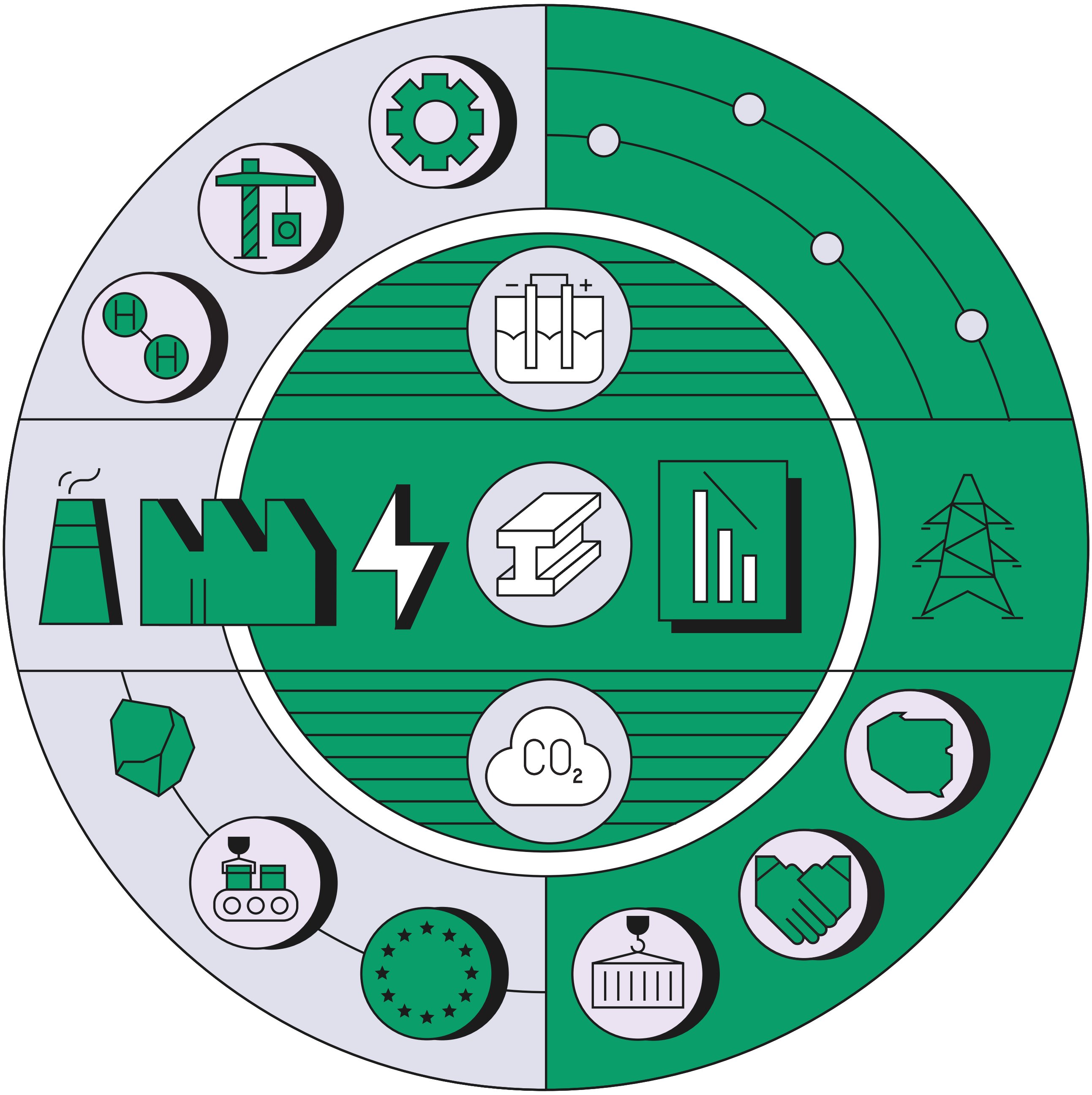
Low- or zero-emission steel?

How to decarbonise steel production in Poland



Instrat Policy Paper 02/2024

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instrat

Warsaw, October 2024

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Recommended citation:
Hetmański, M., Laskowski, K., Kulbacki, M., Kopeć, J. (2024). *Low- or zero-emission steel? How to decarbonise steel production in Poland.* Instrat Policy Paper 02/2024.

Recommended citation for the calculator:
Hetmański, M., Laskowski, K., Kulbacki, M., Swoczyna, B. (2024). *Calculator of Steel Production Cost in Poland.* Instrat.

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This publication was created with the support of the European Climate Foundation (ECF).

Spreadsheet containing a calculator of steel production cost in Poland presented in Chapter 3 is available for download at:
www.link.instrat.pl/stal-nisko-czy-zeroemisyjna-kalkulator

All errors are ours.
Usual caveats apply.

Instrat Policy Paper 02/2024

Warsaw, October 2024

ISBN: 978-83-970396-7-4

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Key findings and numbers

0.6%	was the share of basic metals production in gross value added of the Polish economy in 2021.
77–98%	emission reduction can be achieved in a low- or near-zero-emission option compared to today's blast furnace and basic oxygen furnace method of steel production.
795–807 EUR/t	can be the cost of producing green steel using Direct Reduced Iron technology (DRI-EAF + H_2).
822–863 EUR/t	can be the cost of steel production at Poland's last integrated steelworks using blast furnace and basic oxygen furnace technology in Dabrowa Gornicza, if it invests in CO_2 capture technology (CCS) and achieves a capture rate of 75%.
1 074 EUR/t	could be the cost of producing steel in the same steelworks if it does not invest in CCS, with CO_2 prices rising to 300 EUR/t in 2040 or later.
7.2 TWh	could be the annual electricity demand of a green steel plant (DRI-EAF + H_2) for the production of high-temperature heat in an electric arc furnace (approx. 1.4 TWh) and for the production of hydrogen used as a reducing agent (approx. 5.8 TWh).
110 thousand tonnes	hydrogen may be needed annually for green steel production (DRI-EAF + H_2) - that's about 10-15% of the current annual production of grey hydrogen used in the chemical and refining industry (2023) or the production potential of decarbonised hydrogen in 2040.

- Steel production with Direct Reduced Iron technology using an Electric Arc Furnace and hydrogen as a reducing agent (DRI-EAF + H_2) can be cost-competitive compared to other primary steelmaking methods.

- The Polish economy needs a strategic decision on the direction of transition pathways for the domestic steel market and associated state support. Leaving the sector to its own devices may lead to the extinction of primary steel production in Poland.

- Poland's total reliance on low- or zero-emission steel imports is not an optimal solution, but its eventual choice must be a conscious one. It should also be accompanied by a strategy for meeting domestic demand for steel, in particular for primary steel.

- The decision to choose a model for the decarbonisation of primary steel production should not be postponed - on the contrary, it should be accelerated without waiting for the increase in the cost of CO_2 allowances in the EU ETS in the 2030s.

- Regulatory and financial support is needed, as well as investment in infrastructure to accompany low- or near-zero-emission steelmaking, i.e. hydrogen and CCS economy, for DRI-EAF + H_2 and BF-BOF + CCS options respectively.

- Poland needs large volumes of renewable energy and low electricity prices to meet the significant demand by all low- and zero-emission steel production technologies.

- The state must actively provide support to regions and social groups potentially affected by the transformation of the steel industry. The agenda for a just transition, which currently focuses on mining regions, must therefore be extended to industrial regions as well.

Introduction

In this report, we answer questions on why Poland needs to and from where it can source low- or zero-emission steel. Steel is indispensable in many sectors of the economy. Among the most important are the defense, automotive or construction industries. In order to keep these key domestic industries competitive, we need cheap and clean energy and low- or zero-emission steel. How do we achieve it? We aim to answer this question in this report, presenting the results of modelling the production costs of decarbonised steel.

Polish industry, including the steel sector, faces the historic challenge of decarbonisation and maintaining its competitive position. Domestic steel producers are under increasing pressure from competition from non-European producers. In addition, in 2026, free allocation of CO_2 allowances in the EU ETS will start phasing down. From 2034 onwards, steel mills will have to pay for all CO_2 emissions they generate. In 2023, the EU's Carbon Border Adjustment Mechanism (CBAM) came into force, which is unfortunately likely to cause carbon leakage and not protect European producers against their non-EU competitors who do not bear CO_2 costs. Energy prices in Poland are likely to remain higher than in the rest of Europe for a long time to come.

All over Europe new investments in green steel plants are developing. These are based on Direct Reduced Iron technology using an Electric Arc Furnace and hydrogen as a reducing agent (DRI-EAF + H_2). Ultimately, they are to be zero-emission through the use of green energy and green hydrogen, making them more competitive with steel produced using traditional coal-based blast furnace technology. All these factors negatively affect the position of the domestic steel industry, for which no decisions on the decarbonisation pathway have been taken so far.

Steel production in Poland has been declining for almost a decade, making us an increasingly bigger importer of steel. Domestic producers are not benefiting from the economic growth and increasing demand for steel, as they remain uncompetitive vis-à-vis imports, i.a. due to energy prices. Despite the significant consumption of steel in many sectors of the economy (e.g. construction, infrastructure, automotive industry), Poland lacks a consistent industrial policy.

The Polish government and manufacturers face a strategic choice:

- save the current primary steelmaking plant in Dabrowa Gornicza (ArcelorMittal) using blast furnace and basic oxygen furnace (BF-BOF) and equip it with CO_2 capture technology (CCS),
- build a new green steel plant (DRI-EAF + H_2),
- bet on the production of only scrap melted steel (EAF) and rely on imports of primary steel.

Every major industrial economy in Europe has already chosen the method of deep decarbonisation of steel production. Further years of delaying this decision in Poland will only widen the trade gap, leading to an uncontrolled, ”wild” transformation of the steel sector. In particular, the closure of the ArcelorMittal plant in Dabrowa Gornicza would have severe consequences. If it proves impossible to save this plant, the government and the local government must take this into account in managing the just transition of Upper Silesia and mobilise resources from the EU’s Just Transition Fund (JTF).

In our report, we identified four technology options for steel production and sourcing in Poland and the scenarios subordinated to them:

OPTION
1

Construction of a green steel plant with Direct Reduced Iron technology using an Electric Arc Furnace and hydrogen as a reducing agent (DRI-EAF + H_2) - at the current location of the steel plant in Dabrowa Gornicza (brownfield) or at a new location with access to large volumes of RES energy and green hydrogen (greenfield, in the north of Poland).

OPTION
2

Equipping the current coal-based steel plant in Dabrowa Gornicza with CO_2 capture technology (CCS) while investing in the infrastructure for its transport (by rail or pipeline) and storage (in or outside Poland).

OPTION
3

Further development of electric arc furnace (EAF)-based metallurgy using electricity, either through the construction of a new EAF plant located close to existing plants of this type (e.g. in Dabrowa Gornicza on the site of the BF-BOF plant, brownfield) or in a new location (greenfield) closer to large volumes of energy from RES (in the north of Poland).

OPTION
4

Importing green and competitively priced steel from abroad.

Each of these options requires government support through the creation of new regulations and enabling investment in sectors crucial to decarbonising the steel sector. These are primarily the hydrogen economy (option 1) or CCS infrastructure (option 2).

Our analysis shows that most such activities in leading European economies take place with strong state support that co-finances new investments. Further steps on the part of the government and potential investors are:

- determining which of the possible technology options is worth supporting,
- the choice of support instruments - regulation, subsidies and preferential financing, carbon contracts for difference, etc.,
- a detailed viability study from an investor perspective.

This report provides the knowledge to take these steps thoughtfully.

The analysis consists of the following chapters:

① Chapter 1 synthesises key facts about the steel market in Poland - production, trade balance and CO_2 emissions, as well as the challenges for steel production in relation to European climate policy.

② Chapter 2 takes a closer look at the possible technology options.

③ Chapter 3 presents the results of Instrat's Calculator of Steel Production Cost in Poland by listing technology options. The model is based on the Agora Industry's recognised tool and is available under an open licence. It is attached as an appendix to this paper - please feel free to download it for further analysis of your own, at the address indicated in the editorial footer.

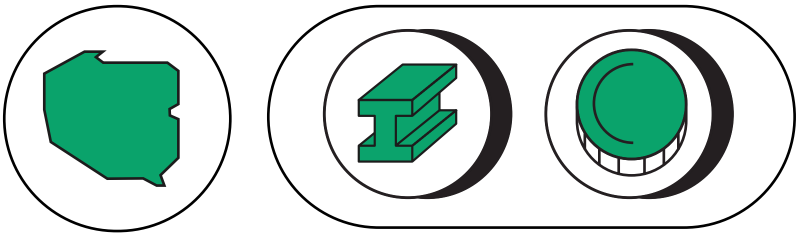
1. Steel production in Poland

1.1. Importance of steel production for the Polish economy

Poland's steel production fell to a record low of 6.5 million tonnes in 2022. In 2023 Poland ranked 23rd in the global ranking of the largest crude steel producers. Among European countries, Russia (76 million tonnes), Germany (35.4 million tonnes), Italy (21.1 million tonnes), Spain (11.4 million tonnes), France (10 million tonnes) and Austria (7.1 million tonnes) produce more steel (World Steel Association, 2024).

The role of basic metals manufacturing in Poland is similar to that in the economies of Germany, Italy or Spain. The entire basic metals sector[1] accounted for 0.6% of the gross value added of the Polish economy in 2021 - a value very close to the European average. Among the largest EU economies, a higher share of the basic metals sector in gross value added was recorded in Italy (0.7%), while a lower percentage was recorded in Spain (0.5%) and France (0.3%) (Eurostat, 2024). In Germany, the share is at a similar level to Poland.

Crude steel production in Poland has been declining for more than five years. Between 2012 and 2021, production remained at 8-10 million tonnes of steel. In 2022, it fell to 7.5 million tonnes and in 2023 already to 6.5 million tonnes, down 13.5% y-o-y (Figure 1). This decline was larger than in Germany (-4%), Italy (-2.3%) or Austria (-5.3%), but smaller than in France (-17.4%) (World Steel Association, 2024). Reasons for the decline in crude steel production in Poland included the closure of ArcelorMittal's integrated steel plant in Cracow in 2020 as a result of the recession caused by the COVID-19 pandemic, the increase in CO_2 prices from 2020 onwards, and then the energy crisis of 2022-2023 and the sudden increase in energy prices.



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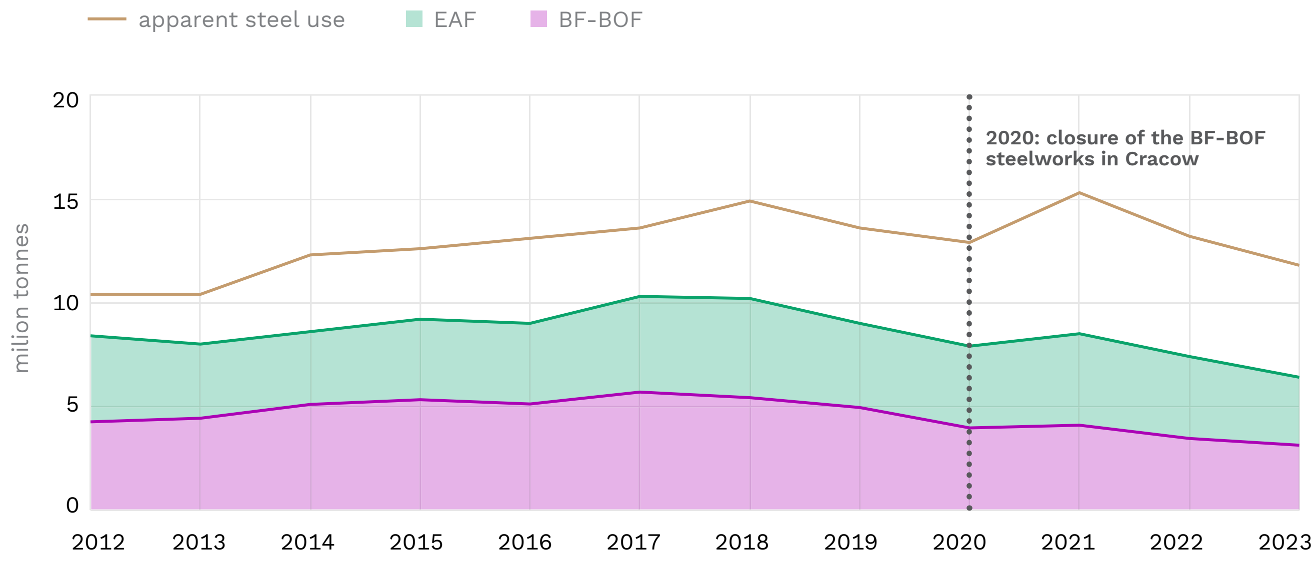
[1] This includes not only steel producers, but also other metals, including aluminium. Accurate data on the steel industry alone is not available.

FIGURE 1. Crude steel production by blast furnace and basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) technologies in Poland in 2012-2023 versus estimated domestic consumption of apparent steel use (million tonnes)



Source: Instrat's own elaboration based on World Steel Association (2024).

Poland's steel production is not meeting domestic demand. In 2023, Poland consumed nearly 5.5 million tonnes more steel than it produced, while in 2012 the gap was still 2 million tonnes. Over the decade, the gap between domestic production and consumption has thus widened by 3.5 million tonnes, i.e. by 170% (Figure 1). Poland has thus become one of the largest steel importers in the world. In 2023, the surplus of steel imports over exports was 6.5 million tonnes (World Steel Association, 2024; Bukowski, Bocian; 2024). This is the highest import balance among EU countries. Most of the steel produced in Poland is exported, and domestic demand is met by imports, mostly from Germany (Kapczyńska, 2024). The trade balance is steadily deteriorating. Since 2015, steel imports have increased by around 20% and the trade deficit has widened by 2.4 million tonnes between 2015 and 2023 (World Steel Association, 2024).

The world's main customers for steel are industries as follows:

- construction,
- mechanical equipment,
- automotive and transport,
- metal products,
- related to the construction of renewable energy sources, including wind turbines (World Steel Association, 2024).

BOX 1. Key players in the Polish steel industry

Polish crude steel production is dominated by large foreign companies. ArcelorMittal is responsible for more than half of Polish production. It is also the second largest producer of crude steel in the world, producing 68.5 million tonnes in 2023 (World Steel Association, 2024).

ArcelorMittal Poland's most important plants include:

- primary steelmaking plant based on a blast furnace and basic oxygen furnace in Dabrowa Gornicza,
- steel processing facilities in Kraków, Sosnowiec, Chorzów and Świętochłowice,
- coking plant in Zdzieszowice.

ArcelorMittal, through a separate company, also manages Huta Warszawa, which produces steel using an electric arc furnace. The Dabrowa Gornicza steelworks, since the Cracow furnace was shut down in 2020, is the only steelworks in Poland producing primary steel using traditional BF-BOF technology using coke.

In 2023, the two **ArcelorMittal** companies produced a total of nearly 3.6 million tonnes of crude steel in Poland - about 55% of the total domestic production (ArcelorMittal Poland, 2024; ArcelorMittal Warsaw, 2024; Statistics Poland, 2024)[2]. Such a result ensures the group's dominant position in the Polish market. The Warsaw-based company, together with its subsidiaries, employs 631 people (ArcelorMittal Warsaw, 2024). ArcelorMittal Poland - over 9 000 (ArcelorMittal Poland, 2024).

In 2023 ArcelorMittal has earmarked PLN 720 million to modernise the blast furnace in Dabrowa Gornicza. This will reduce the carbon intensity of production, and the furnace itself is expected to be in use for another dozen years or so. With co-financing from the National Research and Development Centre, the company spent PLN 200 million to expand its steel product range. In total, ArcelorMittal Poland has earmarked around PLN 1.5 billion for investments in 2023 (ArcelorMittal Poland, 2024). ArcelorMittal Warsaw spent PLN 120 million for investments in 2022-2023 (ArcelorMittal Warsaw, 2024). These initiatives are expected to contribute to the company's stated goal at the European level of reducing CO2 emissions by 30% by 2030 and achieving climate neutrality by 2050.

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[2] Steel production in 2023 was lower than usual due to the furnace overhaul in Dabrowa Gornicza resulting in the reduction in production.

Another important producer in the Polish steel market is **Liberty Steel**, subsidiary of the global industrial conglomerate GFG Alliance. In 2021, it took over the Huta Czestochowa (Czestochowa steel plant), currently based on electric furnace (EAF) technology, from its previous owners (Industrial Union of Donbas, ISD). At the time of publication of this text (October 2024), however, the plant is in bankruptcy. Discussions are underway with investors regarding the takeover of the plant by a new owner (Mamoń, 2024).

The Cognor Group is another major player on the domestic steel market, with electric arc furnaces in Gliwice and Stalowa Wola. The company has Polish owners and is listed on the Warsaw Stock Exchange.

Another important entity is **CMC Poland**, which is part of the US-based Commercial Metals Company. The company's most important plant is the electric arc furnace in Zawiercie, which also houses rolling mills, a paint shop and a welding shop.

The Swietokrzyskie region is home to Huta Ostrowiec (Ostrowiec steel plant), which has been part of the assets of Spanish metals company **Celsa** since 2003. However, in July 2024, the Ostrowiec Swietokrzyski furnace was put up for sale. At the time of publication of this report, discussions with potential buyers were ongoing, but the transaction had not yet been completed (Myszor, 2024b).

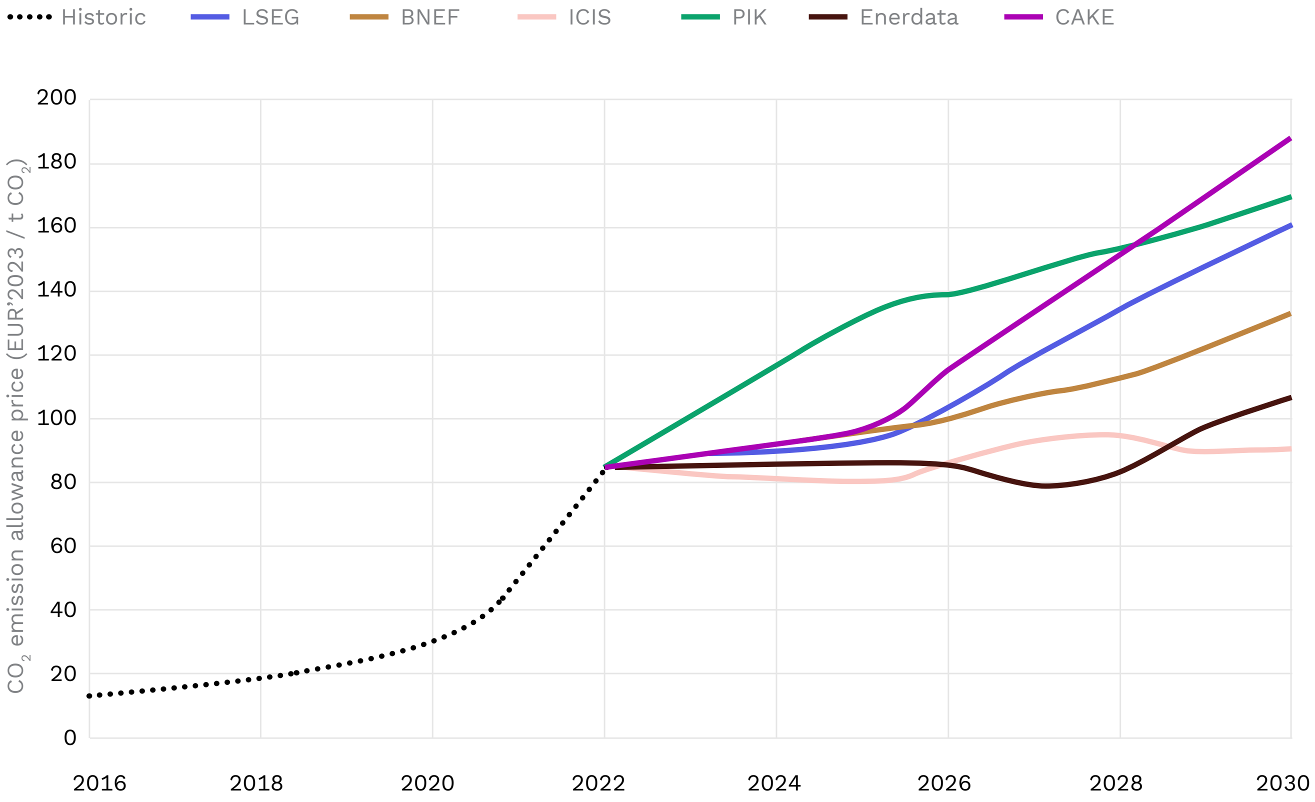
One of the smaller crude steel producers in Poland is **Alchemia S.A.**, owner of the Chorzow electric steelworks. It is part of the Boryszew Group, a holding company with Polish capital listed on the Warsaw Stock Exchange.

1.2. European climate policy as a stimulus for the transformation of the Polish steel sector

Meeting the EU's climate targets is a key challenge for energy-intensive industries, including steel producers. As a result of the reform of the EU Emissions Trading System (EU ETS), the number of free CO_2 allowances for energy-intensive industries, including steel, will fall to zero between 2026 and 2034 (European Parliament, 2022). This means that from 2034 onwards, industrial plants will have to pay the full price for each tonne of CO_2 emitted. Estimates by various intelligence providers indicate a further increase in the price of emission allowances to as much as 190 EUR per tonne of CO_2 in 2030 and 440 EUR per tonne CO_2 in 2050 (KOBiZE, 2023; Pyrka et al, 2023; Ariadne, 2023; Figure 2).

In parallel to the phase-out of free CO_2 allowances CBAM will come into effect from 2026 (European Parliament, 2022). The aim of the Carbon Border Adjustment Mechanism is to protect European companies from competition of the non-EU producers of steel and products with a key share of steel not paying the full carbon price. The import levies are supposed to mirror the CO_2 costs that producers in the EU would incur.

FIGURE 2. CO_2 emission allowance price projections until 2030 according to six major EU intelligence providers (EUR'2023/t CO_2)



Source: Instrat's own elaboration based on KOBiZE (2023) and Ariadne (2023).

From 2039 onwards, no more new CO_2 allowances will be issued for the power and industrial sectors. This is due to the reduction rate currently assumed in the EU ETS Directive for the total pool of emission allowances (European Environment Agency, 2023). It is likely that this schedule will still be subject to change or that an EU trading market for CO_2 removal certificates will be established. However, the carbon sequestration technologies required for this are only just entering a phase of mass development and may not develop to a level allowing to generate the number of certificates meeting the demand of CO_2 emitters by 2039. Nevertheless, the actions of the European Union indicate that it is determined to decarbonise industrial production and the regulatory pressure to reduce CO_2 emissions will increase.

In the next decade, the competitiveness of low- or near-zero-emission steel production will increase (as opposed to so-called dirty steel). This is because it will not be burdened by the cost of more expensive CO_2. The price increase will be fastest and highest for steel produced in the particularly emission-intensive blast furnace and basic oxygen furnace technology (BF-BOF), i.e. for about half of the steel produced in Poland. To a lesser extent, increases will affect the much less emissive electric arc furnace (EAF) technology.

BOX 2. Green steel plants in Germany

The steel sector is responsible for about 30% of emissions from the German industry (Schreck et al., 2023). Therefore, decarbonising this industry is one of the key challenges, the German government has introduced a number of policies, regulatory and financial instruments to support the transformation of this sector towards more sustainable production.

Such government measures include a strategy for the development of the hydrogen economy (German: *Nationale Wasserstoffstrategie*; BMBF, 2023), as well as direct involvement in investments in specific steel plants. The federal government, together with the state government of North Rhine-Westphalia, has committed a total of around EUR 2 billion to invest in the decarbonisation of the Thyssenkrupp steelworks in Duisburg, which will change the technological process from blast furnace and basic oxygen furnace to Direct Reduced Iron technology. The plant owner's share of the project was less than EUR 1 billion (Thyssenkrupp, 2023; Reuters, 2023). In October 2024, however, Thyssenkrupp announced that it had begun to revise its plans for steel production using green hydrogen. The authorities in North Rhine-Westphalia have already announced that Thyssenkrupp will have to give back a EUR 1 billion subsidy if the investment is abandoned. The company, however, has not confirmed that it plans to abandon the project, although it is calculating the possible costs of such a decision (wnp.pl, 2024; Euronews, 2024).

Also with the support of the federal and state government, the SALCOS project is being implemented to bring about a technological change at the Salzgitter AG steelworks. Emission-intensive production will be replaced by low-carbon steel production using a technology of Direct Reduced Iron and Electric Arc Furnace (DRI-EAF + H_2), which is expected to lead to a 95% reduction in emissions. The total federal and state aid will amount to around EUR 1 billion (Salzgitter AG, 2023). Using support from Horizon 2020, the company is also conducting implementation research related to increasing the efficiency of hydrogen generation using high temperatures (Salzgitter AG, 2024).

Germany has also pioneered the use of carbon contracts for difference as a form of public support for green investment in industry. In March 2024, the first call for applications was launched under the programme (BMWK, 2024), the essence of which is to subsidise green industrial production until, as the cost of emissions rises, it becomes cheaper in relation to the reference price for CO_2 set in the contract. At that point, the company begins to reimburse the government for the difference between the price set in the contract and the actual price of the CO_2 allowance. This instrument is aimed at all industrial companies in Germany, including steel companies.

2. Four options for sourcing low- or zero-emission steel in Poland

The decarbonisation of steel production and use in Poland can take place through four options:

1	**Construction of a new primary steel plant** at the current location (Dabrowa Gornicza) or at a new location (in the north of Poland) based on Direct Reduced Iron (DRI) technology using hydrogen (H_2) as a reducing agent and an Electric Arc Furnace (EAF), which together form an integrated steelworks.	**DRI-EAF + H_2**
2	**Modernisation of the current integrated steelworks** (Dabrowa Gornicza) based on coke-fired blast furnace and basic oxygen furnace (BF-BOF) technology through the construction of a carbon capture facility and infrastructure for onward transport to storage sites (CCS).	**BF-BOF + CCS**
3	**Production of steel from scrap** at existing or new locations based on Electric Arc Furnace (EAF) technology.	**EAF**
4	**Imports of green steel** from countries with a developed production base - transported overland from nearby markets or by sea from southern Europe or northern Africa.	**Import**

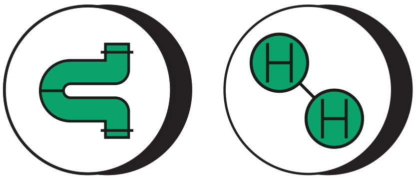
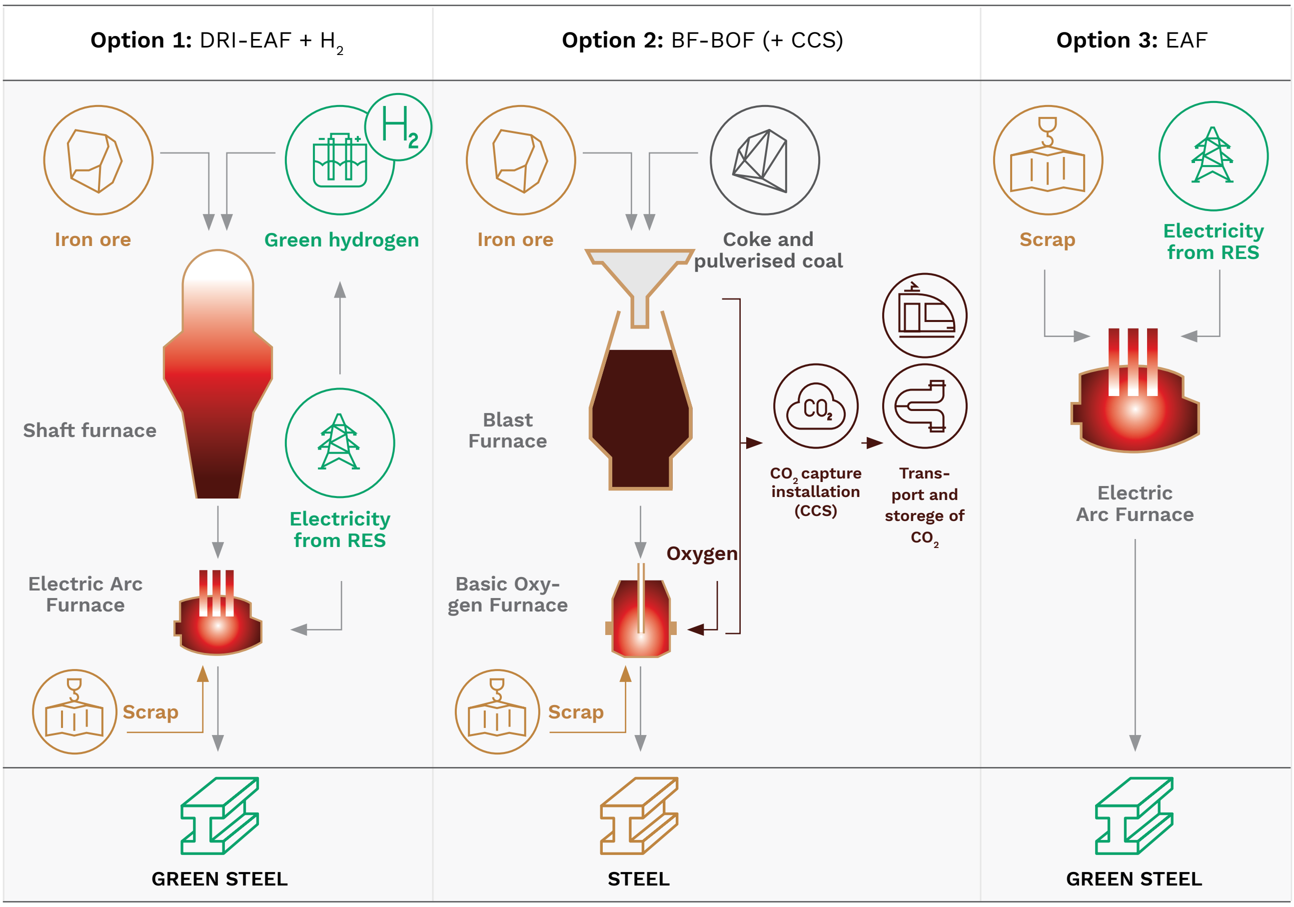


Diagram 1 illsutrates in a simplified way the first three technology options, which are discussed in detail later in the chapter.

DIAGRAM 1. Simplified process of producing low- or zero-emission steel in a steel plant based on Direct Reduced Iron (DRI-EAF + H_2), in a blast furnace and oxygen converter with CO_2 capture (BF-BOF + CCS) and in an Electric Arc Furnace (EAF)



Source: Instrat's own elaboration based on IRENA (2022). Significant adaptations have been made relative to the original version of the scheme.

2.1. Option 1: Direct Reduced Iron using hydrogen and Electric Arc Furnace (DRI-EAF + H_2)

In the process of direct reduction of iron and further smelting in an electric arc furnace, steel is produced from iron ore using hydrogen or possibly natural gas as a reducing agent (DRI - *direct reduction of iron*; EAF - *electric arc furnace*). The heat energy comes from the combustion of hydrogen (or natural gas), which also serves as a reducing agent (analogous to the role of coke in a blast furnace).

If produced from renewable energy sources, the hydrogen (so-called green hydrogen) used in this technology makes it possible to decarbonise steel production by 95% compared to today's default option - the blast furnace and basic oxygen furnace (Keßler, Lovisolo, 2023). In such a process, the by-product is steam instead of CO_2. The pig iron produced by the direct reduction process from the melted iron ore must then be melted in an electric arc furnace (EAF) - hence the acronym DRI-EAF.

A key constraint to the deployment of DRI-EAF + H_2 technology is access to green hydrogen. Access to locally produced hydrogen is dependent on the availability of large volumes of green electricity (renewables acceleration area). Furthermore, the current low ability of electrolyser manufacturers to provide highly reliable equipment (electrolysers and associated apparatus) is a constraint. The industry is still at an early stage of development. Another constraint is the legislation that is being developed to regulate hydrogen economy. In Poland, projects are being developed to increase the scale of hydrogen production and reduce its costs.[3]

Currently, natural gas is cheaper than green hydrogen for use as reductant in the DRI process (Kopeć et al., 2023). However, the disparity in prices of both may change.[4] It may be caused, on the one hand, by an increase in the emission costs associated with the use of gas and, on the other, by an increase in the efficiency of high-volume green hydrogen production and the production of the electrolysers themselves. The International Energy Agency (IEA) predicts that by 2030, the price of an electrolyser could fall by 60% compared to 2023 (IEA, 2023).

In what follows, we take into consideration only the option of using green hydrogen for the green steel mill (DRI-EAF + H_2). We do not consider a scenario in which natural gas would be used as a reducing agent at the DRI steelworks. Such a solution would, in our opinion, be transitional and most likely economically and geopolitically unjustified (high upfront investment in gas supply infrastructure and rising costs of CO_2, lack of adequate domestic natural gas resources).

The cost of producing green steel through the DRI process could fall as electricity and hydrogen prices fall. This would improve the competitiveness of this production. At the same time, the cost advantage of this technology over others, especially BF-BOF, will increase as the price of CO_2.

A green steel plant (DRI-EAF + H_2) is much more sensitive to the price of externally sourced electricity than a traditional steel mill (BF-BOF) obtaining electricity through energy recovery from heat generation processes. In turn, an increase in the price of CO_2 emission allowances in the EU ETS will increase the production costs of the BF-BOF steel.

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[3] One example is the LOTOS Green H2 project, which is being implemented with public support and involves the construction of a 100 MW electrolyser next to the refinery in Gdansk (MKiŚ, 2023b). Orlen has also announced the construction of electrolysers using surplus electricity from wind farms in the Baltic Sea (Orlen, 2022). In turn, Polenergia's project is being developed in Silesia, where the EU IPCEI Hy2Infra project envisages the construction of a green hydrogen plant (H2Silesia) with a capacity of approximately 105 MW, while the production volume is expected to reach 13 000 tonnes of hydrogen per year (Polenergia, 2024).

[4] The vast majority of existing DRI plants are operating in Arab countries precisely because of the low cost of locally sourced natural gas. In the European context, it should be noted that most of the DRI projects being started are based on natural gas in the initial phase rather than directly on green hydrogen as a reductant not because of the price, but the current availability of both raw materials.

This may increase the difference between the production costs and thus the potential margin of the green steel producer, i.e. the difference between the selling price of the steel and its production costs at the DRI plant. A detailed sensitivity analysis is presented in the next chapter.

A comparison of the production costs of green steel is not sufficient for investors to decide whether to invest in the construction of a new steelworks. This is because an assessment of the cost competitiveness of one technology compared to another does not allow for a clear-cut assessment as to which of the option will win in the technology race. The analysis of the profitability of the investment also relies on other detailed financial indicators[5], which in the long time horizon of an investment of the size of a steel mill are more complex and variable than in the case of smaller, simpler investments.

This is why countries betting on the development of DRI-EAF + H_2 technologies offer generous financing: grants to cover capital expenditure (CAPEX) or debt financing (credit, guarantees) at below-market interest rates (Box 2). The latter is particularly relevant for Poland and non-Eurozone countries, where currently persistently high interest rates reduce investors' willingness to undertake investments.

The European Commission offers funds and grants for decarbonisation projects in industry and the hydrogen economy. The EU Innovation Fund supports projects reducing greenhouse gas emissions in the industrial sector, including steel production (European Commission, 2024b). Among others, the HYBRIT project, which will deploy DRI technology in Sweden, and several projects in Poland, although not in the steel sector, received support from this instrument (European Commission, 2022).

There is an ongoing discussion on how to strengthen decarbonisation funding from the EU funds in the next EU financial perspective (after 2027) to complement that offered by Western governments (Korolec, 2024; Kopeć et al., 2023; Financial Times, 2023).

At least 13 DRI steel plants using green hydrogen technology are being built in Europe. These investments are mainly outside the CEE region (Table 1). Some are to focus only on direct reduction and transfer the iron to other plants for further processing. Others plan to produce steel on-site in electric furnaces (EAFs). There are also projects involving the construction of electrolysers (ELS), including one building RES capacity.

Table 1 provides an overview of green metallurgy investment projects from across Europe - these are being carried out by both industry-experienced metallurgical companies and new investors, in virtually all parts of Europe. The exception to this list is Central and Eastern Europe, as only in Romania there is the LibertySteel project underway.

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[5] A correspondingly high rate of return - IRR (internal rate of return), or positive NPV (net present value).

TABLE 1. Green steel plant projects in Europe

Company	Location	Technologies	Planned launch	Production capacity (million tonnes per year)
ArcelorMittal	Ghent, Belgium	DRI + EAF	2030	2.5
Blastr Green Steel	Inkoo, Finland	DRI + EAF + ELS	2026	2.5
ArcelorMittal	Ghent, Belgium	DRI + EAF	2030	2.5
GravitHy	Fos-sur-Mer, France	DRI	2027	2
ArcelorMittal	Gijón, Spain	DRI + EAF	2025	1.1
H2 Green Steel	Spain	DRI + ELS	2025	2
Hydnum Steel	Puertollano, Spain	DRI + EAF + ELS + RES	2026	0.6
ArcelorMittal	Hamburg, Germany	DRI + EAF	2026	1.75
Dillinger Saarstahl	Dillingen, Völklingen, Germany	DRI + EAF	2027	3.5
Salzgitter	Salzgitter, Germany	DRI + EAF	2033	1.9
Thyssenkrupp	Duisburg, Germany	DRI	2026	2.5
Metalloinvest	Zheleznogorsk, Russia	DRI	2024	2.1
Liberty Steel	Galač, Romania	DRI + EAF	2024	2.5
H2 Green Steel	Boden, Sweden	DRI + EAF + ELS	2024	5

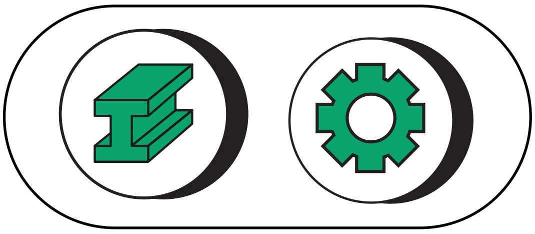
Source: Instrat's own compilation based on data from DIW Berlin (Hüttelm, Lehner; 2024).

DRI - *Direct Reduced Iron*.

EAF - *Electric Arc Furnace* (EAF).

ELS - electrolyser.

RES - *Renewable Energy Sources*.



2.2. Option 2: Blast Furnace-Basic Oxygen Furnace with CO_2 capture and storage (BF-BOF + CCS)

Blast Furnace-Basic Oxygen Furnace (BF-BOF) technology is currently the world's leading method of steel production. Approximately 70% of the world's crude steel is currently produced annually via this route (Bukowski, Bocian, 2024).

In the blast furnace, iron ore, at temperatures above 900°C, undergoes so-called reduction, or purification. The reduction is made possible by supplying coke to the blast furnace, and the whole process is stimulated by blowing hot air and pulverised coal. The coke is burned in the blast furnace and the products of its combustion react with the iron oxides present in the ore, attaching oxygen to each other. The products of this reaction are carbon dioxide and iron in the form of so-called pig iron. The pig iron is further purified in an oxygen converter, where the remaining impurities are oxidised (and thus removed) by blowing pure oxygen.[6]

CCUS technology involves the capture of CO_2 from plants relying on fossil fuels. The captured CO_2 can then be transported to:

① storage sites (CCS - Carbon Capture and Storage),

② further use in other industrial processes (CCU - Carbon Capture and Utilisation).

This method can allow existing steel plants to be upgraded without having to completely rebuild them and potentially save them from closure (World Steel Association, 2024b; Laskowski, 2023). The key parameters that define the application of CCUS technology are:

- investment costs,
- concentration level of CO_2 in the flue gas stream,
- capture efficiency (share of captured CO_2 in total CO_2 produced),
- the energy intensity of the process,
- the technical readiness of the plant to install an effective CCS installation (CCS readiness),
- possibility to use CO_2 for the production of other materials,
- method and cost of transport (by rail or pipeline),
- method and cost of storage (locally or abroad).

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[6] In Chapter 3 we present the details on CO_2 emissions from this technology.

CCUS technology has not been implemented on a large scale at any major BF-BOF steel plant (Nicholas, Basirat, 2024). Instead, it is at an increasing stage of development in the cement sector. Unlike DRI-EAF + H_2 technology there are also no major projects underway to change this. The exception is ArcelorMittal's Ghent smelter, where the first pilot plant to capture CO_2 and convert it into CO (carbon monoxide) was commissioned in 2024 in collaboration with Mitsubishi Heavy Industries and D-CRBN. The CO obtained is then used as a reducing agent in the steelmaking process or in the chemical industry. However, this project is limited in scope as it captures CO_2 from only one emission point within the steelworks (the blast furnace). The efficiency of this process is not publicly known (ArcelorMittal, 2024b).

Existing BF-BOF integrated steel mills have technological limitations hindering the achievement of high CO_2 capture efficiency. A significant challenge in achieving high levels of CO_2 recovery, and thus reducing the cost of purchasing CO_2 allowances, is the inherently leaky and multi-step process steel production. Therefore, literature and research on the feasibility of CCS in all energy industries and processes considers the steel sector to be one of the more difficult to decarbonise through this pathway.

The assumed CO_2 capture efficiency of such an installation in the blast furnace and basic oxygen furnace alone is about 60%. The remaining 40% would still be emitted to the atmosphere (Clean Air Task Force, 2022). Nevertheless, CCS can be successfully applied to all other parts of the carbon steel value chain, in particular the power and CHP plants supplying the steel mill with energy utilities.

In the case of the Dabrowa Gornicza plant, CCS would also need to be located at the NOWA CHP Plant (owned by the TAMEH company), where this efficiency can reach 80-90% due to the more tightly controlled technological process (ibid). Hence, the weighted average capture rate from the entire total CO_2 stream that we examined is around 75% at this particular plant.

CCS technology is associated with high investment and operating costs and regulatory uncertainty. Estimated by the Clean Air Task Force (CATF, 2022), the cost of CO_2 capture, transport and sequestration for the Dabrowa Gornicza steelworks ranges from 79-160 EUR per tonne CO_2 (see Chapter 3 for detailed calculations and sensitivity analysis).

CCS technology is supported by the EU Innovation Fund, but so far projects in the steel sector have not received a grant. In the last call for large-scale projects completed in 2023, CCUS projects in the cement and lime sector in Belgium, Germany, Croatia and Greece were supported (European Commission, 2024a). In an earlier call, a project at the Kujawy Cement Plant in Poland also received funding. In both calls, no support was granted to large-scale CCUS projects in the steel sector.

In Poland, the only candidate for large-scale CCUS implementation in the steel sector is the last steelworks to use blast furnace and basic oxygen furnace technology, the ArcelorMittal-owned plant in Dabrowa Gornicza.

BOX 3. CO$_2$ capture technology at the Kujawy Cement Plant - Kujawy Go4ECOPlanet project.

The manufacture of cement, like steel, is associated with significant CO$_2$ emissions. Unlike the steel sector, however, the cement industry practically lacks technological alternatives to produce emission-free cement with identical parameters (Kopeć et al., 2023). That is why Kujawy Cement Plant, a member of the Holcim Group, is leading a project to implement CCS. CO$_2$ capture will start there as early as 2027, and the installation will capture 100% of the emissions from the core production process of clinker production. This amounts to more than 1 million tonnes of CO$_2$ per year (Holcim, 2024).

The CCS technology at the Kujawy Cement Plant involves capturing CO$_2$ from the cement production process and then compressing and transporting CO$_2$ to storage sites in the North Sea, and potentially to onshore national storage sites in the future. Air Liquide is the company developing the cryogenic CO$_2$ recovery technology, Cryocap™ FG.

The CCS project at the Kujawy Cement Plant required significant investment. The total cost of the project is estimated to be around 380 million euro. The investment is co-financed with as much as EUR 228 million by the EU ETS-funded Innovation Fund.

The long-term operating costs associated with the CCS technology can be significant due to the energy intensity of the process. However, these are expected to be offset by savings from avoided CO$_2$ emission allowances. In Europe, CO$_2$ emission allowance prices currently amount to around 70 EUR per tonne of CO$_2$, but will consistently increase as a result of the evolution of the EU ETS and the decrease in the allocation of free CO$_2$ allowances to energy-intensive industries.

2.3. Option 3: Electric Arc Furnace (EAF)

In an Electric Arc Furnace (EAF), steel is produced by melting steel scrap using an electric arc at a temperature of approximately 1800°C. In addition to scrap, the raw material can be iron obtained from the direct reduction of iron (DRI, cf. subsection 2.1.) process, also in cold form (HBI - *hot-briquetted iron*) - transported from a DRI steelworks. In our scenario, however, we assume the use of EAF furnaces exclusively for scrap remelting.

The EAF process is associated with up to 20 times lower emissions than the BF-BOF process. In the BF-BOF process in Poland, direct emissions reach 1.9 tonnes CO_2 per tonne of steel produced. If the emissions of coking plants are added to this, the emissivity of a tonne of crude steel rises to 2.1 tonnes CO_2 per tonne of steel. Meanwhile, the EAF process, when provided with 100% emission-free electricity, is associated with emissions of only about 0.06 t CO_2 per tonne of steel[7] (Figure 6). However, the process uses small amounts of coal and natural gas, so caution is advised in describing this technology as fully green.

Access to cheap and emission-free electricity in Poland is crucial for a viable EAF steel production. The development of electric steel mills will be supported by investments in the decarbonisation of the Polish energy sector, in particular the possibility to purchase energy under the formula of power purchase agreements (PPAs) or through direct lines.

The construction and operating costs of an EAF plant are lower than those of blast furnaces. The construction of an EAF mill with an annual production capacity of 1 million tonnes of steel in a brownfield formula is around €500-900 million[8] (Hüttelm, Lehner, 2024). Operating costs depend mainly on electricity and scrap prices.

Polish steel mills, apart from Dabrowa Gornicza, currently operate using electric arc technology. These are plants in Czestochowa, Warsaw, Zawiercie, Gliwice, Ostrowiec Swietokrzyski, Stalowa Wola and Chorzow (Box 1). The presence of know-how from this sector in Poland and the fact that EAF is a mature technology can significantly reduce the cost of building new plants. ArcelorMittal, which operates not only the only BF-BOF plant in Poland but also an EAF plant in Warsaw, is planning significant investments in European EAF plants as part of its decarbonisation strategy (ArcelorMittal, 2021).

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[7] In the case of the BF-BOF process, coal combustion plays both a process role (iron reduction) and an energy role (heat). For this reason, it can be considered that treating CO_2 emissions from coal combustion in this process as direct emissions distorts calculations on direct emissivity compared to EAF technology, whose energy emissions take place off-site - in scope 2. However, the inclusion of coal is supported by the fact that the provision of zero-emission electricity will not reduce BF-BOF emissions, while it will reduce emissions from the EAF process to almost zero. Taking into account Scope 2 emissions and, by extension, the structure of the electricity mix, the global average emissivity of steel produced from scrap in the EAF process is about 0.68 t CO_2 /t (World Steel Association, 2024) - still more than double that of BF-BOF.

[8] Average calculated on the basis of the four European projects included in our analysis.

The challenge for Polish EAF steel producers is to remain price competitive. This is made difficult by high electricity prices and increasing pressure from importers. The low level of capacity utilisation, currently reaching only 60%, is a consequence of the high price differential between domestic and imported production (Myszor, 2024a). The difficult financial situation of most Polish producers also translates into their low capacity for significant investment.

In Poland, the government planned to develop the capacity of electric steel plants. In 2022, the construction of a modern EAF steel plant in Ruda Slaska was announced with the involvement of the government. The project was to be implemented by Weglokoks S.A. (state-owned company) and was officially supported by the Ministry of State Assets. It was announced that the steelworks would be able to produce 1 million tonnes of steel per year. Its construction was to start in 2023 and last until 2027 (Węglokoks, 2022). The inactivity of the new government on this issue and the failure to start the investment indicate that its implementation has been suspended (bankier.pl, 2024).

2.4. Option 4: Importing green steel

A scenario in which Poland relies on imports of decarbonised steel instead of investing in its own capacity is also possible. Imports may also be the answer to the problems of the transition period until adequate domestic green steel production capacity becomes operational.

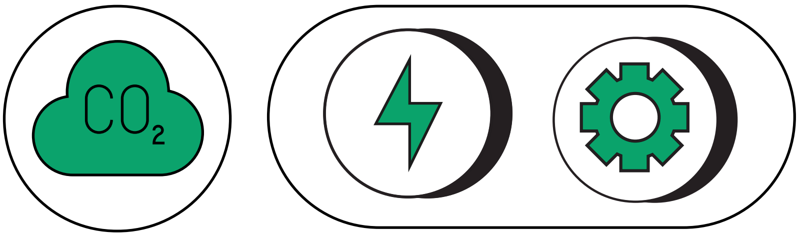
Polish steel mills are already unable to meet domestic demand for steel. In 2022, the volume of domestic production covered 56% of domestic consumption (Bukowski, Bocian, 2024). Thus, Poland is highly dependent on imported steel, and this dependence may worsen if we do not decarbonise steel production. In such a scenario, due to the rising cost of CO_2, domestic production facilities would supply material that is increasingly less cost-competitive compared to imported steel from abroad, even including its transport costs. This would result in a decline in capacity utilisation and consequently in the profitability of steel production in Poland, which in turn could force the closure of Polish steel plants (especially the high-carbon steel mill in Dabrowa Gornicza).

A scenario in which Poland relies on steel imports is not improbable. This is evidenced by the past history of the Polish steel sector. The increase in steel imports to Poland started after 1989, when domestic steel mills began to compete with foreign ones in the international market. After the communist era, the plants were not prepared to compete with foreign competition. In addition to the disproportionate capacity and the generous subsidisation of steel production by the state in the past, the reasons for the low competitiveness of Polish steel included technological backwardness.

It was necessary to restructure the Polish steel industry, which on the one hand meant reducing production and opening up to imports, but on the other hand made it possible to modernise the technological process and keep some steel production in Poland (Council of Ministers of the Republic of Poland, 2001).

Expensive energy and technological inadequacy could make the Polish steel sector lose out to foreign competition again. Producers of low- or zero-emission alternatives remain active. In Germany, our main foreign steel supplier, at least three DRI steel mill projects are in the pipeline (Table 1). New players from the Middle East and North Africa may join the race for dominance in the decarbonised steel market, also in Europe (IEEFA, 2023; GMK Center, 2023; Trollip et al, 2022; Hermwille, 2022). Metallurgy in the Arab countries is already largely based on Direct Reduced Iron (DRI) technology, but using natural gas instead of hydrogen (as a reducing agent). However, this geographic area shows great potential for hydrogen production due to the high availability of solar energy, creating favourable conditions for the decarbonisation of steel there.

Steel is a strategic material and will continue to be so in the future. It is an important material for defense production, the manufacture of green technologies or infrastructure and construction investments. Steel imports to Poland will probably always be necessary, not least because of the lack of access to iron ore, which is necessary for the production of primary steel. However, a question arises from the field of security: can Poland, and to what extent, give up its autonomy in the production of such a strategic material and rely on trading partners?



3. Low- and zero-emission steel - calculator of production cost in Poland

How much will it cost to produce green or decarbonised steel in Poland? We provide an answer to this question on the basis of the analysis and modelling of the steel production cost structure for three predefined technological options and scenarios resulting from them, described in more detail in chapter two.[9] We present their detailed configuration in Table 2.

TABELA 2. Overview of technological options and decarbonisation scenarios

Technological option		Decarbonisation scenario
1. DRI-EAF + H_2	Direct Reduction of Iron (DRI) using hydrogen as a reducing agent and an Electric Arc Furnace (EAF), which together form an integrated steel plant	1.1. Location in northern Poland in a renewables acceleration area (greenfield)
		1.2. Location in Dabrowa Gornicza (brownfield)
2. BF-BOF	Blast Furnace - Basic Oxygen Furnace in Dabrowa Gornicza	2.1. Equipping the steel plant with a CO_2 capture facility and transporting compressed CO_2 by rail to storage sites (CCS)
		2.2. Equipping the steel plant with a CO_2 capture installation and transporting compressed CO_2 by pipeline to storage sites (CCS)
		2.3. No CO_2 capture facility.
3. EAF	Electric Arc Furnace	3.1. Location of the steel plant in Dabrowa Gornicza (brownfield)
		3.2. Location of the steel plant in the north of Poland in a renewables acceleration area (greenfield)

Source: Instrat's own elaboration.

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[9] Due to the significant discrepancy in estimates of the production costs of decarbonised steel, e.g. in southern European countries, we have decided not to compare the fourth and last option (importing green steel) with the others, also due to the market situation related to the entry into force of CBAM.

The basis for the calculations is our adaptation of the steel production cost model developed by the Agora Industry think tank. To calculate steel production costs, we used the industry-recognised tool *Carbon Contracts for the transformation of industry: Calculator for the assessment of transformation costs for low-CO_2 primary steel production* (Agora Industry et al., 2022). The interactive calculator in the form of a pre-filled Excel spreadsheet (production cost model) was developed by the Agora Industry think tank in cooperation with the Wuppertal Institut research institute and the consultancy Future Camp.

However, we have made significant amendments to the existing tool, as we implemented new computing components that take into account:

1. the hydrogen production plant - we added a module on the activity of electrolysers in technology option 1 (DRI-EAF + H_2) to calculate the price of hydrogen (endogenously within the model, not as an external raw material) on the basis of the same purchase price of electricity as for the steel mill itself, and
2. CO_2 capture installation, transport and storage service (technology option no. 2).

Another important extension is the demonstration of a simplified cost and investment calculator, not available in the original version of the tool.[10] The full version of our calculator with the results described in this chapter is available for download from the Instrat website at the address indicated in the editorial footer (Hetmanski et al., 2024).

3.1. Assumptions and definition of scenarios

Table 3 shows selected key techno-economic and financial assumptions of the steel decarbonisation scenarios in scope of our analysis. Their detailed documentation can be found in the *Calculator of Steel Production Cost in Poland*, which forms the basis of this study, available for download at the address indicated in the editorial footer (Hetmanski et al., 2024).

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[10] The authors of this report thank the Agora Industry team, the Wuppertal Institut and Future Camp for their work and for popularising the tool under an open licence. The authors of the original model are not responsible for modifications made by Instrat.

TABLE 3. Key cost and technical assumptions for the steel production cost calculator

Technology option and decarbonisation scenario Assumptions			Option 1. DRI-EAF + H_2		Option 2. BF-BOF			Option 3. Nowy EAF	
			1.1. Location in the north of Poland	1.2. Location in Dabrowa Gornicza	2.1. CCS – CO_2 transported by rail	2.2. CCS – CO_2 transported by pipeline	2.3. No CCS	3.1. Location in Dabrowa Gornicza	3.2. Location in the north of Poland
Plant parameters	**Maximum annual production capacity** (million tonnes)		2.5		4.5			2.5	
	Annual production (million tonnes) [% of capacity utilisation]		2.0 [80%]		3.6 [80%]			2.0 [80%]	
CAPEX - capital expenditure	**Plant construction cost** (billion EUR)		2.4	2.0	-			1.6	2.0
	Replacement cost (% of variable costs, including CO_2)		-		5%			-	
Finance	**Depreciation period** (years)		20		1			20	
	Interest rate (%)		6%						
OPEX - key energy commodities	**Iron ore**	**Price** (EUR/t)	160		120			-	
		Consumption (t/t steel)	1.5		1.4				
	Scrap	**Price** (EUR/t)	300		300			300	
		Consumption (t/t steel)	0.17		0.2			1.2	
OPEX - key non-energy commodities	**Coke**	**Price** (EUR/t)	-		300			300	
		Consumption (t/t steel)			0.4			0.02	
	Pulverised coal	**Price** (EUR/t)	-		100			-	
		Consumption (t/t steel)			0.17				
	Natural gas	**Price** (EUR/MWh)	40		40			40	
		Consumption (MWh/t steel)	0.57		0.17			0.50	
OPEX - electricity and hydrogen	**Electricity consumption** (MWh/t steel)		0.7		-			0.75	
	Effective purchase and transmission price of electricity (EUR/MWh)		74	78	-			78	74
	Unit cost of hydrogen production (euro/kg H_2)		4.56	4.77	-			-	
Management of CO_2	**Management of CO_2 Price of CO_2 capture, transport and storage service** (EUR/t CO_2)		-		130	110	-	-	
	Direct CO_2 emissions (t CO_2/t steel)		0.04		1.9			0.06	
	CO_2 capture efficiency by CCS installation (%)		-		75%		-	-	
	The cost of CO_2 emission allowance price in the EU ETS system (EUR/t CO_2)		300						

Source: Instrat's own compilation - detailed cost assumptions and references to data sources can be found in the *Calculator of Steel Production Cost in Poland*, which is available for download at the address in the editorial footer.

Real prices from 2023.

The cost of hydrogen generation was calculated in the model (as an endogenous variable) rather than assumed as a constant value. The cost of CCS service, on the other hand, has been entirely assumed as a constant value based on the literature (CATF, 2022). This cost includes the cost of capital, operating costs and the cost of energy, but these remain independent of other values in the model.

We assume a long-term investment horizon for all decarbonisation options. In order to bring all investment options to a common denominator, we make an assumption about the operation of the three technology options over the long term - starting from 2040 onwards. This has implications for the assumption we make about electricity purchase and CO_2 prices.

However, investments in decarbonised steel mills can start earlier. The state plays a non-negligible role in accelerating them. Before the rising cost of CO_2 makes low- or near-zero-emission primary steelmaking technologies competitive with BF-BOF technologies (without CCS), the government can implement *Carbon Contracts for Difference*. Such a contract would, in simple terms, subsidize additional expenditure of a green steel producer compared to a conventional steel producer (Box 2).

ELECTRICITY CONSUMPTION

Based on the literature and the Agora Industry (2022) model, we assume that technology options no. 1 (DRI-EAF + H_2) and no. 3 (EAF) have similar electricity consumption in the range of 0.7-0.75 MWh per 1 tonne of steel. For option no. 2 (BF-BOF), we also assume, as in the Agora model, that the effective electricity consumption is 0 MWh per 1 tonne of steel.

COST OF PURCHASING ELECTRICITY

Based on Instrat's modelling of the Polish energy mix (Kubiczek et al., 2023), we take as the purchase price of electricity the average cost of electricity generation in 2040 (i.e. we include the cost of capital), which, according to this modelling, is 284 PLN/MWh (after conversion at the relevant exchange rate and rounding up to 65 EUR/MWh).[11] This is considerably less than the value of long-term contracts or PPAs currently observed on the energy exchange.

COST OF ELECTRICITY TRANSMISSION

At the same time, we assume that the level of transmission fee rates will remain at the current level, assuming a return to the current values after the investment wave of the 2020s and 2030s. After taking into account the part of the transmission rate that includes the capacity of the grid connection and after converting the rates expressed in PLN into EUR, we arrive at an effective electricity transmission price of 13.3 EUR/MWh.

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[11] In the ambitious scenario, which assumes ambitious development of RES and nuclear power (scenario S1).

We make an arbitrary assumption of a 30% discount on the transmission charge from the transmission system operator (PSE) for investments in energy-intensive industries, such as steel mills, located in renewables acceleration areas, primarily in the north of Poland. Our approach is based on the assumption that, after an appropriate reform, the law will allow price signals to be applied to electricity consumers located closer to generators, e.g. close to power hubs at offshore wind farms and a nuclear power plant. Then the effective transmission rate drops to 9.3 EUR/MWh.

THE COST OF CO_2

Based on the modelling of GHG emission reduction pathways in the European and Polish economy by CAKE (Pyrka et al., 2023), we take the value of CO_2 allowance price at 300 EUR/t in 2040 (after rounding) as the average of the values for 2030 (180 EUR/t) and 2050 (440 EUR/t).

Evolution of CO_2 allowance price allows to analyse whether the price parity between the different steel decarbonisation options changes over time in favour of the Option 1 (DRI-EAF + H_2) at the expense of Option 2 (BF-BOF + CCS) - these results are presented in the subsection containing the sensitivity analysis (3.3.).

We do not add mark-ups, margins or other forms of profit in any of the technology options. In the long term, we assume that each of the non-energy commodities (e.g. iron ore, scrap) and energy commodities and carriers (e.g. coke, electricity) supplied to the steelworks already includes a mark-up from its producer. We also do not model the revenues and selling prices of steel under different technology options - each type of steel will have different parameters (including emissivity) and thus be priced according to different market rules and achieve different margins.

In order to keep the comparison objective and technology neutral, we face the challenge of bringing several technologies to a common denominator. We therefore make some key assumptions about the configuration of investments supporting the steelmaking process. We assume that the service of supplying hydrogen (Option 1: DRI-EAF + H_2) and CO_2 capture, transport and storage (Option 2: BF-BOF + CCS) is provided by a specialised company separate from the steelworks, which would sign a contract with its customer (the steelworks) for the long-term supply of the service or product.

The aim is to relieve the steelmaker of the burden of capital expenditure and the need to specialise in a sector that does not have to be treated as a constituent part of the steelworks. The delegation of such activities (compared to the default in-house formula) is a common practice in the industry. We thus assume the development of regulation for both hydrogen management and CCS services.

In technology option 1 (DRI-EAF + H_2), we make the assumption of hydrogen production near the steel mill. However, it would not be produced by the company operating the steelworks. An analysis of DRI projects in Europe (Table 1) shows that the construction of electrolysers need not be part of the capital expenditure of the steel mill itself, but can be part of the bill of a separate energy company that enters into a long-term hydrogen supply contract with the steel plant. Thus, we count the cost of hydrogen production in the model (endogenously), but the capital expenditure for the electrolyser (about 1/4 of the CAPEX value for the DRI plant) is not included in the steel production cost account in the CAPEX part, but is included in the unit cost of producing hydrogen as one of the key energy carriers. Estimated hydrogen production costs are in the range of 4.56-4.77 EUR/kg[12]. We do not assume hydrogen transport or storage costs since hydrogen is to be produced locally in our model.

In option 2 (BF-BOF), we make an analogous assumption about the provision of a CO_2 capture, transport and storage service. This would be handled by an external specialised company.[13] We take the cost of the CCS service from the interactive calculator *The cost of carbon capture and storage in Europe* developed by the think tank Clean Air Task Force and the company Carbon Limits (CATF, 2022). It contains the estimated cost of a CCS service broken down by component (capture, transport and storage). The cost also takes into account depreciation of capital expenditure (over a 20-year period, as in our modelling) and operating costs, including energy costs. The calculator also determines estimated efficiencies for virtually all European industrial plants, including the ArcelorMittal Dabrowa Gornicza plant and the TAMEH ZW Nowa CHP plant accompanying the steel plant in Dabrowa Gornicza. The authors of the calculator (CATF, 2022) assumed the use of amine absorption technology for CO_2 capture at the Dabrowa Gornicza steel plant and the TAMEH ZW Nowa CHP plant, and made all calculations for this technology.

We take the estimated costs of the CCS service as an average weighted by the sum of the emissions of each of the two aforementioned plants (implying the provision of a CCS service for both of them) and arrive at a value (after rounding):

- 130 EUR/t CO_2 for scenario 2.1. BF-BOF + CCS, in which CO_2 is transported by rail,

- 110 EUR/t CO_2 for scenario 2.2. BF-BOF + CCS, in which CO_2 is transported by pipeline.

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[12] It must be taken into account that steelmaking technology using hydrogen as a reducing agent is a new technology that is only just entering the key phase of commercialisation. This means that calculations related to capital and operating expenditures may in fact vary significantly.

[13] Orlen Group's May 2023 climate policy calls for the development of CCUS capacity (including CCUS services) to 3 million tonnes CO_2 per year (Orlen, 2023).

Thus, by analogy with option 1, the capital cost of the CCS installation is included not in the steelworks account, but in the cost of the CCS service offered by the external supplier.

Investment assumptions (CAPEX) were based on a global analysis of investment projects and the financial statements of ArcelorMittal Poland. The source of information on the costs of emerging investments in DRI-EAF steel mills is an analysis by the German research institute DIW Berlin (Hüttelm, Lehner, 2024). We selected a sample of representative projects from European countries and arrived at an average (after rounding) of:

- 780 EUR per tonne of steel production capacity for Option 1 (DRI-EAF + H_2),

- 630 EUR per tonne of steel production capacity for Option 3 (EAF).

However, we made an important modification to take into account the difference between greenfield (location in northern Poland) and brownfield (investment at the site of the ArcelorMittal plant in Dabrowa Gornicza) options. In our calculator, we arbitrarily increase the CAPEX value from the DIW Berlin analysis by an additional 25% for greenfield investments to reflect the capital expenditure required to purchase the investment plot and to equip it with the appropriate infrastructure (in particular, a connection to the power grid).

We bring different plant capacities in each scenario to one common denominator. While some technologies prove to be more cost-competitive than others in terms of unit steel production cost, they allow for steel production in different volumes. In options 1 (DRI-EAF + H_2) and 3 (EAF), we assume lower capacities than in option 2 (BF-BOF + CCS) - 2.5 million tonnes and 4.5 million tonnes respectively.[14]

3.2. Modelling results - competitiveness of technological options

We present the results of the modelling in terms of the unit cost of steel production expressed in real 2023 prices (EUR'2023) per tonne of steel. In each scenario, we break down costs into five categories:

- capital expenditure (CAPEX),
- operating costs of non-energy commodities (OPEX - non-energy commodities),
- operating costs related to energy commodities (OPEX - energy commodities),
- CO_2 operating costs, including the costs of the CCS service (OPEX - CO_2),
- other operating costs (OPEX - other).

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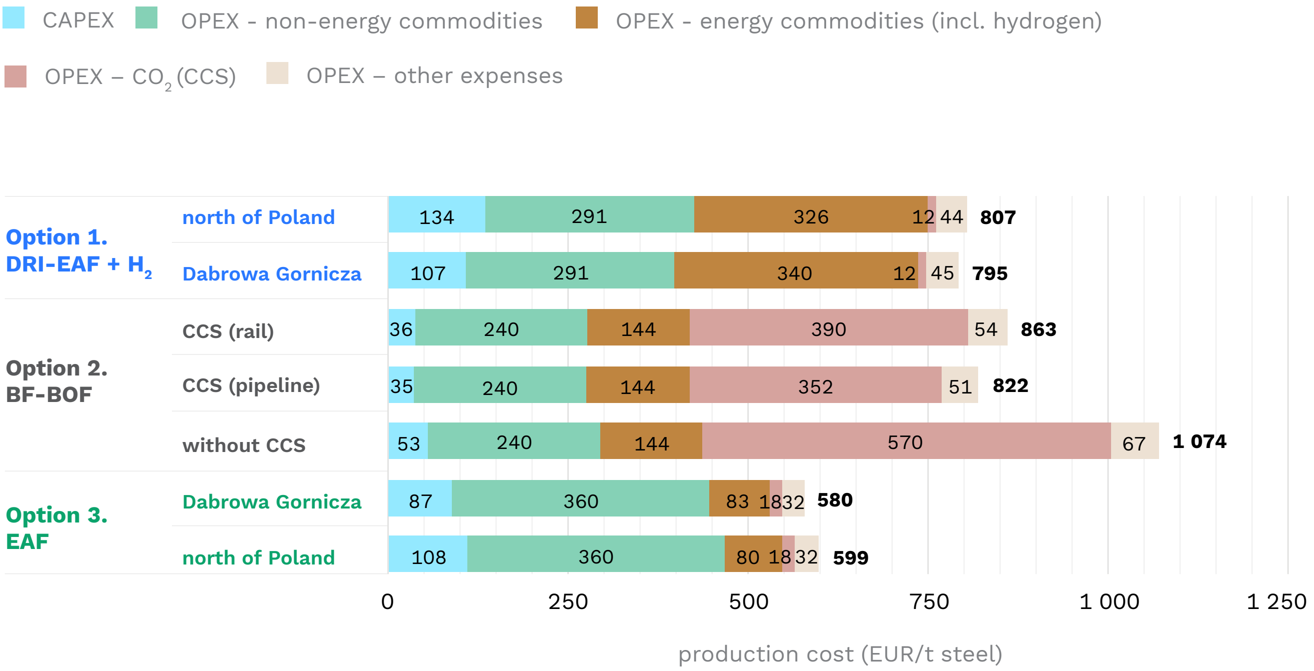
[14] For electrified mills, the limitation is the capacity of the electric arc furnace. For BF-BOF (+ CCS) technology, the capacity is 4.5 million tonnes of steel in our model and corresponds to the current capacity of the ArcelorMittal mill in Dabrowa Gornicza.

3.2.1. Comparison of total unit steel production costs

Steel production based on near-zero-emission technologies (DRI-EAF + H_2 and EAF) can be cheaper than in a BF-BOF option, even with CCS applied. The cost of producing one tonne of steel with the DRI-EAF + H_2 technology (scenarios 1.1. and 1.2.) would remain lower in our model by an amount in the order of 15-68 EUR/t of steel compared to the BF-BOF + CCS scenarios (scenarios 2.1. and 2.2.). This is mainly due to the costs of the CCS service and the insufficient efficiency of the CO_2 capture plant (75%). With high CO_2 prices this will translate into a significant additional cost of uncaptured CO_2 (Figure 3).

The most expensive would be to keep today's primary steel production process unchanged (scenario 2.3). The steel manufactured there would cost almost 1 100 EUR/tonne and would be about 270-280 EUR/tonne more expensive than in the hydrogen scenarios (1.1. and 1.2.) and almost twice as expensive as steel obtained from scrap in an Electric Arc Furnace (scenarios 3.1. and 3.2.), even if it were built from the scratch (Figure 3).

FIGURE 3. Structure of steel production costs under different technological options (EUR/t steel)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

In fact, the cost of steel production in a steelworks built from scratch will not be significantly higher than in the case of a brownfield investment. The difference between the two options in favour of the brownfield scenario is only 11 EUR/t steel for the hydrogen pathway (1.1. and 1.2.) and 19 EUR/t steel for the Electric Arc Furnace (scenarios 3.1. and 3.2.).

The savings on the cost of electricity transmission, resulting from the location of the greenfield plant in a renewables acceleration area, would largely offset the cost of the additional capital required to build the steelworks from scratch on a new investment site. The DRI-EAF + H_2 mill located in the north of Poland benefits the most from this phenomenon in our model, as hydrogen costs are 12 EUR per tonne of steel lower in this scenario (1.1.) compared to the same mill located in Dabrowa Gornicza (scenario 1.2. and Figure 4).

Therefore, should the DRI-EAF + H_2 technology be selected as the decarbonisation path for Polish steel production, the new primary steel plant would not at all have to be based on the current location of the integrated steelworks in Dabrowa Gornicza.

By far the lowest is the cost of EAF steel production. Depending on the greenfield or brownfield scenario, it is either 599 EUR/t steel or 580 EUR/t steel, respectively. This cost is lower than the steel production costs in the DRI-EAF + H_2 mill (scenarios 1.1. and 1.2.) by an amount in the range of 196-227 EUR/t steel and by an amount in the range of 223-283 EUR/t steel compared to the BF-BOF + CCS scenarios (scenarios 2.1. and 2.2.). When compared with the BF-BOF without CCS scenario (2.3.), the production cost of EAF steel is almost twice as low, i.e. the difference can even reach more than 490 EUR/t steel in favour of EAF steel.

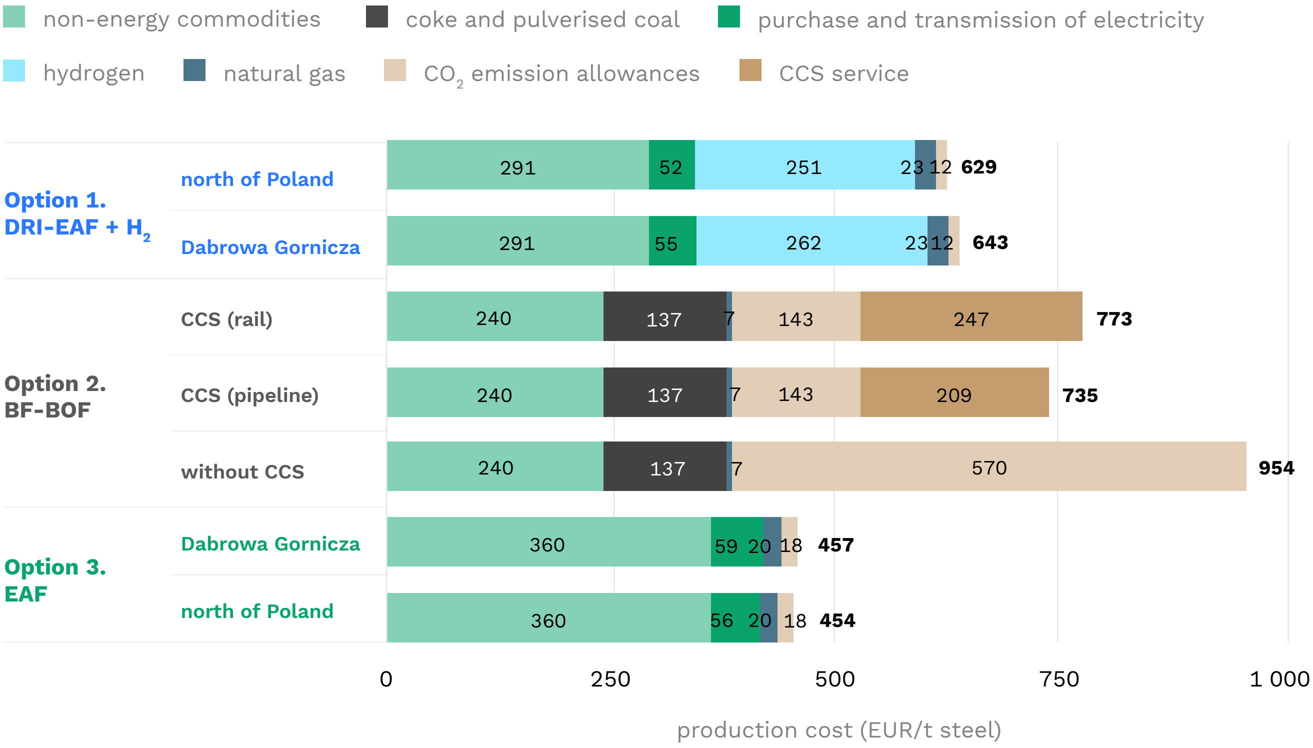
EAF technology, while winning in terms of production costs, does not provide primary steel. Implementation of the EAF scenario would therefore require a decision that Poland would import primary steel and that the capacity of the high-carbon integrated steelworks in Dabrowa Gornicza would be replaced by a near-zero-emission electric arc furnace due to high carbon costs.

3.2.2. Energy and CO_2 costs.

The CO_2 management costs for a BF-BOF + CCS steel mill can be greater than all energy costs for a DRI-EAF + H_2 steel mill, including hydrogen costs. The emission, capture, transport and storage costs of CO_2 are 390 EUR/t steel (CO_2 transport by rail) and 352 EUR/t steel (CO_2 transport via pipeline) in the BF-BOF + CCS scenarios, whereas for the hydrogen scenarios all energy costs, including the limited costs of CO_2, amount to 338 EUR/t steel (DRI plant in northern Poland) and 352 EUR/t steel (DRI plant in Dabrowa Gornicza). The difference can therefore be as much as 52 EUR/t of steel.

The competitiveness of the DRI-EAF + H_2 scenarios is due to the fact that they do not require coke and pulverised coal, unlike the BF-BOF + CCS technology. As a result, the energy cost of producing steel with the DRI-EAF + H_2 technology will be, according to our modelling, lower by 137 EUR/t of steel than the energy cost of primary steel made in a blast furnace and basic oxygen furnace. These advantages of the hydrogen scenario over the BF-BOF scenario are not even offset by the fact that iron ore in pellet form, as it must be used in the DRI furnace, is 40 EUR/t more expensive than the ordinary or sintered iron ore required in the blast furnace process (Figure 4).

FIGURE 4. Structure of variable costs of steel production under different technological options (EUR/t steel)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

The high price of CO_2 allowances also makes CCS technology a competitive option for decarbonising primary steel production in Poland. Although only 75% of CO_2 is captured in scenarios including CCS (CATF, 2022), the cost of uncaptured emissions and the costs of CO_2 capture, transport and storage (CCS service) in scenarios 2.1. and 2.2. combined are still lower than the costs of purchasing CO_2 allowances in scenario 2.3. in which all emissions are released to the atmosphere. The difference in CO_2 management costs amounts to 218 euro/t steel in favour of scenario 2.1, in which CO_2 is transported by rail, and 180 EUR/t steel for scenario 2.2, in which CO_2 is injected into the pipeline. It is therefore less costly (by 38 EUR/t steel) to transport the captured CO_2 by pipeline (Figure 4).

However, it is in the DRI-EAF + H_2 technology that the vast majority of primary steel decarbonisation projects are currently being implemented, which may indicate that hydrogen scenarios are seen as more cost-effective. This diagnosis coincides with the results of our calculations.

EAF technology is the most competitive in terms of energy and CO_2 costs (Figure 4). The difference in energy variable costs in favour of EAF steel (scenarios 3.1. and 3.2.) is between 236 and 254 EUR/t steel compared to the DRI-EAF + H_2 scenarios (1.1. and 1.2.) and between 394 and 435 EUR/t steel compared to the BF-BOF + CCS scenarios (2.1. and 2.2.). Against BF-BOF technology without CCS, on the other hand, the difference reaches as much as 613 or 616 EUR/t of steel, depending on the implementation of the EAF scenario in brownfield or greenfield option, respectively. Electric arc furnace, however, uses scrap (classified as a non-energy resource), which is almost three times more expensive than iron ore in purchase price. The high price of scrap, however, does not change the fact that total steel production costs are lowest in the EAF scenario (3.1. and 3.3.). The main reason for the advantage of EAF technology over the other scenarios included in the model are therefore much lower energy-related costs.

3.2.3. Energy intensity of steel production

The challenge for decarbonising the steel industry will be to provide large volumes of green electricity. This is because all the technologies we have considered for decarbonising steel production in Poland have a large electricity demand (Figure 5), larger than the BF-BOF steel plant in Dabrowa Gornicza today. This is why energy costs are so important to the results of our modelling.

With the electrification of the economy, a decarbonised steel mill will compete with other sectors for electricity. Current domestic installed generation capacity will not be sufficient to meet electricity demand in 2040.[15] Potential problems in developing adequate new renewable capacity would therefore favour a steel mill with the highest possible efficiency in electricity use. We are therefore analysing our electricity consumption scenarios in detail.

EAF technology, the most competitive in terms of energy costs, does not consume the least electricity at all. However, the EAF does not require energy commodities, which are more expensive than electricity itself in our model. This is particularly true for hydrogen in the DRI-EAF + H_2 scenarios. The production of hydrogen itself is very energy-intensive (Figure 5) and thus expensive.

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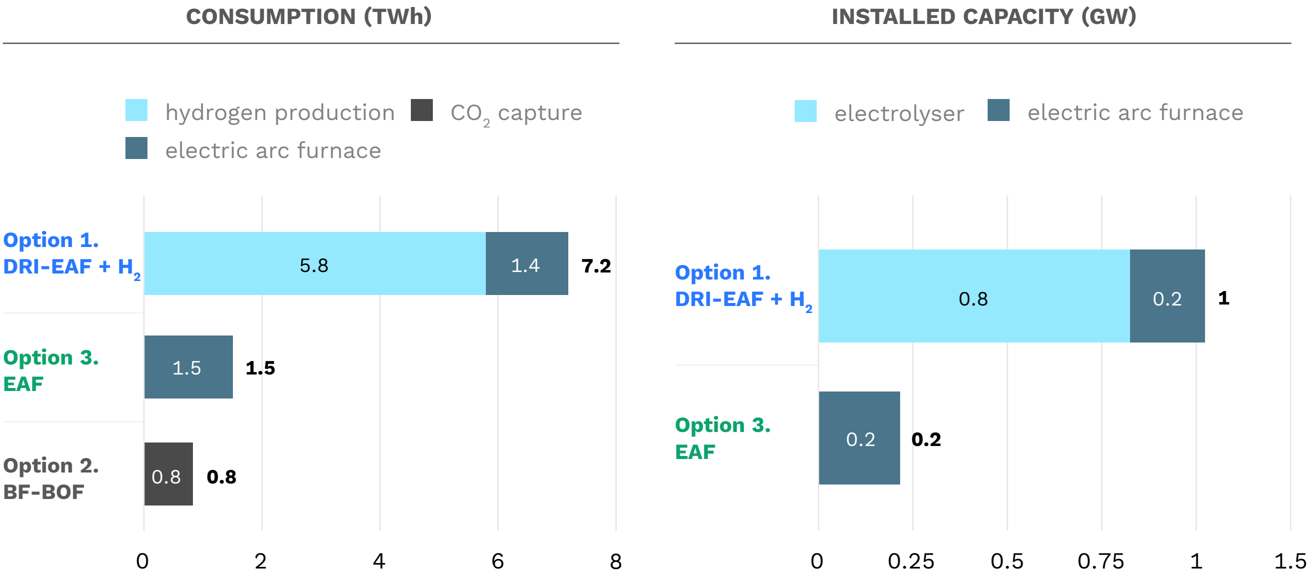
[15] According to the Instrat's energy modelling, national installed electricity capacity is expected to almost triple in the ambitious scenario (S1), from 63.6 GW in 2022 to 175 GW in 2040.

FIGURE 5. Electricity consumption and installed capacity of installations used in steel production in low- and near-zero-emission technology options



Source: Instrat's own elaboration based on Sasiain et al. (2020) and Facchini et al. (2021). We calculated the electricity demand of the CO_2 capture plant based on the source documents for the CATF calculator (CATF, 2022; National Petroleum Council, 2021), which indicate an electricity consumption of 0.16 MWh/t of CO_2 captured for the amine absorption technology assumed by CATF. For other CO_2 capture technologies electricity consumption may vary. In addition, the steel mills in the different scenarios have different capacities, so the unit electricity consumption per tonne of steel also differs between technological options.

The DRI-EAF + H_2 technology has the highest electricity demand. According to our model, it requires several times more electricity supply than the other steel decarbonisation technologies (Figure 5). The electricity demand in the hydrogen scenarios (1.1. and 1.2.) is 7 TWh of electricity. This is five and nine times higher than in the EAF and BF-BOF + CCS scenarios, respectively. In comparison, the estimated electricity demand of the considered medium-sized DRI-EAF + H_2 steel plant of 7 TWh is also:

- approx. 4.5% of today's total electricity production in Poland,
- approx. 2% of total electricity production in Poland estimated by Instrat for 2040 in the ambitious (S1) scenario (Kubiczek et al., 2023),
- more than twice as much as today's electricity consumption of Poland's largest consumer, KGHM (approx. 3 TWh).

The vast majority of this 7 TWh (80%) would be consumed by the electrolyser in the production of hydrogen. This amount of electricity allows 110 000 tonnes of hydrogen to be produced in our model. For comparison, in 2023 Poland produced 729 000 tonnes of grey hydrogen through refinery processes. Instrat's energy modelling estimates the potential to produce decarbonised hydrogen from surplus RES production and nuclear power in an ambitious scenario at around 1 million tonnes of hydrogen.

Meeting the electricity needs of the electrolyser and electric arc furnace in the DRI-EAF + H_2 scenarios would require 1 GW of installed grid connection capacity (Figure 5). Operating the DRI-EAF + H_2 steel plant and the accompanying electrolyser would therefore require in our model an annual operation of a 1.5 GW wind farm. This is more than the first Polish offshore wind farm, Baltic Power with nearly 1.2 GW, which is to be installed in the Baltic Sea. In comparison, the 1 GW, needed in this case could be (simplifing) supplied by nearly 17% of the installed capacity of the offshore wind farms to be built in the Baltic under Phase I of the support until 2030 and 9% of the installed capacity under Phase II until 2040 (in total 33 GW). The annual production of just 2 million tonnes of DRI-EAF + H_2 steel would therefore require supply of electricity from renewable energy sources in large volumes.

The application of CO_2 capture at the BF-BOF steelworks would not be as energy-intensive compared to other low- and near-zero-emission technologies. In the modelled scenario, which assumes the use of amine absorption technology for CO_2 capture, CO_2 capture would require an additional electricity supply of approximately 0.8 TWh per year. The CO_2 capture plant would consume two times less electricity in total than the EAF mill (i.e. 1.5 TWh; Figure 5), despite the fact that the BF-BOF + CCS mill would produce 3.6 million tonnes of steel in our model, which is as much as 1.6 million tonnes of steel more than in the case of the EAF mill.

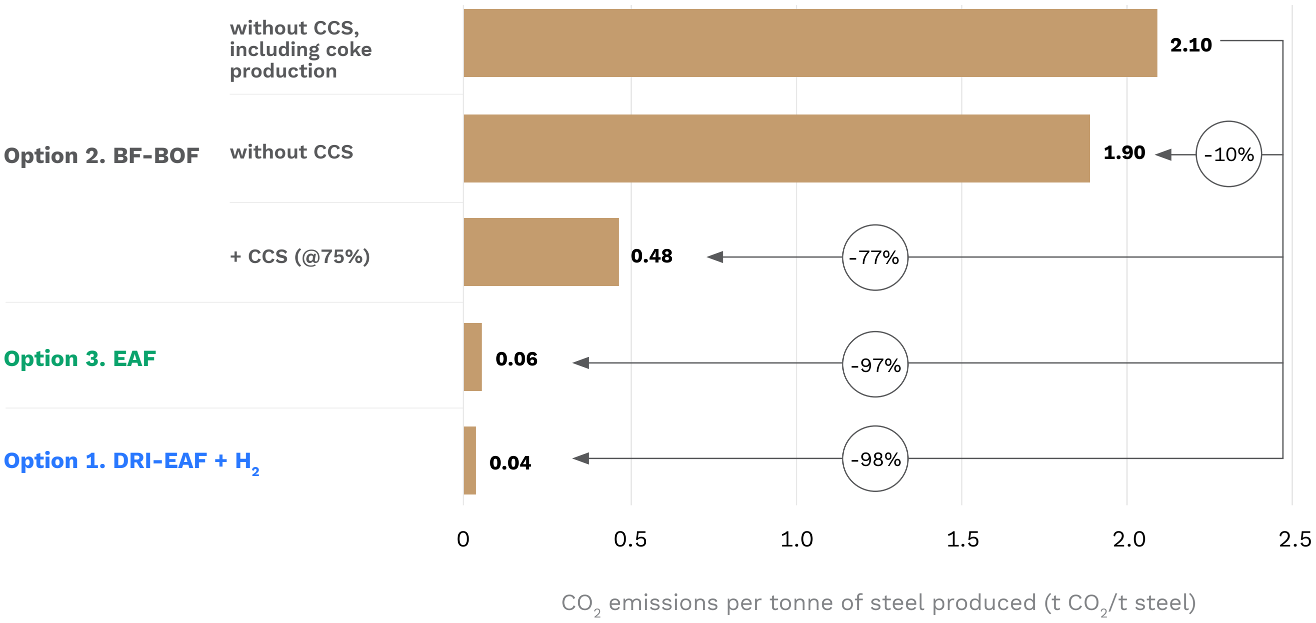
The energy efficiency advantage of the CO_2 capture plant compared to an electric arc furnace is therefore even greater. It consumes 0.23 MWh of electricity per tonne of steel produced at the BF-BOF steelworks, while the efficiency coefficient for the EAF steel is almost three times higher and amounts to 0.75 MWh per tonne of steel. In terms of electricity demand, the BF-BOF + CCS scenarios are therefore more feasible to implement than both the DRI-EAF + H_2 and EAF scenarios.

3.2.4. CO_2 emisisons

CO_2 emissions is a key feature of steel production in the 2040 perspective. The European Union's climate policy makes CO_2 emissions increasingly costly and low- or near-zero-emission steel mills will therefore be the most competitive steel plants.

This is reflected in our model by including an increase in the cost of CO_2 emission allowances to 300 EUR/t in 2040 and beyond (CAKE, 2023). The costs of these emissions per tonne of steel result, among other things, from our assumptions on the carbon intensity of the various technologies and further calculations, the results of which are shown in Figure 6.

FIGURE 6. CO_2 emissions of steel production under different technology options per tonne of steel produced (t CO_2/t steel)



Source: Instrat's own elaboration based on data: for the BF-BOF steelworks in Dabrowa Gornicza and other ArcelorMittal plants (Zdzieszowice coking plant and CHP plant, TAMEH ZW Nowa CHP plant) - EU ETS and E-PRTR; for DRI-EAF + H2 - Sasiain et al. (2020); for EAF - Facchini et al. (2021).

A significant reduction in CO_2 is possible with the use of BF-BOF + CCS technology. Its emissivity is 0.48 t CO_2/t steel and is 77% lower compared to the conventional BF-BOF method used today in Dabrowa Gornicza. However, due to the unsatisfactory CO_2 capture efficiency (75%), CCS is in a losing position in the steelmaking emissivity category against the DRI-EAF + H_2 and EAF technologies.

Electric arc furnace has very low CO_2 emissions per tonne of steel produced. This factor, in addition to its attractiveness in other cost-effective terms, should argue for the massive deployment of EAF technology. The challenge, however, is the availability of scrap, especially if steel production were to strongly rely on electric arc furnaces in the face of climate challenges. Steel recycling would then have to be very efficient at all stages of the process. In addition, EAF steel extracted solely from scrap is characterised by a lower quality compared to primary steel produced by BF-BOF and DRI-EAF steel plants.

The largest CO_2 reduction per tonne of crude steel produced is achieved by the DRI-EAF + H_2 steel mill (scenario 1. in Figure 6). It is therefore the most climate-friendly solution, and the only near-zero-emission primary steelmaking technology - less polluted and more resistant than steel from EAF furnaces.

3.3. Sensitivity analysis

The results of the calculator are highly dependent on variables whose value is difficult to predict, especially in the 2040 perspective for which the calculator was drawn up. We therefore carried out a sensitivity analysis and investigated how a change in key input values affects the model output and the cost of steel production. In the sensitivity analysis we have taken into account the factors we have considered most relevant to the calculations and most susceptible to fluctuations or uncertainties. These factors are as follows:

- the cost of purchasing and transmission of electricity - due to the significant potential impact of this factor on our hydrogen production model and due to the uncertainty surrounding the evolution of the Polish energy mix, changes in the electricity market, including the evolution of grid costs and the risks associated with making large-scale investments in hydrogen production,

- interest rate - due to the unpredictability of monetary policy,

- CO_2 allowance price - due to the unpredictability of the development of the EU ETS and EU climate policy,

- CO_2 capture plant efficiency - due to technological uncertainties.

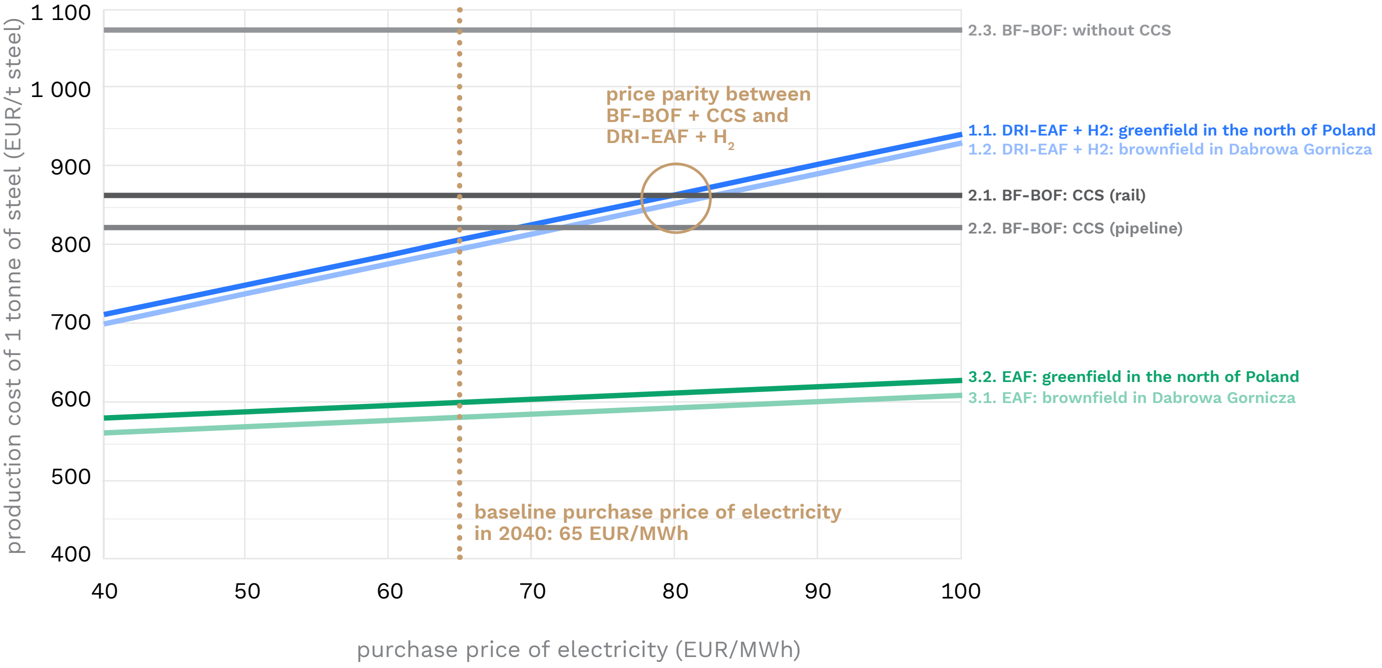
3.3.1. Electricity purchase price

The change of electricity purchase price affects the most scenarios with the DRI-EAF + H_2 steel mill, regardless of its location. With the electricity price fluctuating between 40 and 100 EUR/MWh, the cost of steel production rises from 700 to 950 EUR/t (cf. the two blue lines in Figure 7). Indeed, as much as more than 30% of the total cost of steel production (at the baseline purchase price in the calculator of 65 EUR/MWh) in this scenario depends on electricity costs, mainly due to their impact on the price of hydrogen. The cheaper the electricity, the more competitive the DRI-EAF + H_2 technology.

The electricity price should also affect the competitiveness of the BF-BOF + CCS scenario due to the energy intensity of the CO_2 capture plant. Due to the limitations of our model, however, we do not show this relationship analogously to the DRI-EAF + H_2 option. In the BF-BOF + CCS technology option, however, the cost of electricity is included in the externally sourced (CATF, 2022) overall cost of the CCS service and is not affected by changes in the electricity purchase price in our calculator.

A change in the purchase price of electricity does not significantly affect the cost of steel production in EAF technology. Although steel production in this technology relies on electricity, its cost at the base values in our calculator represents only about 9% of the total production cost. Therefore, the change in the production cost of electric steel within the assumed electricity price range does not exceed 100 EUR/t of steel (cf. the two green lines in Figure 7).

FIGURE 7. Production cost of 1 tonne of steel (EUR/t) at different electricity purchase prices (EUR/MWh)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

A change of 10 EUR/MWh in the electricity purchase price changes the cost of steel production in the DRI-EAF + H_2 technology option by 38 EUR/t of steel, and in the EAF technology option by only 8 EUR/t of steel.

3.3.2. Interest rate

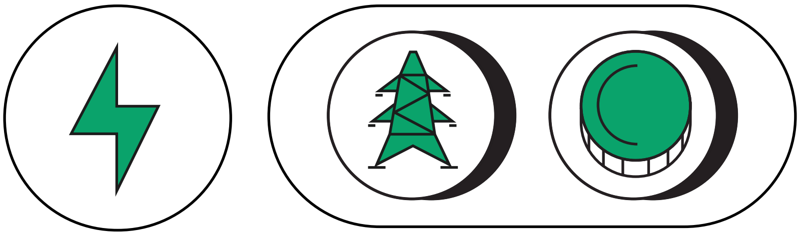
The cost of capital and the interest rate on debt financing have a particular impact on the cost of steel production in the DRI-EAF + H_2 and EAF mills. This is mainly due to the fact that capital expenditure on new fixed assets will be required in the respective scenarios, in contrast to the BF-BOF scenarios, which will be based on already existing capacity and technologies subject to replacement (we assume 5% variable costs as annual replacement expenditure).

The interest rate on capital should also have an impact on the BF-BOF + CCS scenarios (2.1. and 2.2.) requiring finance for the CCS infrastructure. Due to the limitations of our model, the CAPEX costs of this infrastructure are included in the cost of the CCS service provided by an external operator and are not affected by changes in the interest rate.

The impact of the change in the interest rate is not uniform for the DRI-EAF + H_2 and EAF scenarios. The change in the cost of steel production in a given range of values for the interest rate (from 2% to 12%) is around 100 EUR/t steel for electric steel (scenarios 3.1. and 3.2.) and even 150 EUR/t steel for hydrogen steel (scenarios 1.1. and 1.2.). This is because the DRI-EAF + H_2 steel plant requires more financial investments, especially in the greenfield scenario.

We point to the close price parity of the two options for producing low- and zero-emission primary steel (DRI-EAF + H_2 versus BF-BOF + CCS) for an interest rate of 8%. Stimulating investment in a green steel plant would therefore require a lower interest rate, but not just as a result of a change in monetary policy. An interest rate of 8% is standard for the Polish economy at the time of publication of this study (October 2024), but this is due to counteracting previously rising inflation. Our assumption of a baseline interest rate of 6% is based on the expected decline in interest rates in the following years. The decision to invest in a new steel plant (final investment decision) would be made after further detailed analysis a few years from today.[16]

At this interest rate (6%), the construction of a DRI-EAF + H_2 steelworks is already the most competitive option for decarbonising Polish primary steel production in our model, and could be an even more viable solution if preferential loans and other support is received from the state and national development institutions, including the Polish Development Fund (PFR) and Bank Gospodarstwa Krajowego (BGK, Polish national development bank) (Box 2).



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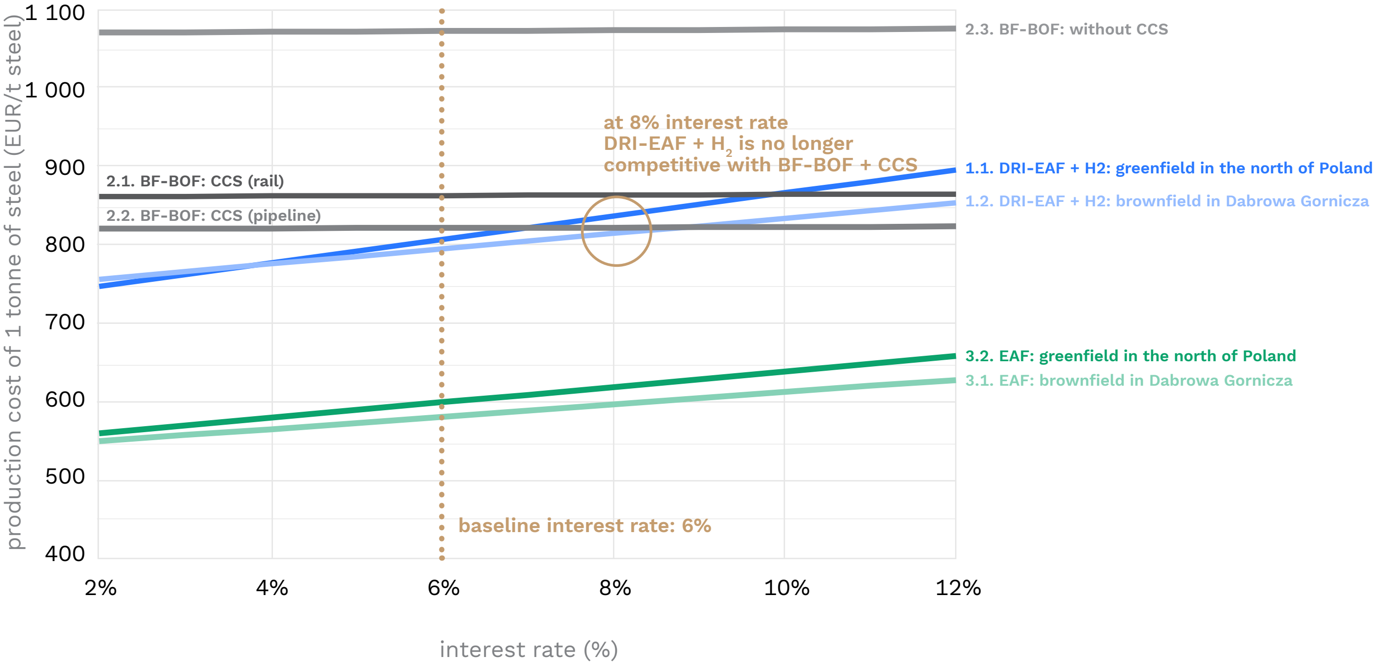
[16] We also make the assumption of considering this investment in the context of competition in the European steel market from global producers enjoying lower effective interest rates through access to financing from global capital markets.

FIGURE 8. Production cost of 1 tonne of steel (EUR/t) at different interest rate values (%)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

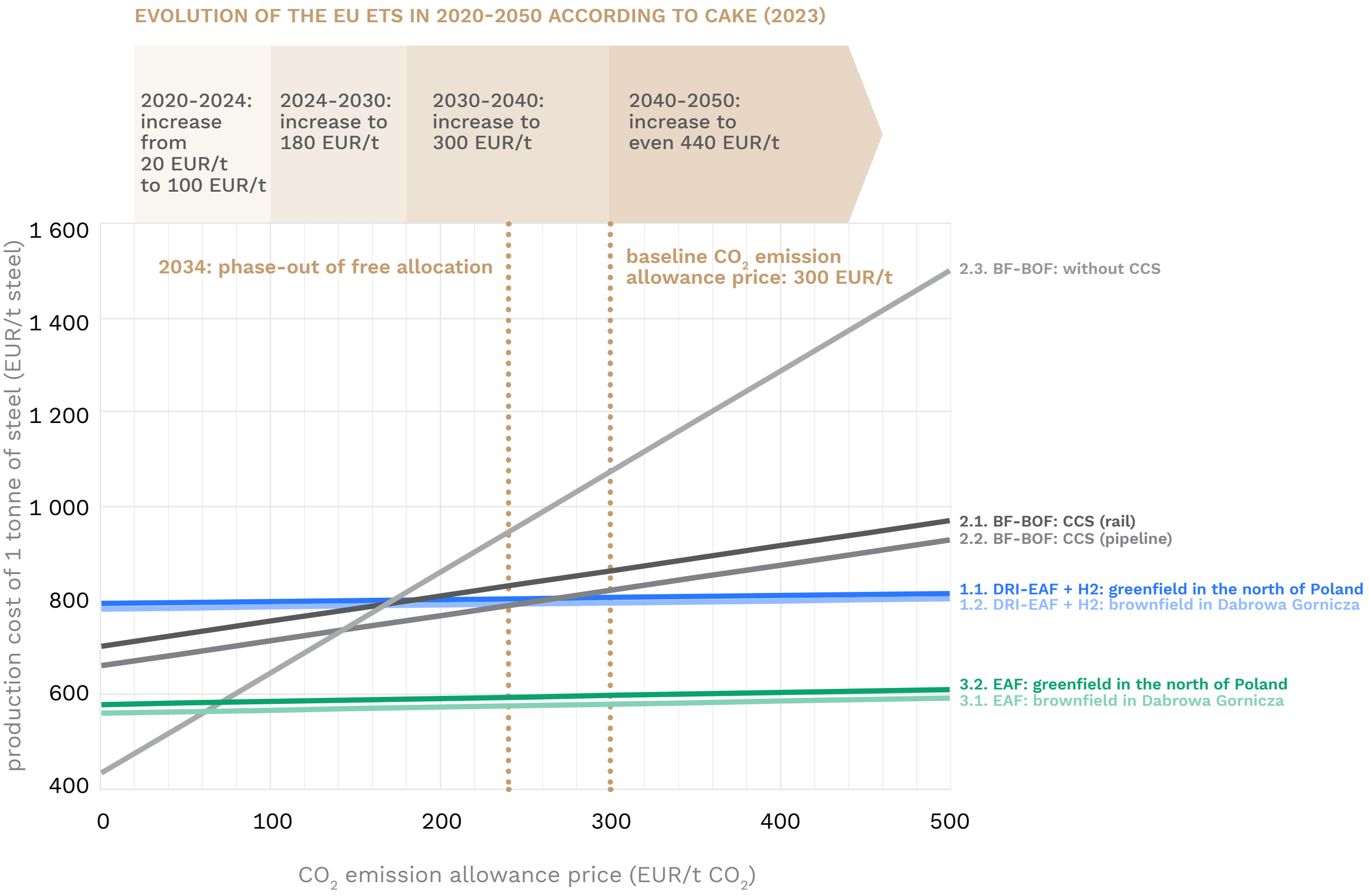
An increase by 2 percentage points in the interest rate increases the cost of steel production in the DRI-EAF + H_2 technology option by 30 EUR/t steel for the greenfield scenario and 20 EUR/t steel for the brownfield scenario. For the EAF technology option, the change is 20 EUR/t steel for the greenfield scenario and 16 EUR/t steel for the brownfield scenario.

3.3.3. The price of CO_2 emission allowances

In the event of a radical increase in the cost of CO_2, i.e. even to the level of 500 EUR/t, maintaining the current method of primary steel production would translate into extreme uncompetitiveness. The cost of steel production in the BF-BOF scenario without CCS (2.3.) would then rise to 1 500 EUR/tonne of steel and would be higher by 500 EUR/tonne of steel than in the most expensive low-carbon scenario (2.1. BF-BOF + CCS (rail)), and twice as high as in the DRI-EAF + H_2 scenarios. An increase in the CO_2 allowance price to nearly 500 euro is not at all improbable. EU ETS market development scenarios by the KOBiZE forecast an increase in the price of CO_2 allowances to 440 EUR/t CO_2 in 2050 (CAKE, 2023).

Maintaining primary steel production in Poland unchanged would therefore mean increasingly expensive steel. The solution is low- and almost zero-emission technologies, which are less sensitive to changes in the price of CO_2, despite limited CO_2 emissions occurring in these processes, too.

FIGURE 9. Production cost of 1 tonne of steel (EUR/t) at different CO_2 allowance prices (EUR/t)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

A change in the price of CO_2 by 50 EUR/t CO_2 alters the cost of steel production in the technology option DRI-EAF + H_2 by 2 EUR/t steel. For the BF-BOF + CCS scenarios this change is 27 EUR/t steel, and for the BF-BOF scenario without CCS as much as 107 EUR/t steel. In the EAF scenarios, the cost of steel changes by 3 EUR/t steel.

3.3.4. Capture efficiency of CO_2

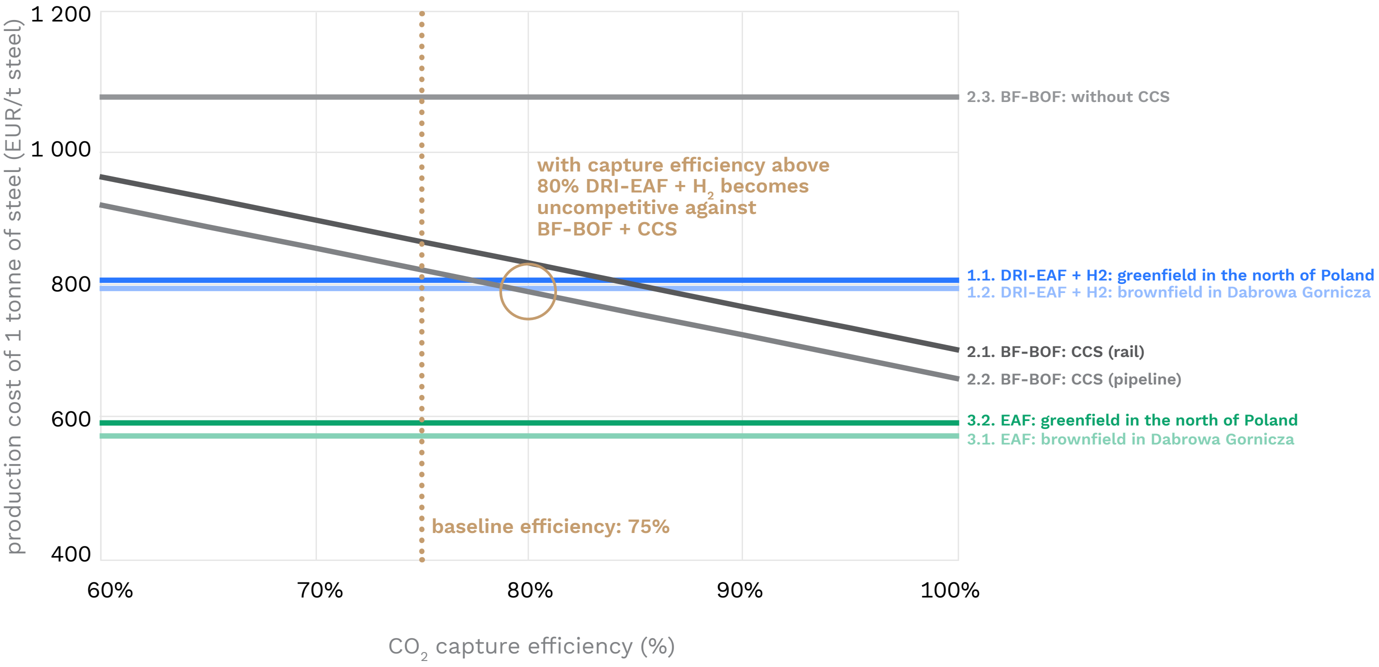
A CO_2 capture efficiency of more than 90% would allow the BF-BOF + CCS scenarios to overtake the DRI-EAF + H_2 scenarios in terms of cost competitiveness, as higher CO_2 capture efficiency means that fewer CO_2 capture allowances have to be purchased. Increasing the efficiency from the baseline value of 75% assumed in the calculator based on the literature (CATF, 2022), however, may not be feasible.

Amine absorption by itself is characterised by a capture efficiency of up to over 90% (Karayil et al., 2024) but it would not be cost-effective for all small CO_2 emission points in a steelworks. Even if technically feasible, this would involve additional capital expenditure, disproportionate to the benefits gained, which in turn would translate into an increase in the cost of the CCS service.

The BF-BOF + CCS scenarios are borderline competitive with the DRI-EAF + H_2 scenarios already with the baseline assumptions of the cost of CCS service in the calculator. An increase of this cost above the baseline 110 and 130 EUR/t CO_2 (depending on the mode of transport of CO_2 - pipeline and rail, respectively) would negatively affect the competitiveness of this technology. This effect could be mitigated by the low cost of electricity and the low interest rate for building the necessary infrastructure, but then steel production cost in the DRI-EAF + H_2 scenarios (1.1. and 1.2.) would also decrease. We also do not expect a radical decrease in the capital expenditure required to deploy CCS infrastructure.

In light of such assumptions and the joint dependence of both technologies on the cost of electricity and the cost of capital (interest rate), steel from a BF-BOF + CCS mill is likely to remain on the losing side compared to DRI-EAF + H_2 technology. Steel production in the current BF-BOF steelworks would prove to be the most cost-competitive in the unlikely scenario of low CO_2 prices and/or very high hydrogen procurement costs.

FIGURE 10. Production cost of 1 tonne of steel (EUR/t) at different CO_2 capture efficiencies (%)



Source: Instrat based on *Calculator of Steel Production Cost in Poland*.

A change in CO_2 capture efficiency by 5 percentage points changes the cost of steel production in the BF-BOF + CCS scenarios by 32 EUR/t steel.

4. Recommendations and conclusions for policy makers

The Polish economy needs a supply of low- or zero-emission steel to maintain not only price competitiveness but also a low carbon footprint of steel products. Top quality primary steel will be also indispensable in steel structures and products exposed to the atmospheric conditions. Therefore, the private sector and the government must jointly decide on the decarbonisation path or paths based on the available technological options presented in this analysis. Despite the liberalisation and privatisation of the steel sector, the government must actively engage and take on the role of shaping the strategic directions of the sector.

On the basis of our analysis of trends in the global and European steel market and our modelling of the production costs of this commodity under different technological options, we formulate the following conclusions for decision-makers:

1

We should not slow down the green transformation of the steel industry

On the contrary, decisions to invest in deep decarbonisation should be taken now, long before the effective cost of CO_2 allowances rises and the necessary investments would have to begin. The government should support the private sector in deciding to invest in steelmaking decarbonisation in at least one of the technological options presented in our report. A proactive industrial policy should encourage risk-taking and investment in clean technologies, even if a dynamic increase in the price of CO_2 allowances in the EU ETS is not expected until the 2030s, thus delaying the start of the relevant investments for at least a few years. We already have sufficient evidence that maintaining the current production of primary steel at the ArcelorMittal steel mill in Dabrowa Gornicza as it stands today (without CCS installation) is impossible in the long term.

2

Regulatory and financial support for the infrastructure accompanying low- or zero-emission steelmaking is needed.

The development of a CCS service or a hydrogen economy will be key to securing the supply of low- or zero-emission steel for Poland. Currently, these sectors are at a very early stage of development, which requires increased state activity - not only in creating regulations, but also in developing dedicated infrastructure for the transmission and storage of hydrogen

(DRI-EAF + H_2) and CO_2 (BF-BOF + CCS). Financial support in the form of non-refundable grants or low-interest loans and guarantees may not be sufficient to mitigate risks for investors. Based on the experience of the German steel sector, carbon contracts for difference (CCfD) will be a possible support instrument.

3

We need low electricity prices for industry

These will be key to the viability of all decarbonisation scenarios (apart from the import scenario). Each of the steel decarbonisation technologies presented here implies greater electricity consumption (both overall and per unit of steel) than today's primary steel production in Dabrowa Gornicza. The price of decarbonised steel will therefore be very much dependent on electricity prices. The state has an influence on the decrease in effective electricity purchase prices by increasing the share of RES in the energy mix and shaping transmission tariffs. Point solutions in the form of rebates for electricity consumers located in renewables acceleration areas, e.g. in the north of Poland, would also be desirable.

4

Support for regions and workers potentially affected by the steel decarbonisation

The steel industry should be more present in the Just Transition efforts. In the current EU budget perspective for 2021-2027, the energy-intensive industry and industrial regions in Poland are not beneficiaries of the Just Transition Fund. Measures for economic diversification and mitigating social costs in the Polish coal regions, in particular in Silesia, should be extended to the steel sector, which is currently undergoing significant turbulence. The possible relocation of steel production from the south to the north of Poland (thanks to access to large volumes of green energy) may imply support for the regions and workers in the steel sector located in current locations.

Poland is currently facing the historic challenge of transforming the steel sector and its potential restructuring. Such a challenge was faced for the last time by Jerzy Buzek's government at the turn of the 20th and 21st centuries, resulting in the 2001 *Iron and Steel Industry Restructuring Programme* (Sejm RP, 2001). We hope that with this report we are contributing to an understanding of the strategic dilemmas in the steel sector among decision-makers and to the choice of at least one of the technological options presented above. If no decision is made, Poland will be in jeopardy of being limited to the role of a producer of scrap-based steel (EAF) only and of becoming more import reliant.

Explanations and abbreviations

BF-BOF	Blast Furnace - Basic Oxygen Furnace
CAKE	Centre for Climate and Energy Analyses (pol. *Centrum Analiz Klimatyczno-Energetycznych*)
CAPEX	Capital expenditure
CATF	Clean Air Task Force
CBAM	Carbon Border Adjustment Mechanism
CCfD	Carbon Contract for Difference
CCUS	Carbon Capture, Transport, Utilisation and Storage
DRI	Direct Reduction of Iron
EAF	Electric Arc Furnace
ELS	Electrolyser
E-PRTR	European Pollutant Release and Transfer Register
EU ETS	EU Emission Trading Scheme
HBI	Sponge iron, product of the direct reduction of iron ore in cold form (hot-briquetted iron)
IPCEI	Important Projects of Common European Interest
IRENA	International Renewable Energy Agency
KOBiZE	National Centre for Emissions Management (pol. *Krajowy Ośrodek Bilansowania i Zarządzania Emisjami*)
OPEX	Operating expense
PPA	Power Purchase Agreement

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