices, this structural change thus multiplies the cost of production of primary steel by **1.8**, **1.2** and **1.5** respectively, in the *Hydrogen Bet*, *Reduced Competitiveness* and *Sobriety and Diversification* scenarios.

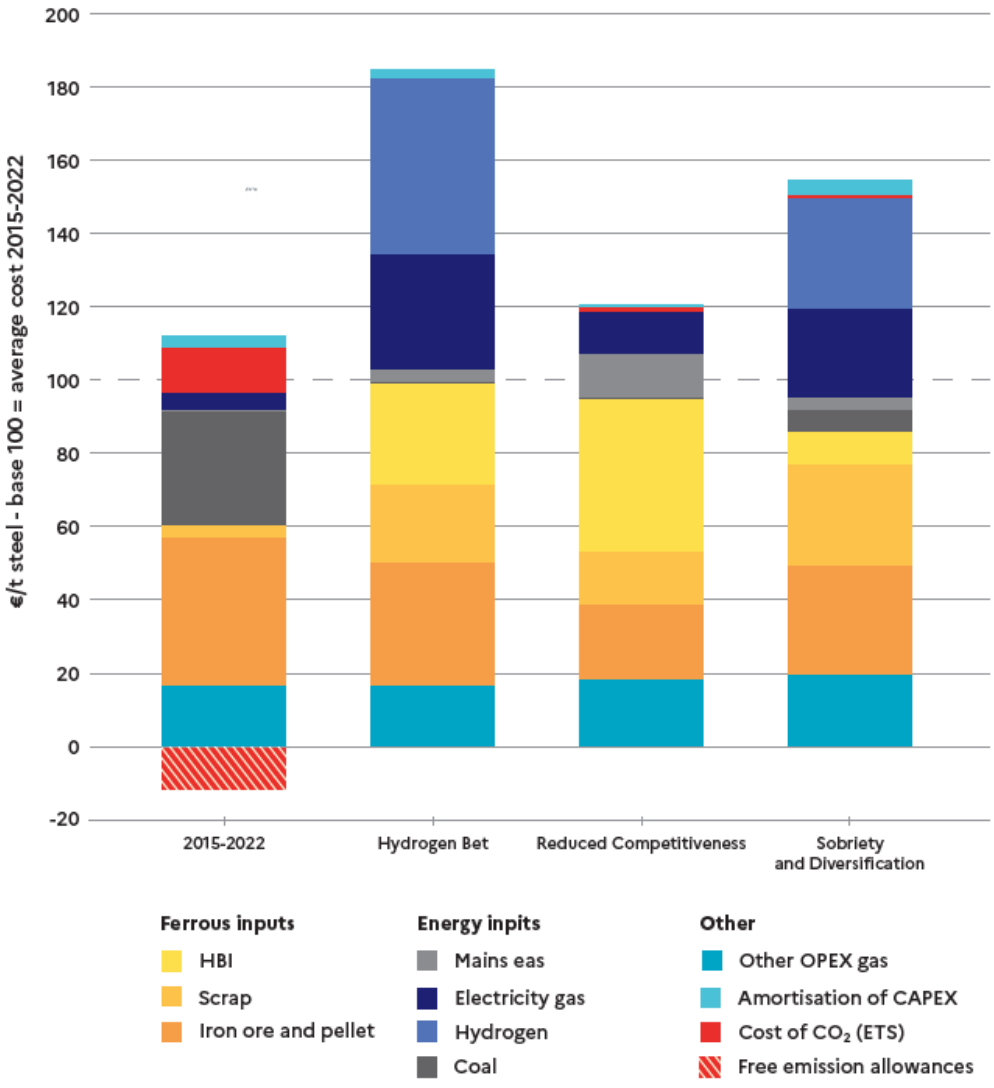


Figure 101: Structural comparison of the production cost of primary steel between today and 2050, in the three scenarios, at constant prices

This fact is only marginally modified when the price change assumptions (cf. Annexe 2) are taken into account. By 2050, the cost of production is then multiplied by a factor of between **1.7 and 2** in *Hydrogen Bet*, **1.2 and 1.5** in *Reduced Competitiveness* and **1.5 and 1.9** in *Sobriety and Diversification* (Figure 102). **These increases nevertheless need to be set against the multiplication of production costs by a factor of between 1.9 and 3.1 were the blast furnace sector's installations to be retained until 2050, due to the rising price of CO_2.** The decarbonisation scenarios therefore appear "cost-effective" in relation to underlying trends from the 2040s. Nevertheless, this is not the case in the short term for the *Hydrogen Bet* scenario, so

[69] Considered in constant prices (for a highly energy-intensive industry): €25/$t_{CO2\ emitted}$; €51/$MWh_{electricity}$; €28/$MWh^{LHV}_{mains\ gas}$; €71/$t_{iron\ ore}$; €124/t_{pellet}; €237/t_{scrap} (2015-2022 averages); €380/t_{HBI} (ADEME assumption); and €42/$t_{CO2\ captured}$. "Other OPEX" corresponds to other operational expenditure (e.g. wages, purchases of ferro-alloys, limestone etc.).

much so that incentive mechanisms appear necessary for the achievement of this scenario, incentives which could also improve competitiveness in relation to low-carbon steel production costs in other countries.

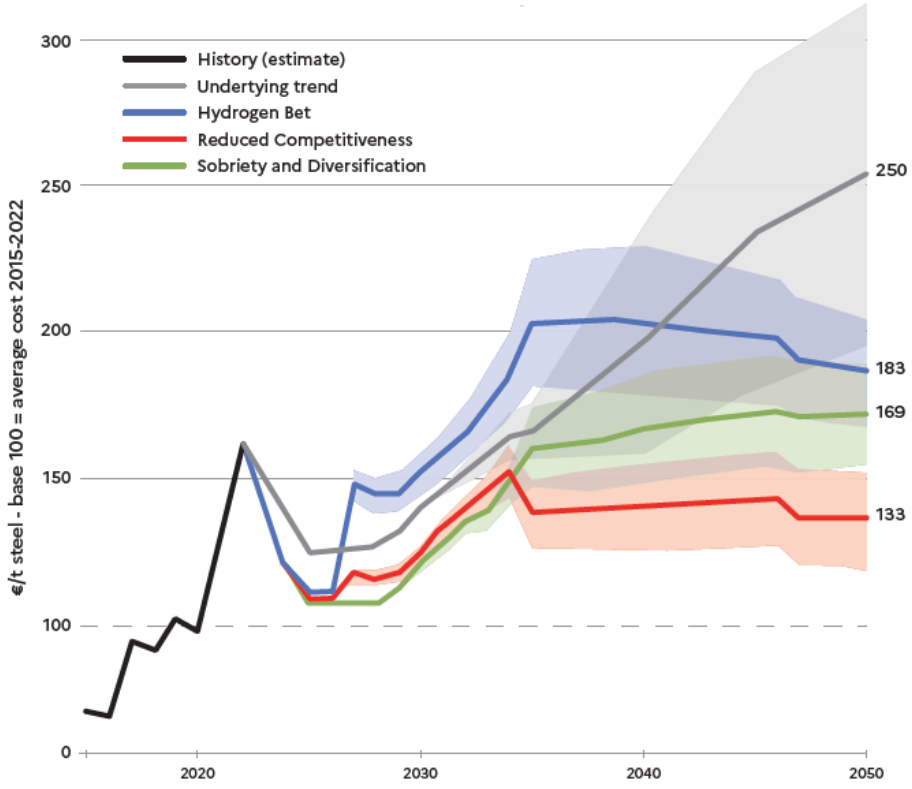


Figure 102: Comparison of production cost levels for primary steel between the present and 2050, in the three scenarios, with changes in prices

5.8. Direct reduction using hydrogen: a highly advantageous technology that remains particularly costly under current price conditions

Independently of the scenarios presented above, which enable dynamic assessment of the costs associated with the deployment of different technologies, a static comparison of the cost of the different technological options provides a valuable indicator for deciding between them (see text box below). In particular, the completion of sensitivity analyses with regard to these costs makes it possible to determine the inputs that have the greatest impact on each technology's profitability, and to identify the thresholds at which one technology becomes cost-effective – or more cost-effective than another.

However, the figures obtained need to be treated with caution; they essentially reveal orders of magnitude and tendencies, but have no predictive value. Indeed, they make it necessary to set certain particularly uncertain assumptions, liable to vary from one player to another and over time, such as the prices of inputs, CO_2 and the anticipated overall rate of return for the projects (discount rate).

Lastly, these economic assessments are not sufficient for deciding between technological options, which requires other considerations to be taken into account, such as their maturity, their environmental value and their consistency with industrial policy choices (e.g. sovereignty, jobs etc.).

In what follows, excess costs and abatement costs are calculated on the basis of a **constant production of 10 Mt of steel** – that is to say a level similar to current annual production in the French primary sector, a project duration of 15 years and a discount rate of 4.5%. Differences in operational expenditure are considered as constant over time, and the price assumptions used to calculate them are identical with the constant prices considered in section 4.1 [70].

[70] With the exception of the price of CO_2, which is taken as €88/tCO_2 (average between 1 January and 26 October 2023).

Method – excess cost and abatement cost of technologies

Two indicators may be used to compare the development cost of technologies: their excess cost and their abatement cost.

The **excess cost** associated with a technology is defined as the difference between the expenditure connected with the application of a technology (the discounted amount, according to a discount rate r, of capital expenditure – CAPEX – and operational expenditure – OPEX, over a fixed period T) and that associated with the maintenance of existing plant (in this case, the blast furnace sector's installations, which also require investments in reconditioning for their prolongation).

This indicator enables assessment of the profitability of a technology. If the excess cost is zero, it is cost-effective at the end of the time of the project. If it is negative, it is cost-effective before the end of the project, and generates a profit. If it is positive, the project is not cost-effective. In particular, if the savings in operating expenditure are too small (or if the $\Delta OPEX$ is positive), a return may never be secured on the investments, whatever the duration of the project.

$$Excess\ cost = \sum_{t=0}^{T-1} \frac{\Delta CAPEX_t + \Delta OPEX_t}{(1+r)^t}$$

The abatement cost of a technology is defined as the excess cost of this technology in relation to the cumulative quantity of CO_2 that it saves over the time of the project, as compared with the situation in which existing plant is maintained.

This indicator can be used to compare the cost-effectiveness of decarbonisation levers with a view to prioritisation, but needs to be supplemented by other indicators such as maturity, the level of decarbonisation enabled by each technology and their coherence with each other[71].

$$Abatment\ cost = \frac{Excess\ cost}{\sum_{t=0}^{T-1} \Delta CO2_t}$$

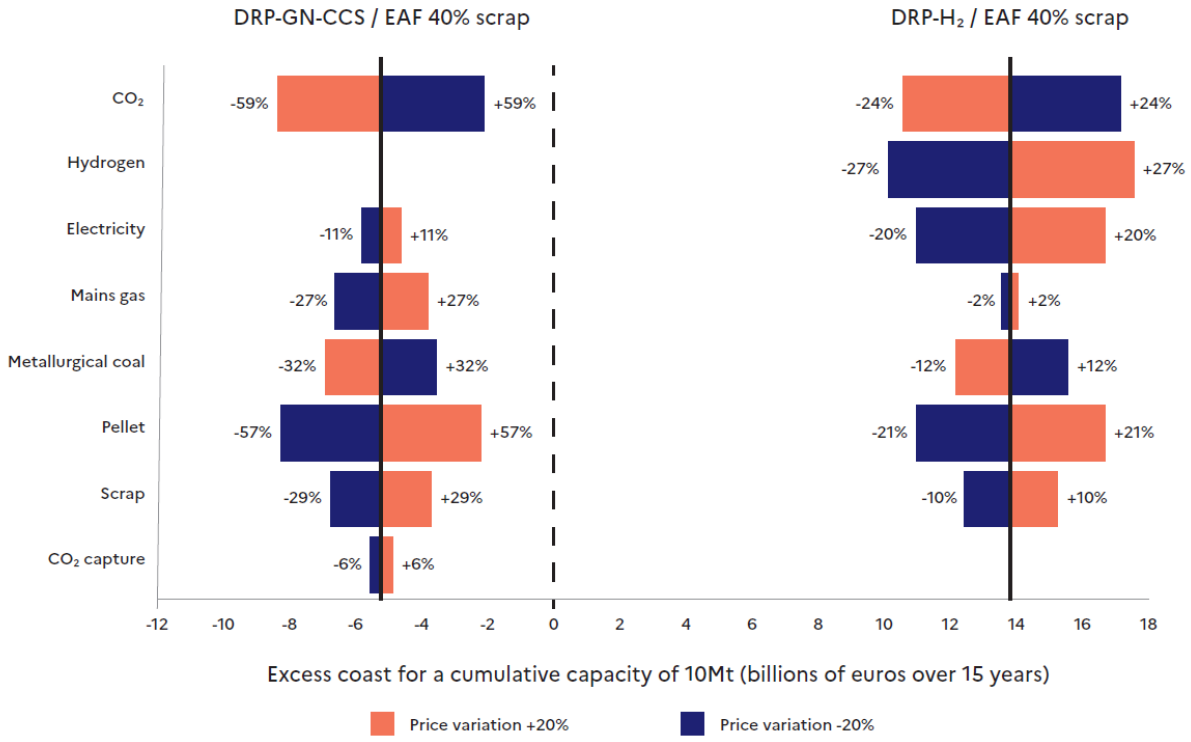
5.8.1. A DRP-H_2 route that is expensive, unless the price of CO_2 is raised and the price of electricity and hydrogen is lowered, as against a DRP-NG-CCS route that is already cost-effective

Under current price conditions, the transition of French blast furnaces to direct reduction by means of hydrogen would represent an excess cost of almost 14 billion euros over a 15-year period[72], due to the associated investments and higher production costs. Conversely, a transition to direct reduction using natural gas coupled with CO_2 capture would be cost-effective in less than 15 years (a profit of 5.3 billion euros shown over the period).

As illustrated by the sensitivity analysis in Figure 103, this excess cost (or gain) is highly dependent on the prices of CO_2, ferrous inputs and energy inputs – hydrogen and electricity for the DRP-H_2 sector and natural gas for the DRP-NG-CCS sector.

[71] Indeed, with the aim of achieving total, rather than partial, decarbonisation, the implementation of technologies that are low-cost but only partially reduce emissions is liable to create counter-productive technological deadlock.

[72] We here consider transition of the blast furnace sector to DRP-EAF installations (using hydrogen or natural gas) incorporating 40% scrap.



Key for interpretation: *If the price of electricity were to fall by 20%, all other things being equal, this would lower the 15-year cost of the transition from blast furnaces to hydrogen-based direct reduction by 20%, bringing it to 10 billion euros, and would increase the 15-year gain associated with the transition to natural gas-based direct reduction coupled with CCS by 11%, bringing it to 6 billion euros.*

Figure 103. Sensitivity analysis of the cost of transition from the blast furnace sector to the DRP-NG-CCS / EAF and DRP-H_2 / EAF routes according to input prices.

Other prices remaining constant, the transition to hydrogen-based direct reduction becomes cost-effective in 15 years with a **CO_2 price of more than €162/tCO_2** (point A1 in Figure 104), which would only be reached in 2037 in the European Commission's "WAM" scenario[73]. Alternatively, hydrogen-based direct reduction becomes profitable, at a constant CO_2 price, with an **electricity price of less than €25/MWh** (half the current price paid by electro-intensive industries), which corresponds to a hydrogen price of €2.4/kgH_2 (point A2).

Until the price of CO_2 changes, a transition to hydrogen-based direct reduction therefore requires the activation of various levers, such as contracts for the supply of low-cost energy, reduction of margins, an increase in the price of sale of low-carbon steel (referred to as a green premium), and moreover public subsidies for investment, and operating subsidies[74].
Natural gas-based direct reduction, for its part, would remain cost-effective in 15 years' time as long as the price of CO_2 remains higher than **€58/tCO_2** (as against €88/tCO_2 in 2023) and the price of natural gas remains lower than **€49/MWh** (point A3), which is 75% higher than the current price.
Under very specific price conditions, hydrogen-based direct reduction could nevertheless prove less costly than natural gas-based reduction coupled with CCS. For this to be the case, all other things being equal, the price of electricity would have to be lower than €10/MWh – i.e. €1.6/kgH_2 (point **B1**) or the price of gas higher than €112/MWh (point **B2**).

[73] "WEM" (With Existing Measures) and "WAM" (With Additional Measures) are scenarios produced by the European Commission in 2017 respectively simulating the effect of current measures, and measures planned by Member States.
[74] Operating subsidies are subsidies for the purchase of inputs; they are particularly useful in this situation, in which operating expenditure represents the bulk of the excess cost.

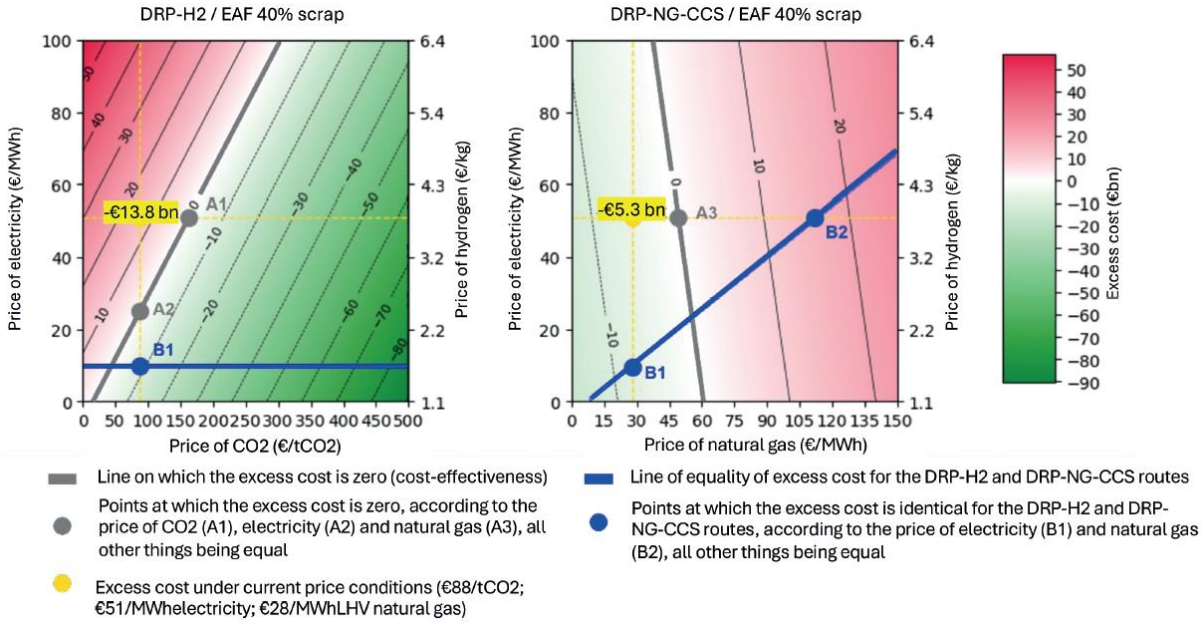


Figure 104. Excess cost over a 15-year period of the DRP-H_2 / EAF, according to electricity and CO_2 prices (left), and DRP-NG-CCS / EAF routes, according to electricity and natural gas prices (right)[75].

It is therefore probable that natural gas-based reduction coupled with CCS will remain more cost-effective than hydrogen-based reduction, unless consumer preference for renewable hydrogen-based – or low-carbon – steel is expressed in the form of a price advantage over steel made on the basis of natural gas combined with CO_2 capture and storage.

Moreover, **non-cost criteria justify the promotion of the DRP-H_2 route**. Indeed, the DRP-NG-CCS route is burdened by the risk of dependence on imports of fossil natural gas and the associated indirect emissions, the prioritisation of alternatives to CCS where they exist, and uncertainty with regard to the development of a CO_2 transport and storage infrastructure[76].

5.8.2. Decarbonisation of blast furnaces: a rapid saving pending the deployment of direct reduction and iron electrolysis?

In order to assess the effectiveness of a decarbonisation technology, the excess cost it represents may be set against the volume of CO_2 emissions it saves: this is the technology's **abatement cost**. The excess cost of 14 billion euros associated with hydrogen-based direct reduction, incorporating 40% scrap, saves 249 $MtCO_2$ of emissions over a period of 15 years, i.e. an abatement cost of **€43/tCO_2**. Natural gas-based direct reduction coupled with CO_2 capture provides a slightly lower level of emissions savings (235 $MtCO_2$), but economises 5.3 billion euros, which is manifested in a negative abatement cost of **-€27/tCO_2**.

As set out in Figure 105, existing blast furnace decarbonisation technologies are the most effective (in particular injection of coke oven gas, at - €123/tCO_2, and increase in the proportion of scrap, at - €72/tCO_2, both of which are cost-effective in less

[75] The price of hydrogen is shown on the right-hand y-axis. It is based on a calculation of the cost of production by electrolysis consistent with the price of electricity shown on the left-hand y-axis.

[76] Also involving a high degree of uncertainty with regard to the price of transport and storage of CO_2, here considered as €42/$t_{CO2\ captured}$.

than 2 years), but only enable partial reduction of CO_2 emissions[77]. It is therefore useful to implement these changes until technical and economic conditions enable large-scale deployment of low-carbon solutions.

For far-reaching decarbonisation, **iron electrolysis appears to be the most effective solution** (-€30€/tCO_2 and cost-effective in 5 years), and could therefore become the preferred solution once its technological development is complete, if this data is confirmed.

The DRP-NG-CCS and, above all, DRP-H_2 sectors, show the highest abatement costs, but their technological lead and the non-cost disadvantages of the DRP-NG-CCS route suggest that **the DRP-H_2 route remains the most appropriate low-carbon solution in the short term.**

Figure 105. Comparison of abatement costs (blue bars) and abated emissions (red dots) for decarbonisation routes in the primary sector

[77] Conversion from blast furnaces to electric arc furnaces supplied with scrap would also be particularly efficient (cost-effective in 1.5 years), but would not meet the need for a primary sector, supplied with virgin iron.

5.9. Initial reflections on the need for direct jobs with 2050 in view

The total workforce in the steel industry, as recorded on average each quarter between 2009 and 2019, fell by 18% (as compared with 7% for manufacturing industry as a whole), totalling about 35,000 people in metropolitan France in 2019, as compared with about 43,000 ten years earlier[78]. A significant fall was observed in particular on sites dedicated to primary and secondary processing (-22%), that is to say excluding the primary sector, in which the workforce was nevertheless reduced by 17%, and excluding the electrical sector, in which the workforce only fell by 3%. There are multiple factors contributing to this erosion. In addition to corporate strategies aimed at reducing production costs and remaining competitive in the face of European and international competition, a number of the steel industry's traditional outlets, such as the oil and gas sector and the building industry, have experienced significant downturns in activity.

Medium and long-term changes in the steel industry's workforce will also depend on the industry's performance in the face of competition and the dynamism of steel-consuming sectors. In addition, the choices to be made in terms of decarbonisation strategy and the more or less ambitious speed of deployment of technologies are also set to bring changes in terms of job volumes and the skills required for the development and sustainability of the industry. **Pending further studies specifically dedicated to changes in employment in the steel industry in a context of decarbonisation, some orders of magnitude are put forward.** On the basis of a given level of employment intensity for steel production, assumptions on changes in production by 2050 as compared with 2022, and the deployment of technological levers, the workforce in the primary sector could thus grow by more than 80% in the best-case scenario (*Hydrogen Bet*) and decrease by 20% in the worst-case scenario (*Reduced Competitiveness*). On the other hand, an increase of 18% is projected within the framework of the *Sobriety and Diversification* scenario. **These estimates illustrate a very heterogeneous net balance, which is highly dependent on the effect of the development of the DRI-EAF process on employment in the primary sector.**

As far as the electrical sector is concerned, the scenarios envisaged in this Sectoral Transition Plan do not include any technological disruption, but only model energy-efficiency improvement technologies. In this respect, apart from the eventual need for skills in order to adapt to these technologies, the workforce volume in this sector is likely to depend above all on production levels. They would increase by 2.2% in the *Hydrogen Bet* scenario, and decrease by 34% and 12% respectively in the *Reduced Competitiveness* and *Sobriety and Diversification* scenarios. These two estimates illustrate the potential effects on employment, by 2050, of a loss of competitiveness vis-à-vis European and extra-European competitors and/or of sobriety-oriented policies.

Among the limitations of these figures, it is important to stress that the effect of the deployment of decarbonisation technologies in heavy industry is still poorly documented in the literature. Similarly, the figures are presented by sector and do not reflect eventual industrial strategies aimed at positioning within growing markets. By way of example, it is assumed that the electrical sector will continue to be principally dedicated to the production of long products for the building sector, whereas in reality, one strategy could consist in redirecting a larger proportion of its output to another sector, or even positioning it within the market for flat products, stainless steel and high alloys for the automotive sector. **Not only are these strategic choices difficult to anticipate with 2050 in view, they are above all specific to each company. For all of these reasons, the estimates should be treated with caution.**

[78] ADEME estimates on the basis of ACOSS-URSSAF (the bodies responsible for the collection of social security contributions in France) data, after reprocessing of statistical data: sites with fewer than 5 employees and/or whose business declarations, and therefore workforce declarations, were made less than 4 years after 2010, are not taken into account. The APE codes (French principal business activity classification system) considered, group together the steel industry (code 24.10), which includes the primary sector, the electrical sector and the other hot metallurgy sites listed under this code, the manufacture of tubes, pipes and hollow sections (code 24.20) and cold metallurgy (codes 24.31, 24.32, 24.33, 24.34).

6. Courses of action

Through discussions with manufacturers and other stakeholders in the sector, a number of courses of action emerged in order to contribute to decarbonisation of the steel industry. These courses of action are listed in the diagram

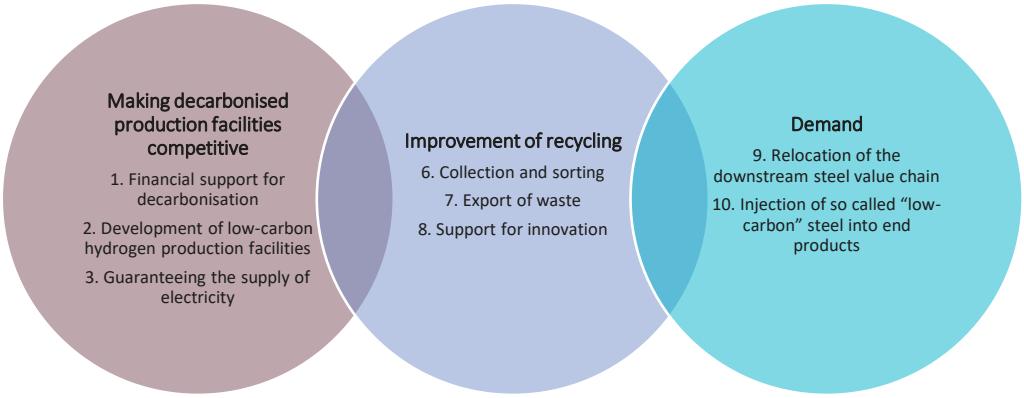


Figure 106: Possible courses of action for decarbonisation of the steel industry

6.1. Making decarbonised production facilities competitive

6.1.1. Financial support to maintain a competitive industry

<table>
<tr><th colspan="3">1. ACCELERATE decarbonisation through various financial support systems</th></tr>
<tr><td colspan="3">CONTEXT and DESCRIPTION OF THE ACTION:
As with capital-intensive primary processing industrial sectors, very heavy investments are required in order to decarbonise steel, particularly investment in new production models (DRP, new EAFs, direct iron electrolysis etc.). These new processes also require work for connection to the electric grid.
Moreover, uncertainty with regard to changes in CO_2 and electricity prices is relatively high in the medium to long term, and poses a significant financial risk to the cost-effectiveness of “disruptive” projects.

Different support mechanisms implemented by the public authorities may be envisaged according to the specific nature of the project, with the aim of accelerating the start of investments by manufacturers:
• Mobilising French support systems:
  • Calls for projects (AAP) in support of innovation and of the demonstration of innovative decarbonisation technologies (AAP DEMIBAC / IBAC PME / Innovation Fund), in particular for iron electrolysis, which is not yet at the commercial development stage.
  • Calls for projects in support of investment (CAPEX) in mature solutions for the decarbonisation of industry, in particular within the framework of France 2030 (ADEME)
  • Specific Operations under the Energy Savings Certificates (CEE) scheme;
  • Scheme for the securance of investment in major decarbonisation projects requiring both investment subsidies and operating subsidies ("OPEX subsidies"): consultation launched by the DGE (the French Directorate General for Enterprise) in June 2024 for a future call for tenders to support major industrial decarbonisation projects, in particular carbon capture and storage, electrification and hydrogen use projects.
• Make better use of European funding agencies, e.g.: Innovation Fund, Horizon Europe, ERDF, Just Transition Fund, etc.</td></tr>
<tr><td colspan="2">STRENGTHS:
• Numerous incentive schemes implemented within the framework of the France 2030 investment programme, the Heat Fund (Fond Chaleur) and the Circular Economy Fund (Fond économie circulaire).</td><td>WEAKNESSES:
• Absence of long-term visibility for these schemes, which consume large amounts of public money
• Beyond a mechanism for financial support from the State, effective implementation of economic tools such as the CBAM (Carbon Border Adjustment Mechanism) would be required as a complement in order to avoid failed investments while preserving French industrial sovereignty.</td></tr>
<tr><td>IDENTIFIED STAKEHOLDERS:
• Strategy for acceleration of the decarbonisation of industry Task Force (SGPI)
• Strategy for acceleration of recycling Task Force (SGPI)
• “Mining and Metallurgy” Industry Strategy Committee (Comité Stratégique de Filière)
• “Waste” Industry Strategy Committee</td><td colspan="2">COURSES OF ACTION:
• France 2030 programme: 5 billion Euros over a 5-year period for the decarbonisation of industry (launch of a CCFD-type call for tenders in the second half of 2024 - cf. Press Release November 2023)
• Combining the investment requirements of the road maps for the 50 sites with the highest emissions and the Road Maps of the Industry Strategy Committees (ISCs), in line with the results of the STPs, in order to fuel the planning and design of new Public Policies and to engage industry through ecological transition contracts.</td></tr>
</table>

• French Ministry of the Economy and Finance (DGE – Directorate General for Enterprise) • ADEME (Department for the Decarbonisation of Industry and Hydrogen)	
FOR FURTHER INFORMATION: • France 2030 • CEE scheme • Heat Fund • Innovation Fund • O. Sartor and C. Bataille, 2019, Decarbonising basic materials in Europe: How Carbon Contracts-for-Difference could help bring breakthrough technologies to market, IDDRI • Agora Energiewende, 2020, A Clean Industry Package for the EU, Berlin • Communication of the European Commission on the "Fit for 55" package • Press Release of 22 November 2023 on the signature of ecological transition contracts for industry	

6.1.2. Development of low-carbon hydrogen production facilities

2. Supporting the development of low-carbon hydrogen production facilities and adopting flexible consumption of electrolytic hydrogen

CONTEXT and DESCRIPTION OF THE ACTION:

In order to ensure long-term French, and indeed European, competitiveness in hydrogen-based direct reduction of iron ore, it is essential to support the development of low-carbon hydrogen production facilities in order to generate economies of scale, guarantee permanence of supply and contain its cost. Moreover, in order to continue to power DRPs at peak times and limit electricity consumption costs, it is necessary to adopt flexible consumption of electrolytic hydrogen by relying on hydrogen storage, input flexibility (natural gas flexibility for certain DRPs) and temporary reduction in power consumption (partial load shedding).

France's national hydrogen strategy is currently under review. The government began consultations concerning the new strategic guidelines for this strategy on 15 December 2023. It should be published by the end of 2024.

In the case of H_2 infrastructures, underground H_2 storage facilities in salt caverns are not located in a geographically balanced manner across France (principally in the Rhône Valley and Eastern France, see the RTE-GRT Gaz study on the challenges of developing the hydrogen storage and transport infrastructures associated with the development of electrolysis and optimisation levers with the electricity system). However, access to these sites, via pipe connections, would make the electrolysers more flexible and therefore reduce the average cost of electricity (over 80% of the cost of hydrogen production is directly linked to electricity), making hydrogen more competitive.

STRENGTHS:

- The possibility of load-shedding of electrolysers at times when electricity is expensive will enable them to benefit from a supply of electricity at a better average price.

WEAKNESSES:

- The development of hydrogen infrastructures will take time, and planning is therefore required in order to give visibility to the whole of the players (manufacturers, network operators, etc.).

IDENTIFIED STAKEHOLDERS:

- Strategy for acceleration of the decarbonisation of hydrogen Task Force (SGPI)
- French Ministry of the Economy and Finance (DGE, DGEC)
- ADEME (Department for the Decarbonisation of Industry and Hydrogen)

COURSES OF ACTION:

- The completion of studies supported within the framework of the call for Low-Carbon Industrial Zones (ZIBAC) projects, in order to identify possible decarbonisation trajectories by 2030-2050 for the French industrial areas with the highest greenhouse gas emissions. Development of the first H_2 infrastructures (pipes and storage) should probably be envisaged between the present and 2030 for the most emission-intensive industrial hubs, in order to reduce electricity costs by means of flexibility.
- Support scheme for H_2 production (known as the "OPEX H_2 mechanism"): 4 billion euros (over a 15-year period) in order to decarbonise the production of H_2 by electrolysis, principally in the industrial sectors with the highest emissions (steel and ammonia). The mechanism is due to be launched between the present and the end of 2024, with several rounds of calls for tenders.

FOR FURTHER INFORMATION:

- France 2030: ZIBAC calls for projects (AAP ZIBAC): https://agirpourlatransition.ademe.fr/entreprises/aides-financieres/20220204/favoriser-developpement-zones-industrielles-bas-carbone-zibac
- RTE-GRT Gaz study highlighting the benefits of electrolyser flexibility for the electricity grid: https://www.grtgaz.com/sites/default/files/2023-08/grtgaz_rte_etudeh2.pdf
- National hydrogen strategy for which consultations began on 15 December 2023: https://www.ecologie.gouv.fr/rendez-vous/consultation-nouvelle-strategie-francaise-deploiement-hydrogene-decarbone#:~:text=Un%20Conseil%20national%20de%20l,de%2010%20GW%20en%202035 .

6.1.3. Guaranteeing the supply of electricity

3. Facilitating the development of electricity infrastructure in order to guarantee the supply of large quantities of electricity and promote access to competitive electricity prices

CONTEXT and DESCRIPTION OF THE ACTION:

If the hydrogen-based direct reduction sector develops to full capacity, electricity consumption by the steel industry could increase fivefold locally in the industrial zones of Fos-sur-Mer and Dunkirk (in the Hydrogen Bet scenario), in addition to the electrification connected with the decarbonisation of other industrial sites present. New decarbonised means of generation therefore need to be developed in order to meet rising electricity consumption. Moreover, in order to avoid overloading of the grid in the face of local electrical power requirements, major work needs to be undertaken in order to reinforce electrical grid infrastructures.

These changes may be facilitated by the following actions:
1. Encourage the establishment of freely negotiated contracts for supply of electricity.
2. Plan and prioritise grid connection requests by sector and industrial zone.
3. Study decentralised distribution of new steelmaking plants (in particular DRI production and iron electrolysis).

STRENGTHS:

Increasing the competitiveness of French industries through access to decarbonised, competitive electricity

WEAKNESSES:

- Length of procedures for reinforcement of the electricity network (the waiting times for connection to the grid announced by RTE may be as long as 10 years in certain cases)

IDENTIFIED STAKEHOLDERS:

- "Mines and metallurgy" Industry Strategy Committee
- French Ministry of the Economy and Finance (DGE)
- CRE (French Energy Regulatory Commission)
- RTE (France's electricity transmission system operator)

COURSES OF ACTION:

- Encourage the establishment of freely-negotiated contracts for supply of electricity. Indeed, following the scheduled end of the "ARENH" (regulated access to historical nuclear power sources) mechanism by 2026, discussions are in progress on the implementation of long-term electricity contracts within the framework of the reform of the electricity market, for the securance of access to a competitive electricity price, in particular within the framework of the expert mission on this issue entrusted to Philippe Darmayan and the discussions concerning nuclear power allocation contracts (CAPN).
- Plan and prioritise grid connection requests by sector and industrial zone. In order to make it easier to cater for new facilities, Act no. 2023-175 of 10 March 2023 concerning acceleration of the generation of renewable energies simplifies procedures for planning and anticipation of grid connection for renewable energy projects and projects for the decarbonisation of industry. Under article 27 procedural exemptions are thus granted for projects for the decarbonisation of industry under certain conditions, while article 28 organises the waiting list for connection to the public electricity transmission grid. The competent State authority may change the position in the waiting list for connection requests for decarbonisation projects within a geographical area, in accordance with transparent and objective criteria laid down by decree.
- Undertake a study of decentralised distribution of new steel-making facilities across the country (in particular DRI production and iron electrolysis, which can be envisaged with much smaller facilities and therefore spread more evenly across the country, in order to smooth out local electricity grid consolidation requirements).

FOR FURTHER INFORMATION:

- Link to articles 27 and 28 of Act no. 2023-175 of 10 March 2023 concerning acceleration of the production of renewable energy: https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000047294244/
- https://www.edf.fr/groupe-edf/espaces-dedies/journalistes/tous-les-communiques-de-presse/gravithy-signe-une-lettre-dintention-avec-edf-pour-securiser-une-partie-de-lapprovisionnement-en-electricite-de-sa-future-usine-a-fos-sur-mer

6.2. Improvement of recycling

6.2.1. Collection and sorting of scrap steel

<table>
<tr><th colspan="3">5. OPTIMISING the collection and sorting of scrap steel in the country</th></tr>
<tr><td colspan="3">CONTEXT and DESCRIPTION OF THE ACTION:
The collection of scrap for recycling, principally in the electrical sector and foundries, but also to some extent in the blast furnace sector, supplementing the recovery of production scrap, lowers the CO_2 emissions associated with steel production. The electrical sector is heavily dependent on an adequate supply of scrap for its output, and the new decarbonised steel production processes, brought in by the DRI-EAF route, will also need to be supplied with scrap. The demand for scrap containing low levels of impurities is therefore expected to grow in coming years, placing pressure on the scrap market.

It is therefore henceforth essential to mobilise sources of waste upstream, at once by optimising collection channels, in particular through EPR schemes, and moreover by improving the quality of waste sorting in order to increase the value of recycled waste. Indeed, the collection, sorting and dismantling of waste reduces the costs of making materials available to industrial players further down the waste processing chain, which transform them into new raw materials.
The optimisation of collection and sorting channels can be achieved by:
○ Better organisation of collection channels (creation of dedicated collection channels for products not covered by any extended producer responsibility industry),
○ Increase in the collection targets set in the terms and conditions of producer responsibility organisations in the EPR schemes concerned (electrical and electronic equipment, automotive, construction, etc.).
○ Improvement of sorting technologies for improved separation of different metals, and for each metal by alloy, in order to achieve the quality standards required by the steel industry.
○ Improvement of technologies for identifying, characterising and tracing materials after collection.
○ Deployment of systems of adjustment of producers' rates of contributions according to ecological criteria ("écomodulation") in the granting of official approval to producer responsibility organisations and in their targets, in application of the provisions of the AGEC Act
○ Development of eco-design in order to improve the identification, sorting and recycling of materials at the end-of-life of products.
○ Organising more regular cross-functional work (e.g. between the "Mining and Metallurgy" and "Waste Processing and Recovery" Industry Strategy Committees) in order to facilitate communication between the various existing bodies.</td></tr>
<tr><td colspan="2">STRENGTHS:
• Creating and ensuring the permanence of local jobs in the waste collection and sorting sector.
• Reassessment of the collection and recycling targets set in the terms and conditions for each approval granted to producer responsibility organisations.
• Existing funding agencies: France 2030, funding of projects by producer responsibility organisations, etc.
• The Anti-Waste for a Circular Economy Act (loi AGEC): clauses or "useful criteria" concerning the circular economy economy</td><td>WEAKNESSES:
• Lengthy industrial deployment</td></tr>
<tr><td>IDENTIFIED STAKEHOLDERS:
• Ministry of Ecology (DGPR),</td><td colspan="2">COURSES OF ACTION:</td></tr>
</table>

• French Ministry of Economy and Finance (DGE) • FEDEREC • ADEME (DSREP / DEC) • Strategy for acceleration of recycling Task Force • Producer responsibility organisations • “Waste Processing and Recovery” Industry Strategy Committee (ISC) • “Mining and Metallurgy” ISC	• Support R&D into new technologies (in particular more sophisticated scrap sorting and decontamination technologies). • France 2030 recycling programme: new ADEME/BPI "Critical Metals 2" call for projects • The ORMAT AAP call for projects uniquely for re-sorting (https://agirpourlatransition.ademe.fr/entreprises/aides-financieres/20240115/fonds-economie-circulaire-ormat-2024-objectif-recyclage-matieres) • Adjustment of producers’ rates of contributions to producer responsibility organisations according to ecological criteria (“eco-adjustment”): in order to incentivise companies to eco-design the products they place on the market (e.g. facilitating the dismantling of products in order to remove the different materials contained in them more easily), implementation by producer responsibility organisations of the eco-adjustments provided for in the official approvals granted to them and regular review of these eco-adjustments in order to increase the incentives they provide.

FURTHER INFORMATION:

- Presentation of the EPR system on the ADEME website site
- France 2030 (formerly Investment Programmes for the Future or *Programme des Investissements d’Avenir*)
- French strategy for the acceleration of recycling and the transition to a circular economy
- ADEME (2024), Bilan national du recyclage (French National Recycling Report) 2012 -2021
- ADEME (2024), Étude du potentiel de recyclage des métaux en France

6.2.2. Limiting the Exporting of Scrap Steel

<table>
<tr><th colspan="3">6. Limiting the Exporting of Scrap Steel</th></tr>
<tr><td colspan="3">CONTEXT and DESCRIPTION OF THE ACTION:
Like many consumer goods, scrap is traded internationally. Today, more than half of France's scrap is exported, due to excessively low quality and the overly high cost of re-sorting and decontamination, while a part of requirements is imported. Although there is trade with non-EU countries such as Turkey, this market is highly regionalised within the European Union. France is a net exporter of scrap metal, principally to its neighbouring countries (Belgium, Spain and Italy).
If this export rate were to be maintained (in the absence of the establishment of protectionist export measures), the French steel industry would have to import 3.6 times more scrap in the Hydrogen Bet scenario (4.3 Mt in 2050), as compared with today, and 2 times more in the Sobriety and Diversification scenario. In contrast, in the Reduced Competitiveness scenario, almost no imports would be required from 2040 onwards.

The Carbon Border Adjustment Mechanism (CBAM) regulates greenhouse gas emissions caused by products imported into Europe. By limiting the import of raw materials into Europe, this mechanism could lead to a reorganisation of the European market, increasing the use of scrap within the EU.

Lastly, this limitation is part of a short supply chain approach, reducing the impact of transport and contributing to the securance of metal supplies.</td></tr>
<tr><td>EFFECTS ON DECARBONISATION:
Limitation of exports has the potential to increase use of recycled materials in Europe and reduce imports of primary materials.</td><td>STRENGTHS:
• Lever of national sovereignty over materials
• The Anti-Waste for a Circular Economy Act (loi AGEC): clauses or "useful criteria" concerning the circular economy
• Carbon Border Adjustment Mechanism (CBAM)</td><td>WEAKNESSES:
• The market for recycled raw materials (RRM) is often export-oriented for economic reasons, in particular with regard to low-quality recycled raw materials standards.
• Scant means of observation and monitoring of flows of materials (difference between data/customs codes and commercial quality of recycled raw materials)</td></tr>
<tr><td>IDENTIFIED STAKEHOLDERS:
• Ministry of Ecology (DGPR),
• French Ministry of Economy and Finance (DGE)
• FEDEREC
• Strategy for acceleration of recycling Task Force
• "Waste Processing and Recovery" ISC
• "Mining and Metallurgy" ISC
• ADEME (DEC / DSREP)</td><td colspan="2">COURSES OF ACTION:
• Impose a requirement in producer responsibility organisations' terms and conditions concerning ensuring the proximity of waste treatment sites to their place of production.
• Introduce an administrative monitoring system consisting of the declaration of exports in order to incentivise the maintenance of waste supplies (in terms of quantity and quality) for French manufacturers.
• Limit the export of steel scrap by introducing dedicated regulations, at the European level
• Study the feasibility of limiting the export of steel scrap on a national and/or European scale. By way of example, at the beginning of 2022, Italy classified scrap metal in the Critical Raw Material category. The national authorities concerned now therefore have to be informed of exports of this type of waste, and may in turn prohibit the transaction according to demand on the domestic market.
• ADEME study on the correlation between customs data, commercial quality of recycled raw materials, and quality of reference listed recycled raw materials.</td></tr>
<tr><td colspan="3">FURTHER INFORMATION:
• Presentation of the EPR system on the ADEME website site
• ADEME (2024), Étude du potentiel de recyclage des métaux en France
• ADEME (2024), Bilan national du recyclage (French National Recycling Report) 2012 -2021</td></tr>
</table>

6.2.3. Support for Innovation - Recycling Processes

7. SUPPORTING Innovation in Recycling Processes

CONTEXT and DESCRIPTION OF THE ACTION:

Achievement of the -81% target set for industry in the French National Low Carbon Strategy (SNBC) by means of more massive use of recycling of scrap steel. Indeed, recycling needs to remain a priority in order to reduce pressure on natural resources and reinforce France's resilience and industrial sovereignty. The introduction of innovation in order to improve and optimise sorting technologies is therefore proving to be essential.

The aim is to ensure the emergence of technical solutions that are not yet mature up to the industrialisation stage by mobilising funding agencies dedicated to innovation in industry (funding of demonstrations). It is also a question of optimising existing technologies to improve the quality of sorting and decontamination of scrap steel.

EFFECTS ON DECARBONISATION:

The effects of this action would for the most part appear to be felt in the medium and long term, when the technologies have passed through the pilot project stage. A few examples of the decarbonisation potential of non-mature technologies

STRENGTHS:

- Potential outlet for patents and technology exports
- Existing funding agencies: France 2030, ADEME circular economy fund, and the Innovation Fund at the European level.
- The Anti-Waste for a Circular Economy Act (loi AGEC): clauses or "useful criteria" concerning the circular economy

WEAKNESSES:

- Lack of clarity for manufacturers with regard to the different funding agencies
- Low level of dissemination of leading-edge sorting technologies

IDENTIFIED STAKEHOLDERS:

- The French National Research Agency (ANR)
- French Public Investment Bank (Bpifrance)
- French General Secretariat for Investment (SGPI)
- Strategy for acceleration of recycling Task Force
- ADEME (Circular Economy Department, Regional Departments)

COURSES OF ACTION:

- France 2030 Recycling Programme : New ADEME/BPI "Critical Metals 2" call for projects with a new "R&D/Innovation" component
- Funding for theses: Call for thesis applications

FURTHER INFORMATION:

- In France: France 2030 (formerly Investment Programmes for the Future or *Programme des Investissements d'Avenir*)
- European Union: *Innovation Fund*
- ADEME (2024), Bilan national du recyclage (French National Recycling Report) 2012 -2021
- ADEME (2024), Étude du potentiel de recyclage des métaux en France

6.3. Anticipating Tomorrow's Levels of Demand

6.3.1. Relocation of the Downstream Steel Value Chain back to France

4. **RELOCATE the Downstream Steel Value Chain back to France**	
CONTEXT and DESCRIPTION OF THE ACTION: An unanticipated fall in demand is liable to lead to economic difficulties for French steelmakers, which would find themselves in a situation of overcapacity, and fuel a climate of uncertainty that is hardly conducive to the required investments for decarbonisation. It therefore seems essential to plan sufficiency policies in order to provide visibility concerning France's future steel requirements, particularly with regard to the building industry and infrastructures. By way of example, the ecological planning drawn up by the French General Secretariat for Ecological Planning (SGPE) sets out the major trends in the various sectors (building, transport, energy etc.), enabling industry players to anticipate structural changes in the market segments that concern them. Moreover, combining sufficiency measures with a policy of relocating production back to France for strategic imported products, such as equipment connected with renewable energies, would make it possible to increase sovereignty, create jobs and give impetus to new territorial dynamics, without intensifying the pressure exerted by decarbonised steel production on material and energy consumption. It therefore appears necessary to implement measures that facilitate the establishment and maintenance of strategic industrial activities within the country, promoting the use of nationally-produced low-carbon steel. Act no. 2023-973 of 23 October 2023 concerning green industry is aimed at accelerating the reindustrialisation of the country and making France the green industry leader in Europe. Certain measures in this Act are likely to facilitate relocation of the steel value chain back to France, in particular: - Halving the time required for the setting up of industrial facilities, - The creation of an exceptional simplified procedure for projects of major national interest, - Public procurement to more intensively promote environmentally-friendly products from 2026.	
IDENTIFIED STAKEHOLDERS: • French Ministry of Economy and Finance (DGE) • French General Secretariat for Ecological Planning (SGPE)	**COURSES OF ACTION:** Put mechanisms in place to support the relocation of the downstream steel value chain back to France, typically the production of photovoltaic solar panels. At the time of publication of the Green Industry Act (*loi Industrie Verte*), the C3IV tax credit for green industry was implemented, aimed at promoting the setting up of new factories producing batteries, wind turbines, solar panels and heat pumps (and the components thereof, a list of which can be consulted on the dedicated website). - Use the lever of public procurement to stimulate the emergence of low-carbon steel in France.
FOR FURTHER INFORMATION: • Act no. 2023-973 of 23 October 2023 concerning green industry • Ecological planning: Action plan to accelerate the ecological transition • C3IV: https://www.entreprises.gouv.fr/fr/credit-impot-industrie-verte-C3IV-agrement	

6.3.2. Promoting the Use of so called "Low-Carbon" Steel in End Products

8. PROMOTING the Use of so called "Low-Carbon" Steel in End Products

CONTEXT and DESCRIPTION OF THE ACTION:

The use of so called "low-carbon" steel in end products is an important issue, since it makes it possible to economise non-renewable resources, limit emissions – of greenhouse gases in particular – and relocate sourcing as far as possible back to the national level.

The challenges are as follows:

- Produce more low-carbon steel from domestic scrap, avoiding the export of waste and dependence on foreign recovery systems.
- Make better use of "low-carbon" steels and make them more competitive in order to replace carbon steel
- Implement industrial capacity throughout the chain, in order to promote balance between supply and demand for scrap
- Channel the various flows of low-carbon steel (from the electrical and DRI-EAF sector), according to their quality standard, more effectively to the manufacturers that could to use them.
- Encourage manufacturers of end-products to use more low-carbon steel
- Define a method and tools for tracing the use of low-carbon steel in end products

EFFECTS ON DECARBONISATION:

Any replacement of carbon-intensive steel with low-carbon steel avoids both CO_2 emissions and the mining of virgin raw materials.

STRENGTHS:

- Setting targets promoting eco-design for products containing steel covered by an Extended Producer Responsibility system.
- The Anti-Waste for a Circular Economy Act (loi AGEC): clauses or "useful criteria" concerning the circular economy
- Within the framework of the French National Sustainable Procurement Plan, by 2025 100% of public procurement contracts announced during the year will include at least one environmental consideration (including the incorporation of recycled raw materials).

WEAKNESSES:

- Lack of harmonisation of different scrap qualities and standards
- Lack of traceability for identification of the origin of scrap metal

IDENTIFIED STAKEHOLDERS:

- French Ministry of Ecology (DGPR),
- French Ministry of Economy and Finance (DGE)
- Producer responsibility organisations
- ADEME (Circular Economy Department, Regional Departments)
- Strategy for acceleration of recycling Task Force
- Trade and industry federations (end products) -

COURSES OF ACTION:

- Promote increased use of low-carbon steel in new products through EPR schemes covering steel products, by adjustment of the eco-contribution paid by initial marketers according to the level of reuse (or a penalty for those that do not use any at all).
- Put in place a digital platform for the identification of raw materials from recycling of metals. For example, by developing the Mjunction digital platform (marketplace), the Indian group Tata Steel has improved efficiency of flows and use of materials for buyers and sellers of scrap, waste and unused assets.
- Introduce regulatory measures for the utilisation of "low-carbon" steels in public procurement contracts
- Financing of projects and feasibility studies (ADEME Circular Economy Fund)
- Circular Economy Fund - ORMAT (*Objectif Recyclage MATières* - "Materials Recycling Objective"): the call for projects launched by ADEME's Circular Economy Fund provides financial support for the production of recycled raw materials (RRM) and their use in products by processors and initial marketers.

FURTHER INFORMATION:

- Presentation of the EPR system on the ADEME website site
- In France: France 2030 (formerly Investment Programmes for the Future or *Programme des Investissements d'Avenir*)
- French strategy for the acceleration of recycling and the transition to a circular economy
- ADEME (2024) Étude du potentiel de recyclage des métaux en France
- ADEME (2024), Bilan national du recyclage (French National Recycling Report) 2012 -2021

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Annexes

Annexe no. 1 - Carbon Rate and Emission Factor Assumptions

Commodity	Carbon content (kgC/kg)
Pig iron	0.04
Steel	0.0004
Scrap iron	0.0009
Coal tar	0.92
Benzol (C6H6)	0.85
Metallurgical coal	1.00
DRI manufactured using natural gas	0.035

Table 33. Carbon rate assumptions

Commodity	*Unit*	Emission factor
Coke oven gas	*tCO_2/kWh*	0.000171
Blast furnace gas	*tCO_2/kWh*	0.000965
Basic oxygen furnace gas	*tCO_2/kWh*	0.000659
Heating oil	*tCO_2/kWh*	0.000272
Coal	*tCO_2/kWh*	0.000345
Coal used for sintering	*tCO_2/kWh*	0.000337
Coke used for sintering	*tCO_2/kWh*	0.000337
Metallurgical coal	*tCO_2/kWh*	0.000330
Pulverised coal	*tCO_2/kWh*	0.000329
Coke	*tCO_2/kWh*	0.000404
Plastic	*tCO_2/kWh*	0.000268
Natural gas	*tCO_2/kWh*	0.000205
Dolomite (decarbonation)	*tCO_2*	0.48
Limestone (decarbonation)	*tCO_2*	0.44

Table 34. Emission factor assumptions

Annexe no. 2 – Price Assumptions

In order to calculate the changes in the production cost with price fluctuations, it was necessary to set the input price assumptions. For inputs having a significant effect on the cost of production (CO_2, electricity, mains gas, and hydrogen), a "high" and a "low" value were taken into account, while for the other inputs, the average price between 2015 and 2022 was adopted for the "low price" and "high price" trajectories.

Commodity	*Unit*	2022	2030	2050	Source
CO_2 (Low)	*EUR/t*	78	86	146	ADEME according to the European Commission (WEM trajectory)
CO_2 (High)	*EUR/t*		86	375	ADEME according to the European Commission (WAM trajectory)
Electricity (Low)	*EUR/MWh*	87	50	48	ADEME
Electricity (High)	*EUR/MWh*		64	67	ADEME
Mains gas (Low)	*EUR/MWhLHV*	73	29	25	ADEME

Mains gas (High)	*EUR/MWhLHV*		35	51	ADEME
Hydrogen (Low)	*EUR/kg*	5.8	3.9	2.8	ADEME
Hydrogen (High)	*EUR/kg*		3.9	3.7	ADEME
HBI	*EUR/t*	468	370	360	ADEME
Iron ore	*EUR/t*	104	71	71	ADEME
Coal	*EUR/t*	40	22	27	ADEME
Metallurgical coal	*EUR/t*	38	28	34	ADEME
Anthracite	*EUR/t*	40	28	33	ADEME
Limestone	*EUR/t*	18	19	19	ADEME
Lime	*EUR/t*	141	89	89	ADEME
Calcined dolomite	*EUR/t*	291	158	158	ADEME
FeMnC	*EUR/t*	1720	1078	1078	ADEME
FeSi-75	*EUR/t*	2405	1233	1233	ADEME
Aluminium for deoxidation	*EUR/t*	3291	2407	2407	ADEME
Scrap	*EUR/t*	278	231	231	ADEME
Pellets	*EUR/t*	161	103	103	ADEME
Blast furnace slag	*EUR/t*	60	33	33	ADEME

Table 35: ADEME assumptions on input prices (in EUR_{2023})

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Acronyms and Abbreviations

ADEME	The French Agency for Ecological Transition
BF	Blast furnace
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
DRI	Direct Reduced Iron
DRP	Direct Reduction Plant
DRP-NG	Direct reduction plant running on natural gas
DRP-NG-CCS	Direct reduction plant running on natural gas, with CO_2 capture, transport and storage
DRP-H_2	Direct reduction plant running on hydrogen
EAF	Electric Arc Furnace
EU-ETS	European Emissions Trading System
GHG	Greenhouse gases
HBI	Hot-Briquetted Iron
LULUCF	Land use, land-use change and forestry
Mt	One million tonnes
$MtCO_2$	One million tonnes of carbon dioxide
OPEX	Operational expenditure

ADEME AT A GLANCE

At ADEME - the Agency for Ecological Transition - we are firmly committed to fighting climate change and the depletion of resources.

On all fronts, we mobilise citizens, economic actors, and local and regional authorities, giving them the tools they need to move towards a more resource-efficient, low-carbon economy that is fairer and more harmonious.

In every field - energy, circular economy, food, mobility, air quality, climate change adaptation, soils, etc. - we advise, facilitate, and help to fund numerous projects, from the research stage through to sharing solutions.

At every level, we put our expertise and forward-looking capabilities at the service of public policies.

ADEME is a public body under the supervision of the Ministry for an Ecological Transition and Territorial Cohesion, the Ministry of the Economy, Finance and Industrial and Digital Sovereignty and the Ministry for Higher Education and Research.

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FACTS AND FIGURES
ADEME is a reference: It provides objective analysis on the basis of regularly updated statistical indicators.

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ADEME is a facilitator: It draws up practical guides to help stakeholders implement their projects in a methodical manner and/or in compliance with regulations.

THEY HAVE DONE IT
ADEME is a catalyst: Stakeholders talk about their experiences and share their know-how.

EXPERTISE
ADEME provides expertise: It reports on the results of research, studies and collective work conducted under its supervision.

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ADEME looking to the future: It proposes a prospective and realistic vision of the challenges of the energy and ecological transition, for a desirable future to be built together.

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EXPERTISES

STEEL
Final Report

French steel production amounts to 15 million tonnes a year, and is responsible for 5% of French greenhouse gas emissions. **Today, there are two routes for the production of steel: the blast furnace sector, which produces primary steel and is responsible for 85% of the industry's emissions, and the electrical sector, which supplies recycled steel by the conversion of scrap in electric arc furnaces.** This route is the most effective means of decarbonising the steel industry, but it is hampered by the limited availability of high-quality scrap. Two other alternative technologies are also in the course of development for the production of steel without coal: direct reduction and direct iron electrolysis. While the effectiveness of hydrogen-based direct reduction has been tried and tested on a pilot scale, iron electrolysis is still in the course of development. In both cases, large-scale deployment will require favourable conditions, in particular a high price of CO_2 and a substantial, competitive supply of decarbonised electricity.
ADEME has thus elaborated three contrasting scenarios in order to illustrate the challenges of far-reaching decarbonisation of the steel industry, making it possible to achieve the targets set by the French National Low-Carbon Strategy of an -81% reduction in CO_2 emissions by 2050 as compared with 2015.

The Finance ClimAct project contributes to the implementation of France's National Low-Carbon Strategy and European policy on sustainable finance. It aims to develop new tools, methods and knowledge that will enable (1) energy-intensive industries to promote investment in energy efficiency and the low-carbon economy, (2) financial institutions and their supervisors to integrate climate issues into their decision-making processes and align financial flows with energy-climate targets, and (3) investors to integrate environmental objectives into their investment choices.

The consortium, coordinated by the French Agency for Ecological Transition, also includes the French Ministry for Ecological Transition, the Autorité des marchés financiers (French Financial Markets Authority), the Autorité de contrôle prudentiel et de résolution (French Prudential Supervision and Resolution Authority), the 2° Investing Initiative, the Institut de l'économie pour le climat (Institute for Climate Economics), the Institut de la Finance Durable (Paris Sustainable Finance Institute) and RMI.

Finance ClimAct is an innovative programme with a total budget of €18 million and €10 million in funding from the European Commission.

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