Transforming industry through carbon contracts

Analysis of the German steel sector

ANALYSIS

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Transforming industry through carbon contracts

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Transforming industry through carbon contracts: Analysis of the German steel sector

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In the course of the project, workshops were held in December 2020 and March 2021 with stakeholders from business, research, ministries and subordinate authorities to develop the basic concepts and assumptions for the transformation path of the German steel industry, as well as the investment and operating costs for the necessary low-carbon production facilities. In addition, the essential requirements for carbon contracts to secure the necessary investments and options for their design were discussed.

Based on the results and conclusions, a preliminary analysis of the German steel sector and a calculator to estimate the cost of its transformation have been made available to all stakeholders as part of a consultation.

The results of our work were published initially in German in September 2021. Since then, the discussion has evolved, and the economic context has changed, leading to the necessity to update the modelling and discussion of the costs for transforming the German steel sector. With this updated publication, we are now summarising the current state of the discussion in order to support the ongoing implementation of carbon contracts and we are publishing this English version to make it available to international audiences. We offer our sincere thanks to all participants who supported us in the project work and in subsequent discussions for their technical expertise and constructive input.

The conclusions and results of this publication do not necessarily reflect the opinions of the individual participants.

The responsibility for the results lies with Agora Energiewende and its partners FutureCamp, Ecologic Institute and the Wuppertal Institute.

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Preface

Dear reader,

Steel production is a major source of greenhouse gas (GHG) emissions. In this publication we analyse strategies to reduce these emissions using the example of Germany, which is the world's eighth largest steel producer and has committed to achieve climate neutrality by 2045. We put forward a plan that would enable the German steel industry to transform its asset base with the course of its natural reinvestment cycle.

This plan involves substituting coal-based blast furnaces for climate-friendly production of Direct Reduced Iron (DRI) in addition to increasing steel recycling. DRI-technology operates with flexible combinations of natural gas and hydrogen instead of coal and offers significant CO_2 emission reduction potential. Due to its flexibility, it can support the development of a renewable hydrogen infrastructure for other sectors.

However, building and operating DRI plants is initially more expensive than conventional blast furnaces. Carbon contracts are an instrument that can compensate for such incremental costs until climate-friendly steel is able to compete with GHG-intensive products.

We demonstrate how carbon contracts can be designed as an insurance mechanism against incremental costs arising from various changes: differences in the consumption and price of energy carriers as well as feedstocks, the effect of CO_2 prices and the anticipated reforms to the EU ETS. In addition, we discuss how carbon contracts can generate a supply of climate-friendly steel to support and accelerate the growth of market-driven demand.

Our analysis shows that carbon contracts are an effective instrument for accelerating the steel transformation and ensuring the industry's long-term competitiveness.

I hope you enjoy reading this report!

Yours, Frank Peter
Director Industry, Agora Energiewende

Key findings at a glance:

1. **Carbon contracts are needed to ensure that the steel industry's urgent reinvestment needs are used to further its transformation to climate neutrality.** By compensating for the initially higher costs of climate-friendly production, carbon contracts anticipate the effects of evolving carbon pricing and enable the industry to implement its green investment plans.

2. **By 2030, Germany must substitute half of its blast furnace capacity. This can be done by increasing steel recycling by 5 million tonnes and building 12 million tonnes of DRI-based production capacity.** Carbon contracts support this transformation. If appropriately coordinated with other policy measures, the need for financial support is limited to less than 9 billion euros, and green steel can be cost-competitive by 2035.

3. **Replacing blast furnaces with DRI plants accelerates the market ramp-up of renewable hydrogen and the development of the necessary infrastructure.** Running them initially on natural gas will enable a rapid reduction in CO_2 emissions and provides a back-up for the use of increasing volumes of renewable hydrogen.

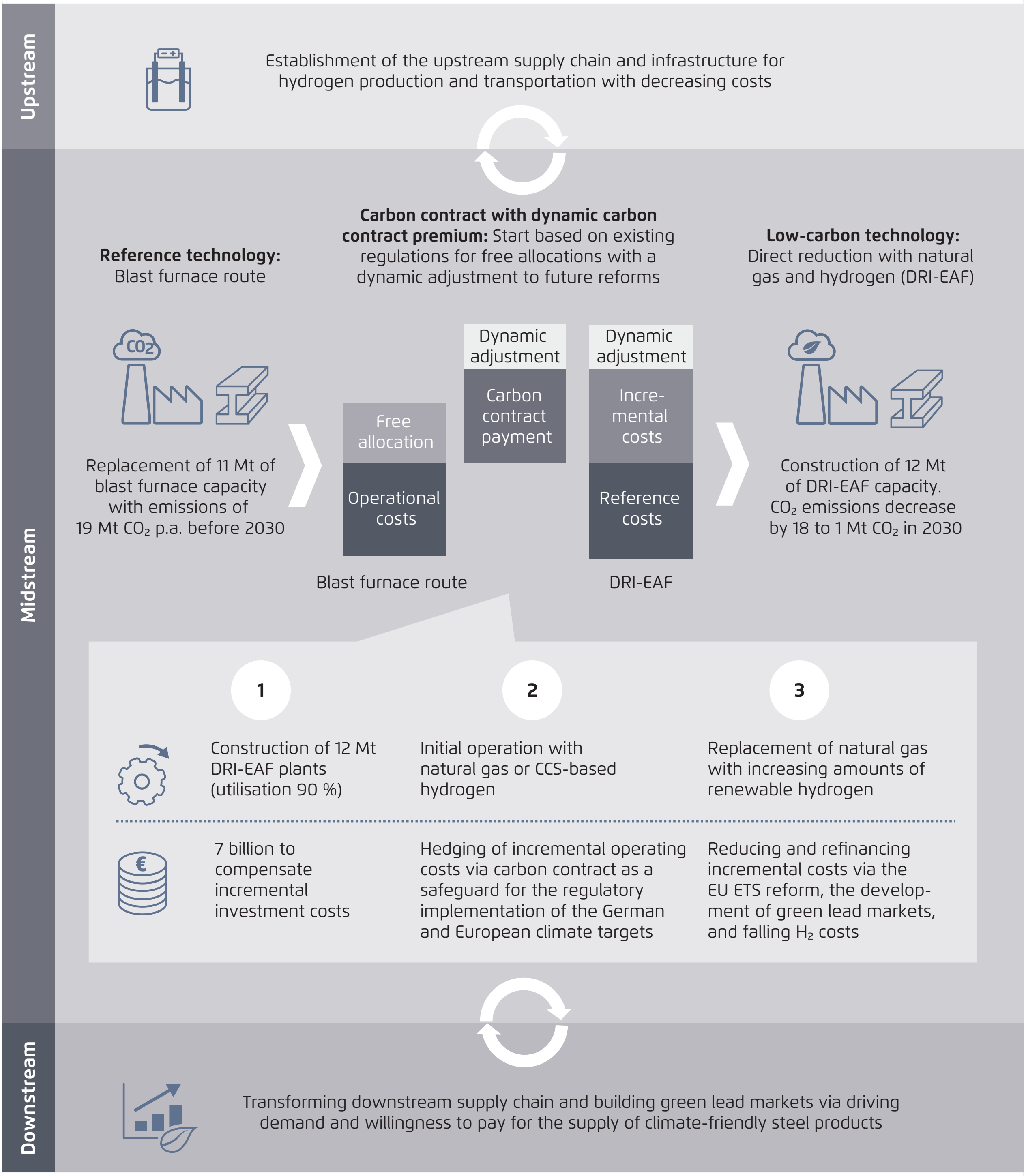
4. **Carbon contracts are a suitable hedging instrument against the incremental costs and uncertainties of climate-friendly steel production in times of crisis.** Alongside the rapid implementation of carbon contracts, the EU ETS must be reformed and green lead markets developed so that climate-friendly steel can establish itself as the industry standard.

Contents

1 Infographic and glossary

Infographic on the role of carbon contracts for transforming primary steel production

Figure 1



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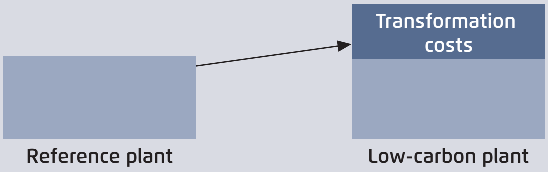
Glossary in images and equations

Figure 2

Incremental costs are incurred when converting production from a reference to a low-carbon plant: **Transformation costs.**



Converting the transformation costs to the tonne of basic material results in the **incremental costs (€/t_{BM})**. Incremental costs for investments [ΔCAPEX] can be supported directly or annualised and allocated to the production volume together with the incremental operational cost [ΔOPEX] for energy, raw materials and other operating resources.

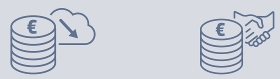
$$\text{Incremental costs } (€/t_{BM}) = \Delta CAPEX^*/t_{BM} + \Delta OPEX/t_{BM}$$

* If ΔCAPEX shall be covered, annualisation is performed using a suitable interest rate over the amortisation period.

The **CO_2 reduction costs** are the quotient of the incremental costs (€/t_{BM}) and the CO_2 reduction resulting from the conversion of production from reference [x] – to low-carbon technology [y].

$$CO_2 \text{ reduction costs } (€/t\,CO_2) = \frac{\text{Incremental costs } (€/t_{BM})}{CO_2 \text{ reduction } [x\text{-}y]\ (tCO_2/t_{BM})}$$

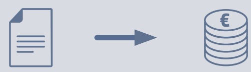
The projection of the average CO_2 reduction costs yields the **contract price.**



$$\varnothing\ CO_2 \text{ reduction costs } (€/tCO_2) = \text{Contract price } (€/tCO_2)$$

Based on this contract price, a **carbon contract** is negotiated between the public sector and the company.

The contract price is the basis for calculating a dynamic **carbon contract premium.** The dynamic adjustment is intended to compensate for the influence of fluctuating incremental costs.



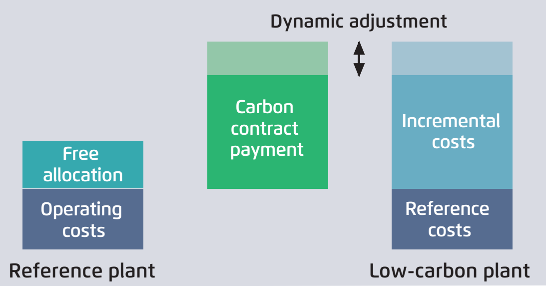
$$\text{Dynamic adjustment} = F\,(\text{incremental costs, time})$$

The carbon contract can take **different forms:**

Carbon contract (CC) for the case that the CO_2 market price plays no or only a minor role

$$CC^* \text{ payment } (€) = \text{Dynamic } CC^* \text{ premium } (€/tCO_2) \times \text{verified } CO_2 \text{ reduction } (tCO_2) \text{ p. a.}$$

$$\text{Dynamic } CC^* \text{ premium } (€/tCO_2) = \frac{\text{Dynamic incremental costs } (€/t_{BM})}{\text{Specific } CO_2 \text{ reduction } (tCO_2/t_{BM})}$$

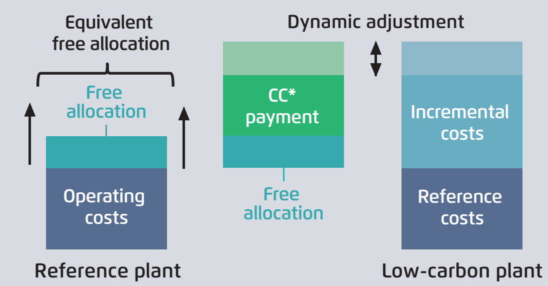


Carbon Contract for Difference (CCfD) for the case of equivalent free allocation* for reference and low-carbon plant

$$CC^* \text{ payment } (€) = \text{Dynamic } CC^* \text{ premium } (€/tCO_2) \times \text{verified } CO_2 \text{ reduction } (tCO_2) \text{ p. a.}$$

$$\text{Dynamic } CC^* \text{ premium } (€/tCO_2) = \frac{\text{Dynamic incremental costs } (€/t_{BM})}{\text{Specific } CO_2 \text{ reduction } (tCO_2/t_{BM})} - \text{free allocation } (€/t\,CO_2)$$

* Equivalence of free allocations is given also in case of abolition.



* CC = carbon contract

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Glossary in a didactic sequence — Table 1

Term	Definition
low-carbon plant/ -technology/ -process (used as synonyms)	The term low-carbon plant refers to a newly constructed plant for the industrial production of basic materials that is compatible with the goal of climate neutrality by 2045 due to the use of a **low-carbon, climate-neutral** or potentially **climate-positive** technology. Compared to the **reference plant**, the production leads to a **verifiable CO_2 reduction**, but is usually more expensive due to higher investment and operating costs.
reference plant/ -technology/ -process (used as synonyms)	The term reference plant refers to a conventional plant for CO_2-intensive industrial production of basic materials. Due to lower costs compared to the **low-carbon plant,** the process defines the **reference costs** for basic material production.
reference costs (€/t_{BM})	Reference costs quantify the costs to produce one tonne of basic material (€/t_{BM}) in a **reference plant.** Reference costs are influenced by fluctuating market prices for operating materials and the **effective CO_2 price.**
transformation costs (€)	Transformation costs quantify the total incremental costs of investment and operation of a **low-carbon plant** compared to a **reference plant** with an equivalent production volume. Transformation costs can be reported according to incremental costs for investment (Δ CAPEX) and operation (Δ OPEX) and can be quantified for individual years or for the entire duration of a **carbon contract.** The transformation costs can be used to estimate the need for additional investment and operating support for the transformation of an industrial plant or an entire sector.
incremental costs (€/t_{BM}) **incremental operating costs (€/t_{BM})**	Incremental costs are calculated from the annualised **transformation costs** but refer to one (1) tonne of the basic material produced (€/t_{BM}). To allocate incremental investment costs (Δ CAPEX) to the annual production of basic material, they have to be annualised with a suitable interest rate over their depreciation period. If only incremental operating costs (Δ OPEX) are considered and allocated to the annual production, incremental operating costs result. These are based on higher and fluctuating costs for energy sources, raw materials and other operating resources. Due to the cost fluctuations for **low-carbon** and **reference plants,** incremental operating costs also vary. Depending on the technology and on regulations for the allocation of free EU allowances, the **CO_2 market price** or an **effective CO_2 price** can affect the low-carbon and reference plants and thus influence incremental costs.

CO_2 reduction costs (€/t CO_2)	The CO_2 reduction costs result from the quotient of the **incremental costs** of producing one tonne of basic material (€/t_{BM}) and the **verifiable CO_2 reduction** achieved as a result (tCO_2/t_{BM}). For the determination of the CO_2 reduction costs, either the total **incremental costs** or exclusively **incremental operational costs** can be used. Depending on the perspective and the applicable rules for free allocation of emission rights, the **CO_2 market price** or the **effective CO_2 price** can be included. CO_2 reduction costs fluctuate with the incremental costs. The average CO_2 reduction costs are the basis for defining the **contract price.** Fluctuations are then considered in the context of **dynamic adjustment** of the **carbon contract premium.** CO_2 reduction costs are project-, plant- or company-specific. They are to be distinguished from the economic (and not project-specific) concept of abatement costs.
cost differences (€/t CO_2)	Cost differences refer to the **Carbon Contract for Difference** and denote the difference between the **contract price** and the **CO_2 market price.** The cost difference, together with other elements of **dynamic adjustment,** then corresponds to the carbon contract premium.
CO_2 market price (€/t CO_2)	The CO_2 market price corresponds to the variable price that results within the framework of regular EU ETS trading for the purchase of an emission right. In cases where the CO_2 price influences the **CO_2 reduction costs** directly, it can be directly deducted from the **contract price** to determine the **carbon contract premium.**
effective CO_2 price (€/t CO_2)	Under the prevailing regulations for the free allocation of emission rights for **low-carbon** and **reference technology,** the effect of the **CO_2 market price** on the operational costs and thus the CO_2 reduction costs is significantly reduced. In these cases, we speak of the **effective CO_2 price,** which is the result of differences in the volume of free allocation to the volume of effective emissions from the **low-carbon** and **reference plant.** The reduced impact of the **effective CO_2 price** can be considered in the context of the **dynamic adjustment** of the **carbon contract premium.** By adjusting the rules, an equivalent allocation or abolition of the free allocations for the **low-carbon** and the **reference plant** can be achieved, and thus the **effective CO_2 price** can be converted into the **CO_2 market price.**
verifiable or verified CO_2 reduction	The substitution of the production of a **reference plant** by the **low-carbon plant** results in a CO_2 reduction that must be verified within the framework of the calculation of the **carbon contract premium** based on the effective production. The criteria for calculating and verifying the CO_2 reduction by multiplying the **specific CO_2 reduction** by the production of basic materials to be credited are defined in the **carbon contract.** The verified CO_2 reduction over one year results from multiplying the specific CO_2 reduction by the annual production to be credited. Product volumes that were explicitly marketed as climate-friendly must be deducted for this purpose.
specific CO_2 reduction	The production of one tonne of a basic material in the **low-carbon plant** results in a specific CO_2 reduction per tonne of final product compared to the **reference plant.** The criteria for calculating and verifying the specific CO_2 reduction are defined in the **carbon contract.**

carbon contract	A **carbon contract** is a project-specific agreement between a company and the public sector to support the investment and operation of a low-carbon plant. The agreement offers support to cover the **incremental costs** of production and can be combined with complementary instruments to support direct investment costs. The carbon contract is a generic instrument in which the **CO_2 market price** plays no or only a subordinate role in the definition of the **carbon contract premium** due to the prevailing regulations in the EU ETS. If the regulations are adapted, a carbon contract can be converted into a Carbon Contract for Difference.
Carbon Contract for Difference (CCfD)	The Carbon Contract for Difference (CCfD) is a specific contract design in which the **CO_2 market price** directly influences the incremental costs due to the prevailing regulations. In a CCfD, the **CO_2 market price** is deducted from the contract price to calculate a variable **carbon contract premium.** For the CCfD, the term strike price is also used for the contract price.
contract price (€/t CO_2)	The contract price is defined on the basis of a transparent calculation of the average **CO_2 reduction costs.** The direct or indirect payment of the contract price is necessary to compensate for the incremental cost of low-carbon production. Fluctuations in the **CO_2 reduction costs** can be reflected by **dynamically adjusting** the **carbon contract premium.** The formula for **dynamic adjustment** is contractually defined together with the contract price.
contract period	The contract period defines the entire term of a **carbon contract** and is divided into corresponding settlement periods. It may make sense to flexibilise the start of the contract period to account for potential delays during the construction and commissioning of a **low-carbon plant.**
contract volume (t_{BM})	The contract volume is defined as the maximum production volume of climate-friendly basic material that is secured by the **carbon contract.** As a rule, the contract volume refers to one accounting period. However, it can also be extrapolated to the entire **contract period.**
settlement volume (t_{BM})	The settlement volume of climate-friendly produced basic material is determined at the end of a **settlement period.** It corresponds to the actual climate-friendly produced basic material minus any volume sold as “green” product. The settlement volume may not exceed the **contract volume.**
settlement period	The settlement period is usually one year but can be contractually agreed to be shorter.
carbon contract premium (€/t CO_2)	The carbon contract premium compensates for the **incremental costs.** It relates to the **verified CO_2 reduction** achieved compared to the **reference plant** and is calculated based on the **contract price** using contractually defined formulas for **dynamic adjustment** and, in the case of a **CCfD,** takes into account the **CO_2 market price.**
carbon contract payment	Multiplying the **verified CO_2 reduction** generated during a settlement period by the dynamic **carbon contract premium** results in the amount to be paid for the respective volume and period – the carbon contract payment.

dynamic adjustment	A dynamic adjustment of the **carbon contract premium** compensates for the effects of variable **incremental costs** caused by fluctuations in the price of operating resources. The effect of an **effective CO_2 price** and a change in the regulations responsible for it can also be taken into account in dynamic adjustments. The **CCfD** is a special case of dynamic adjustment in which the **CO_2 market price** is directly offset against the **carbon contract premium.**
climate surcharge	The climate surcharge refers to a system in which CO_2 costs are added as a levy on CO_2- intensive basic materials or end products. Depending on the design, the climate levy is charged on intermediate or end products and calculated based on embedded carbon or with a generalised approach.
renewable hydrogen	Hydrogen produced by the electrolysis of water. Appropriate criteria are used to ensure that the electricity used in the process comes from renewable energy sources. GHG emissions from the production of renewable hydrogen are close to zero over the entire life cycle.
CCS-based hydrogen	Hydrogen produced from **fossil natural gas** with almost complete capture and storage of the resulting carbon or CO_2 (Carbon Capture & Storage – CCS). The residual GHG emissions for carbon or CO_2 capture, transport and storage are lower than for hydrogen without CCS but depend on the efficiency of the whole process.
low-carbon hydrogen	Both **CCS-based hydrogen** and **renewable hydrogen** are referred to as **low-carbon hydrogen** in this paper, provided their use leads to significantly reduced greenhouse gas emissions over the entire life cycle compared to existing hydrogen production.
low-CO_2 steel	Steel produced by using direct reduction of iron technology with **CCS-based hydrogen** or natural gas as a reducing agent.
climate-neutral steel	Steel produced by using direct reduction of iron technology with **renewable hydrogen.** If the hydrogen comes from 100 percent renewable energy, this technology is in principle close to **CO_2-neutral.** If the DRI plant is only operated intermittently or partly with **renewable hydrogen,** only a corresponding share of DRI is counted towards climate-neutral steel production.
green steel	Green steel is a generic term that describes **low-CO_2** and **climate-neutral steel** and refers to its marketing within the framework of **green lead markets.** The aim of marketing is to transfer the climate benefit of a product to customers in return for the payment of an adequate **climate premium** that covers the incremental costs of climate-friendly production. The quality of steel in relation to the climate can be quantified by the specific emissions generated by its production. The relative climate benefit is given by a comparison with the emission benchmark of the reference technology. Based on this definition, different classifications for different qualities of **low-CO_2** or close to **climate-neutral steel** are needed. As these definitions are not yet available, we refer to this discussion and the anticipated results by the general term „green steel“.

green lead markets	This term is used to describe markets that offer high growth potential for innovative climate-friendly equipment, goods, and services through a combination of overall technical and economic development and the political action being taken to achieve **climate neutrality.**
grey steel	In the context of the discussion on **green lead markets,** this term refers to conventional steel with CO_2 emissions at the level of the blast furnace route.
climate premium	The **climate premium** is the additional sum generated by the free-market sale of a **green steel** product compared with an equivalent grey steel product. As this sale replaces the carbon contract support, the climate premium is generally as high as or higher than the agreed **carbon contract premium.**
CBAM: Carbon Border Adjustment Mechanism	A border adjustment mechanism by which imports, depending on their specific CO_2 intensity, are subject to a levy defined by the CO_2 price. A CBAM can thus also generate financial resources for climate protection investments.
stranded assets	The early shutdown of conventional production plants that have not yet been amortised or are still functional if their operation is no longer profitable or justifiable for climate policy reasons. Early shutdown results in costs both to private businesses and to the national economy.
climate-neutral	Climate-neutral means that GHG emissions are completely or almost completely avoided in all sectors, so that residual emissions can be offset by **climate-positive** strategies and technologies. An industrial facility is compatible with the goal of climate neutrality by 2045 if it can be operated in a (nearly) climate-neutral manner or even results in negative emissions.
climate-positive	To achieve **climate neutrality,** remaining residual emissions must be compensated for by means of climate-positive strategies and technologies in which CO_2 is removed from the atmosphere directly or indirectly and stored over a long term.
ETS Innovation Fund	The Innovation Fund has been created by the European Union to support the development and implementation of low-carbon technologies. The fund is financed by revenues from auctioning EU ETS allowances. Traditionally, the ETS Innovation fund has provided investment support. Recently, the EU announced that carbon contracts or CCfD-like instruments are also being developed to support projects with higher operating costs.

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2 Background and objectives

Given the strategic role of industry for climate neutrality in Germany, Agora Energiewende and its partners FutureCamp, Ecologic Institute, and the Wuppertal Institute have initiated a project to support the swift implementation of carbon contracts for key technologies in Germany's energy-intensive industrial sector. The project aims to develop efficient and implementable options for carbon contracts, thereby creating short-term incentives and ensuring planning security for the transformation towards climate neutrality in Germany's steel, chemical, and building materials sectors.

In a general paper focused on the implementation of carbon contracts as an instrument, some general design features and overarching opportunities and risks are summarised (Agora Industrie, FutureCamp, Wuppertal Institut and Ecologic Institut, 2021). This background study is specific to the steel sector and provides updated data and insights to address recent developments relating to this industry.

This study analyses the technology for Direct Reduction of Iron (DRI) and the subsequent smelting in an Electric Arc Furnace (EAF). Initially, the process can operate with natural gas or carbon capture and storage (CCS)-based hydrogen to then use renewable hydrogen as a key strategy for a climate-neutral steelmaking sector. The technology is mature and represents an alternative to further investment in CO_2-intensive blast furnace systems. In synergy with the establishment of renewable hydrogen production, this strategy enables a transformation to climate-neutral steelmaking.

From a business perspective, the investment in and operation of direct reduction plants cannot viably be financed within the current regulatory and competitive framework. Suitable policy instruments are needed to hedge the investment required for the implementation and operation of DRI-EAF plants. In this study, we focus on the concept of carbon contracts as a possible solution.

For an efficient design and implementation of carbon contracts in the steel industry, however, it is necessary to analyse the technical and economic aspects of the DRI-EAF-route compared with the established blast furnace route. This study and the related transformation cost calculator were developed to enable a comparison between the reference and low-carbon technologies. The focus of the work is the calculation of the transformation costs that result from the switch to the production of low-CO_2 steel. These incremental costs, their variance, their dependencies, and their underlying cost drivers need to be identified and understood to enable an efficient design of carbon contracts as a hedging instrument for the investment in and operation of direct reduction plants.

The preliminary results of our work were presented at a workshop with steel industry representatives and stakeholders. The results of our work were first published in German in September 2021. In this updated version and the related transformation cost calculator, we address current economic and regulatory developments, thereby supporting the ongoing discussion on the implementation of carbon contracts by providing updated results.

Since the beginning of the Russian war of aggression on Ukraine, prices in the energy sector, but also for raw materials such as iron ore, have risen significantly. After the current price shock, we expect that prices for natural gas and coking coal will level off at a higher level than before the war. LNG imports will probably also set higher prices for natural gas in the European market in the medium term.

Another relevant development is that since November 2021, as a result of more stringent European climate policies, CO_2 prices in the EU emissions trading system have risen significantly to a level of 80 to 90 euros per tonne. Further increases can be expected in the medium term.

Moreover, the proposals presented by the EU Commission for reforming the EU ETS and the gradual introduction of a border adjustment mechanism (CBAM) were confirmed by the Council and Parliament of the EU. The Parliament calls for a slightly delayed ramp-up leading up to 2030, but wants to set the date for the full implementation of the CBAM for 2032 rather than 2035.

As a consequence of the combination of higher CO_2 prices and the rapid abolition of free allocations for the steel industry as part of the ETS reform, the incremental costs for climate-friendly steel production will fall faster than previously assumed despite higher energy prices.

An additional element is that the new federal government in Germany has decided to increase the proportion of renewable energy in electricity consumption to 80 percent by 2030. The target for achieving climate neutrality in the electricity sector is 2035. This gives rise to new requirements and opportunities for an accelerated ramp-up of the hydrogen economy, which is now becoming more important not least because of the uncertainties surrounding natural gas supply.

Consequently, the new federal government is also pushing ahead with the implementation of carbon contracts. The Federal Ministry for Economic Affairs and Climate Protection wants to initiate the process of selecting the first projects in 2022 already.

Additional impetus for the transformation of the steel industry arises from the increasing demand for climate-friendly steel. The ongoing discussions with regard to the definition of green steel and corresponding announcements from the manufacturing industry give grounds for hope that a significant portion of the incremental costs for climate-friendly steel production can be financed via a market-driven willingness to pay on the part of the industry and its customers.

Our updated analysis also picks up on this trend and shows that the transformation of the steel industry remains worthwile and feasible within these new framework conditions. It also confirms that carbon contracts as a dynamic financial hedging instrument can be implemented efficiently even in the context of greater market turbulences.

The transformation of the steel industry must now rapidly be set in train through EU ETS reform, the development of green lead markets and the financial hedging of the investments required by means of carbon contracts. The transformation of the steel industry, and with it the long-term safeguarding of a key supplier industry for a wide range of downstream industrial sectors, is more urgent than ever against the background of the rapidly worsening climate crisis and the realignment of international economic relations.

3 Brief description of the German steel sector

Steel manufacturing will play a key role in making the industrial sector climate neutral. The sector's CO_2 emissions amount to around 30 percent of total industrial emissions in Germany.

Most of the emissions come from the production of primary steel in blast furnaces. The blast-furnace route accounts for around 70 percent of the steel produced in Germany. The remaining production is mainly accounted for by the electric arc furnace route, the preferred process for melting and purifying steel scrap. This secondary steel route is of minor importance for direct emissions. Currently, natural gas-based direct reduction is rare in Germany.[1]

1 ArcelorMittal Hamburg GmbH is the only facility in Germany to use the Midrex direct reduction process, which uses natural gas as the reducing agent. The plant has a production capacity of 0.7 Mt per year. In addition Germany imports 1 million tonnes of DRI per year.

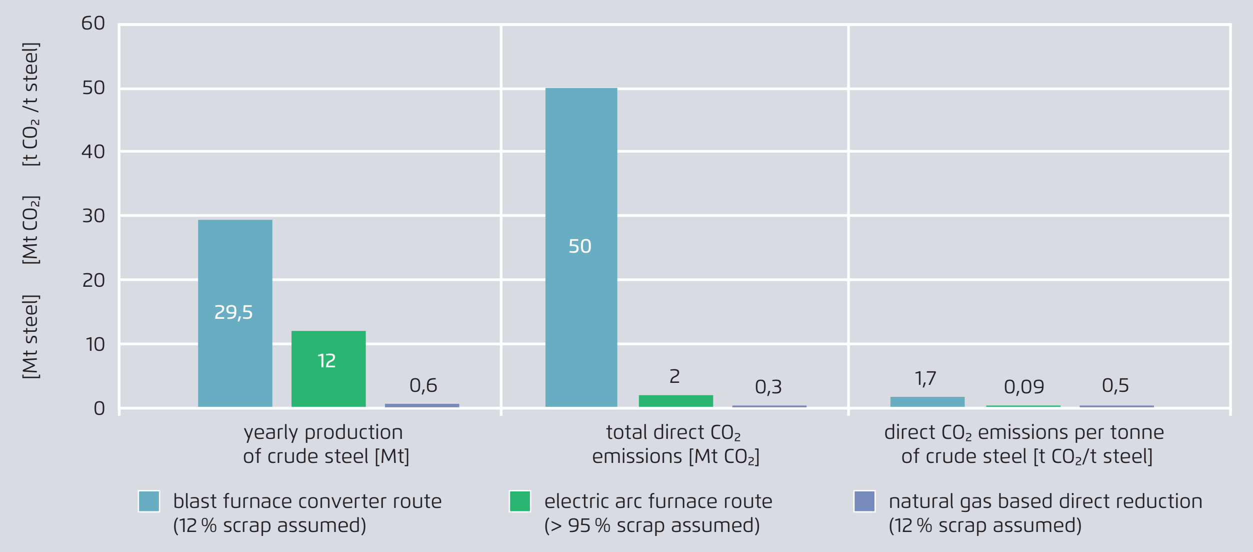
Figure 3 provides an overview of the various production routes and their CO_2 intensity.

The blast furnace converter route is the most CO_2-intensive production method. More than 80 percent of the CO_2 emissions for steel production arise in the reduction of iron ore in the blast furnace. Accordingly, efforts to make primary steelmaking climate-neutral focus on the replacement of the blast furnace with alternative methods of iron ore reduction.

The steel industry is highly competitive at the international level. Germany exports around half of the rolled products it produces. Conversely, it imports around 50 percent of the steel products it processes (see WV Stahl, 2018b).

In contrast to competitors outside Europe, the steel industry in the EU is subject to CO_2 pricing through an emissions trading system (EU ETS). Given the high

Comparison of different steel production processes (Germany 2016) Figure 3



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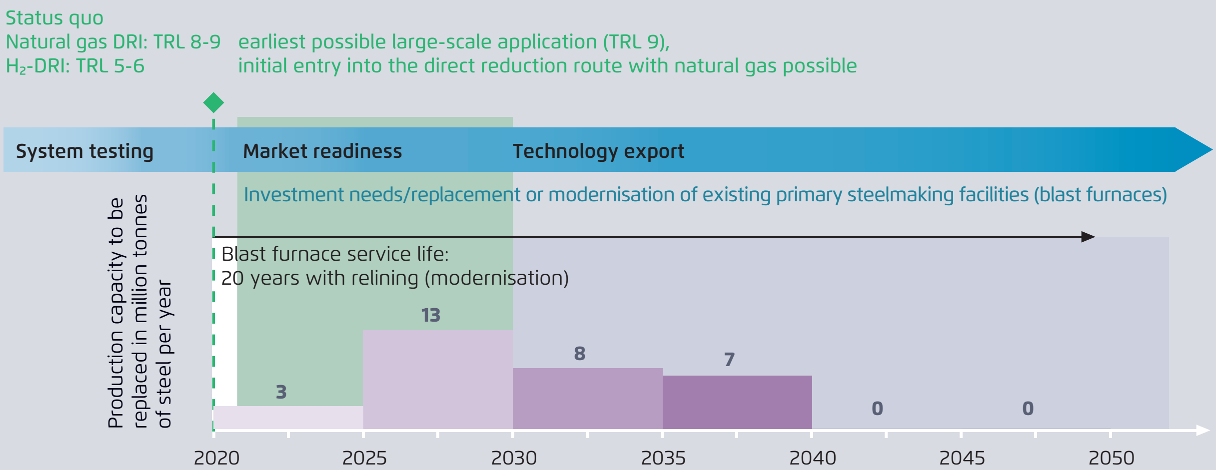
level of emissions in steel production, CO_2 costs can, in principle, have a major effect on the profitability of steel production. However, to avoid disadvantages in international competition, European plants receive free allocations of the emission rights required for steelmaking in the EU-ETS. This results in an effective incentive for energy efficiency measures and operational CO_2 reductions. However, the free allocations for conventional plants do not provide a basis for transformative investments in potentially climate-neutral production plants.

In the decade up to 2030, around 50 percent of the blast furnace capacity in Germany will need to be relined. Additional investment in this conventional technology will further commit manufacturers to CO_2-intensive production, which is incompatible with the goal of achieving climate neutrality by 2045.

An alternative is to replace blast furnaces due to be relined with DRI-EAF-plants. Compared to other processes for low-CO_2 steel production, this technology has the advantage that it can be implemented on a commercial scale before 2030. In addition, the technology is compatible with the goal of climate neutrality when designed for operation with renewable hydrogen. Figure 4 shows an overview of the upcoming reinvestments and the technological availability of direct reduction of iron.

Reinvestment requirements and market maturity of direct reduction low-carbon technology — Figure 4



Reinvestment requirements
The reinvestment requirements in primary steel production up to 2030 include blast furnaces with an annual production of approx. 16 million tons of pig iron (approx. 52 % of total capacity). It was assumed that a significant reinvestment will be due for blast furnaces 20 years after their last relining.

Technology development
With optimal technology development, the earliest possible commercial use (TRL 9) of the technology is 2025. Starting with natural gas instead of hydrogen already enables significant CO_2 reductions (approx. 66 %). An increasing proportion of hydrogen can then be added without significant retrofitting of the plants.

Agora Industry and Wuppertal Institute (2022)

4 Brief description of direct reduction of iron

In direct reduction plants, iron ore that has been processed into pellets is reduced in a shaft furnace using natural gas in a counter flow. This process produces sponge iron (Direct Reduced Iron, DRI) and, as by-products, water and CO_2. The sponge iron (hot DRI) can then be melted and processed directly into crude steel in an electric arc furnace (EAF) (together with scrap if required) or briquetted for transport and later use (hot briquetted iron, HBI). If renewable hydrogen is used instead of natural gas for reduction, essentially this route is CO_2-neutral. A climate-friendly alternative is to use hydrogen produced from natural gas with near-complete capture and geological storage (CCS) of the CO_2 produced during conversion (referred to here as CCS-based hydrogen).

The use of DRI-EAF-plants is already technically feasible in the near term if economic viability is ensured. Starting with natural gas already enables a significant reduction in direct CO_2 emissions of around 66 percent compared with the blast furnace route. The switch to renewable or CCS-based hydrogen can then be made gradually without significant need for retrofitting the plants. The possibility of an increasing admixture of renewable hydrogen can thus accompany and benefit from an increasing share of renewable energies in the electricity system. So the steel industry represents an ideal opportunity for ramping up electrolysis to produce renewable hydrogen.

Three types of primary steel production using DRI can be expected in the future:

1) DRI or HBI can be used as a complementary feedstock in blast furnaces. An example is Voestalpine in Linz, Austria, which uses imported HBI from a DRI plant in Corpus Christi, USA, in the blast furnace.

2) DRI can be melted in electric arc furnaces (EAF), just as they are already used today for scrap recycling, and – if and when required in combination with scrap – processed into crude steel. As part of an integrated DRI-EAF route, hot sponge iron (hot-DRI) can be used directly. In the case of a spatial separation of the DRI and EAF routes, cold sponge iron or HBI must be transported and heated for use. This variant is already widely used on a large scale outside Europe.

3) DRI can also be used as part of a modified Linz-Donawitz process. DRI is liquefied in a melting unit such as a Submerged Arc Furnace, SAF, and serves as a substitute for the liquid pig iron from the blast furnace. The DRI-SAF route is suitable for integration into existing plants, such as those operated today by major German primary steel producers. This concept is new and the first plants to use it are currently in the design phase.

In our work, we focus on the integrated DRI-EAF route, as described in 2). The DRI-SAF route described in 3) differs from the DRI-EAF route in the technology used to melt the DRI, but its economic principles are comparable.

By contrast, the use of DRI in blast furnaces described in 1) represents a different approach as regards the accounting of CO_2 emissions and is not considered here.

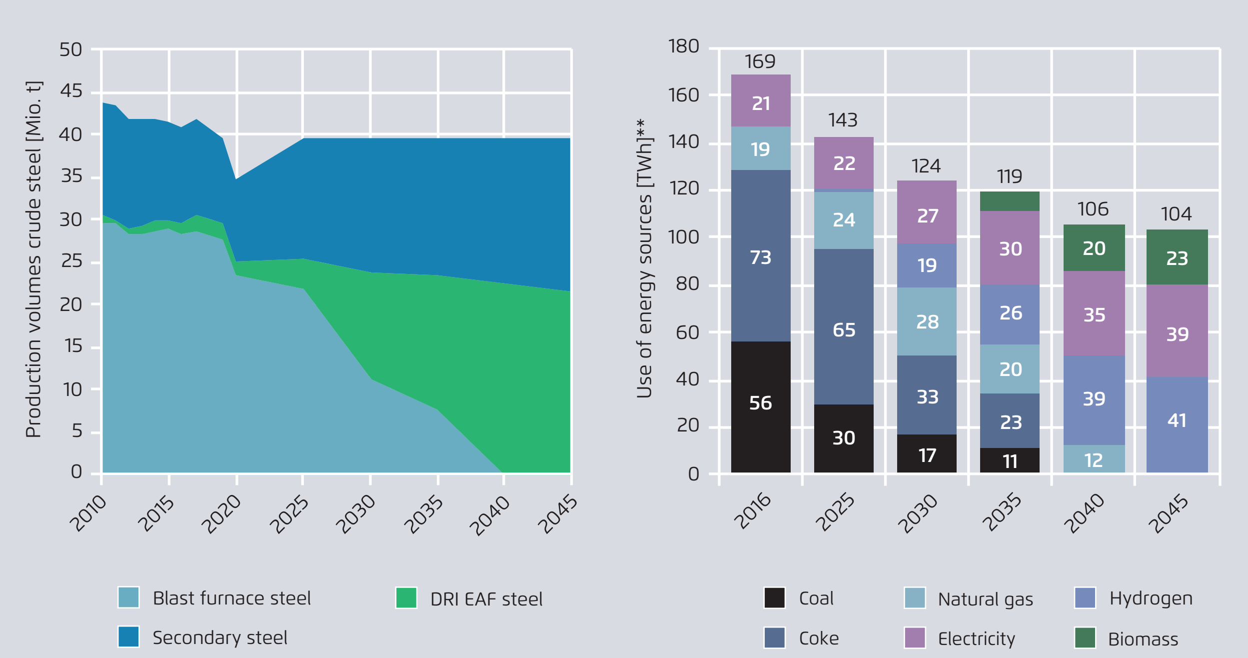
5 A path to climate neutrality by 2045

As part of the 2021 amendment to Germany's Climate Protection Act, a CO_2 reduction target of at least 65 percent by 2030 was defined (Federal Government, 2021b). Germany aims to cut 68 Mt of CO_2 emissions from its industrial sector during this period. This goal roughly corresponds to the scenario presented in the study "Towards a Climate-Neutral Germany by 2045", which modelled the contributions of the individual sectors (Prognos/Öko-Institut/Wuppertal Institut, 2021a). For the steel industry, this means a total reduction of 26 Mt CO_2 by 2030. The transformation path is shown in Figure 5. In this scenario, German steel production settles at a total of just under 40 Mt per year (comparable to that of 2019) and remains there even after 2045.

To achieve this reduction in emissions, no new blast furnaces will be added and the existing ones will be replaced by the development of DRI-EAF capacities for climate-friendly primary steel production and the expansion of the secondary steel route. The proportion of secondary steel increases from 11 Mt in 2016 to 16 Mt in 2030, replacing equivalent levels of blast furnace capacity. This increase in the recycling rate results in a reduction of 7 Mt CO_2. Another 11 million

Scenario for the transformation of crude steel production and the use of energy sources* in the steel industry

Figure 5



*Energy demand is not given here as final energy demand in the sense of the energy balance, but as energy input ex-works (excluding the coke plants). No credit is given here for the generation of electricity from metallurgical gases.
** Specified as lower heating value. The higher heating value for hydrogen is almost 20 per cent higher.

Agora Industry and Wuppertal Institute (2022) based on Prognos/Öko-Institut/Wuppertal Institut (2021a) tons of blast furnace capacity will be replaced[2] by an equivalent amount of DRI-EAF capacity.[3]

For this route, we have assumed a load factor of 90 percent. This would require the building of DRI-EAF systems with a total capacity of 12 million tonnes and an investment volume of 9 billion euros.[4] In order to produce in as climate-friendly a way as possible with these plants and to clearly identify the investment as sustainable, including for institutional investors, suitable locations should be rapidly developed so that renewable hydrogen can be used,at least in some proportion.

2 In the case of the DRI-EAF-route as with the blast furnace route, we calculate with a scrap share of 17 percent. Hydrogen demand and costs are adjusted accordingly.

3 DRI-EAF is a proxy representation of the DRI-SAF route, even if the latter technology requires a slightly modified process.

4 This is an appraisal of the entire investment requirement without deducting the savings from forgoing the relining of existing blast furnaces.

While there is still insufficient renewable hydrogen available, the process can be accelerated by using CCS-based hydrogen.[5] The target should be 80 percent use of hydrogen as a reducing agent and fuel (based on the specific energy content). A certain proportion of natural gas will remain necessary for metallurgical reasons as a carrier of carbon. This approach can reduce emissions by up to 18 Mt CO_2 by 2030.

In a further step after 2030, this currently unavoidable share of natural gas can be replaced by biogenic carbon carriers such as biogas or pyrolysis gases from sustainable biomass. If residual CO_2 emissions are captured and stored via CCS, steel production can help offset emissions from other sectors by creating a CO_2 sink (Prognos/Öko-Institut/Wuppertal Institut, 2021a).

5 CCS-based hydrogen can be delivered by means of a suitable hydrogen infrastructure. Alternatively, the CO_2 can be captured at the DRI plants and transported to geological storage sites via a CO_2 pipeline.

6 Estimating CO_2 reduction costs

Below we consider the incremental costs and CO_2 reduction costs of steel production in DRI-EAF-plants as a basis for calculating and assessing possible carbon contract design options. Steel production in a conventional integrated steel mill via the blast furnace route is used as a reference. We consider two options for the operation of DRI-EAF plants :

1) Using natural gas (option DRI-EAF_NG)

2) Using renewable hydrogen as a reducing agent and to preheat the reducing gas; with supplementary use of natural gas as a carrier of carbon in the reducing agent (option DRI-EAF_H_2)

Between these two options, it is possible to use hydrogen and natural gas together in variable proportions and/or at different times. In addition, as an alternative to steel production in the electric arc furnace (EAF), DRI can be melted in a submerged arc furnace (SAF) in order to use the liquid pig iron in conventional converters. The following calculations refer to the electric arc furnace, but can in principle be transposed to the SAF route.[6]

In order to calculate the incremental costs of climate-friendly steelmaking, a transformation cost calculator was developed, and is available as an appendix to this publication. The results of the calculations are presented in the following chapters. Details on the assumptions and functions of the transformation cost calculator are documented and explained in the appendix.

6.1 Estimating incremental costs

Incremental costs of low-CO_2 steelmaking relative to conventional production can result from higher investment costs as well as from higher operating costs. Investment costs are determined at the moment of taking an investment decision, but they must usually be amortised over many years. Accordingly, investments are annualised over an average amortisation period at an appropriate interest rate. By contrast, operating costs accrue every year. The absolute operating costs and the differences between the low-carbon and the reference plant depend on price developments and price spreads for various energy sources, raw materials, and operating resources.

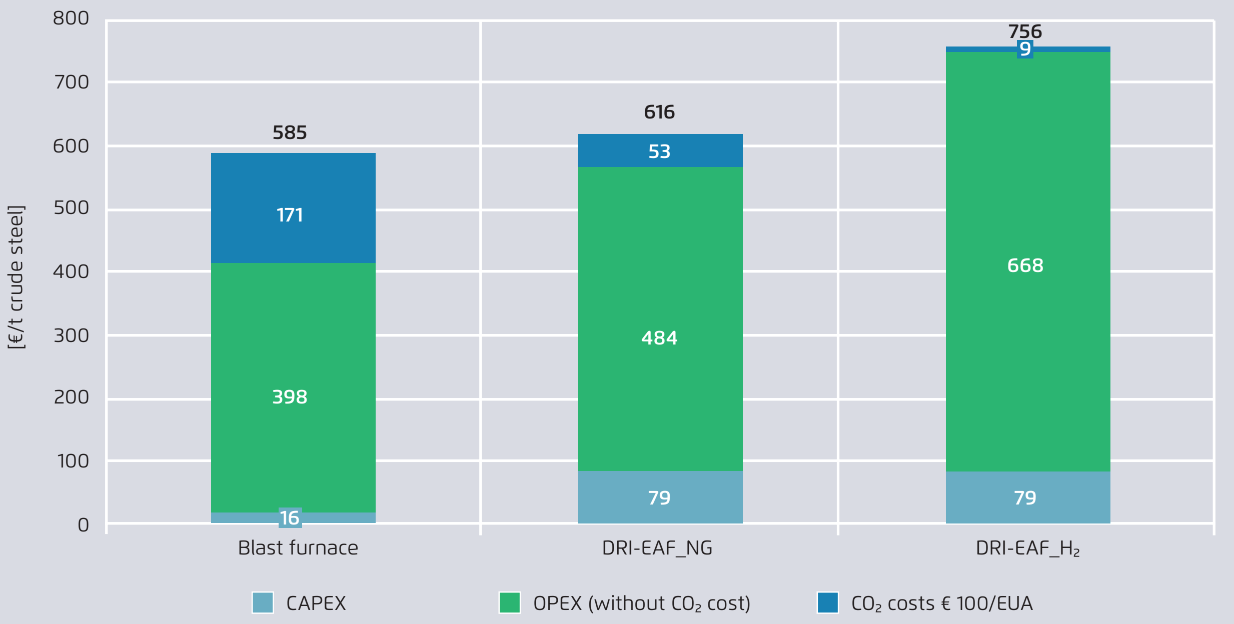
To determine the influence of these variables, Figure 6 shows the annualised investment costs (CAPEX) as well as the operating costs (OPEX) for the production of one tonne of crude steel via the routes considered. The operating costs are presented without details about the specific components. CO_2 costs are shown as a separate item, assuming a fictitious price of 100 euros per EUA. In this first step, we have not considered the effects of free allocation.

Regarding the annualised investment costs, incremental costs of 63 euros per tonne of crude steel accrue for the DRI-EAF relative to the conventional route. The annualised investment costs in the blast furnace route are lower because there is no need to invest in completely new plants, but only to finance measures for the relining of blast furnaces and the associated aggregates.

Significant differences are observed in the operating costs, especially for the hydrogen option. In Figure 7, the operating costs (OPEX) are broken down into the most relevant blocks. With regard to general operating costs (labour costs, maintenance,

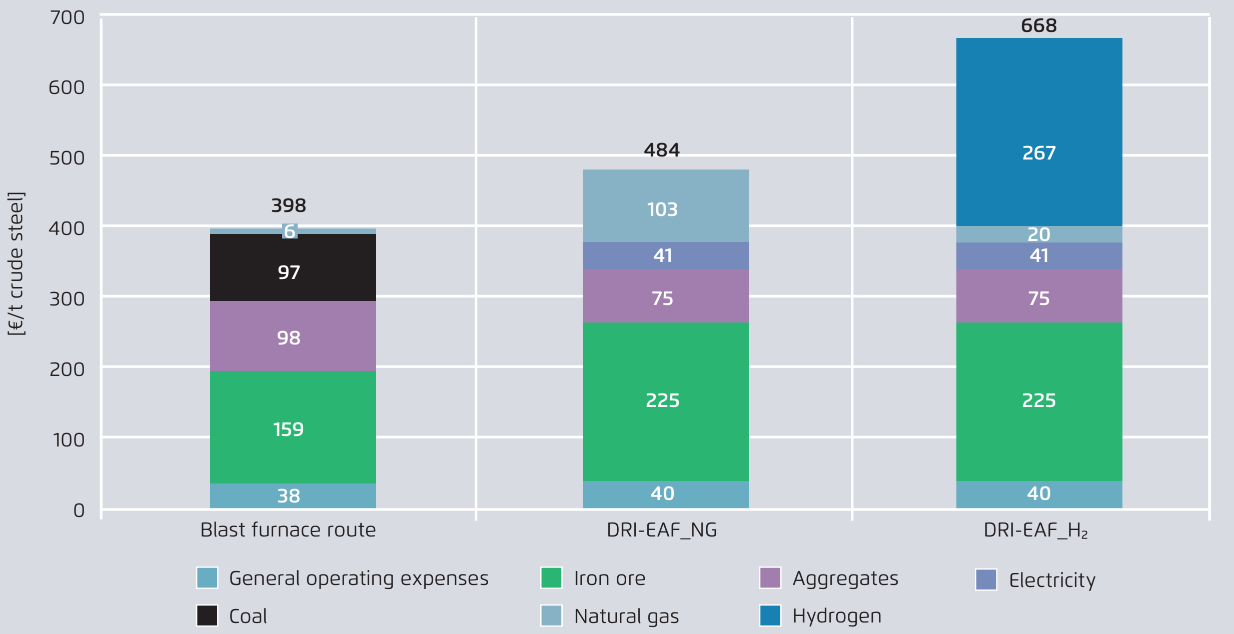
6 With the SAF route, the use of renewable hydrogen is more restricted for metallurgical reasons, but it is still appropriate for combination with CCS-based hydrogen and, if needed, for biomass operation (BECCS).

Cost blocks for producing one tonne of crude steel by route (€/t crude steel) — Figure 6



Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

Breakdown of relevant OPEX cost blocks by route (€/t crude steel) — Figure 7



Agora Industry, Future Camp, Wuppertal Institute and Ecologic Institute (2022) other), no significant differences between the technologies are to be expected. For the raw material iron ore, there are relevant incremental costs for the DRI options. These result from the higher costs of DRI-grade iron ore pellets compared to the ore grades that can be used in the blast furnace. Lime, scrap, oxygen, alloying elements, and, in the case of EAF, graphite electrodes are included among the aggregates. All in all, in this category cost advantages result from lower lime and oxygen requirements for the DRI option. The most important cost differences between the options result from the energy source used, i.e. the reducing agent. Of particular relevance for the DRI routes is the natural gas price (initially set at 35 euros per MWh) and the hydrogen price (set at 140 euros per MWh higher heating value – HHV). In Section 6.3, we carry out sensitivity considerations with regard to these price assumptions.

Other factors from by-products of the blast furnace route, such as the export of metallurgical gases and the sale of slag, are not taken into account. However, internal use of the metallurgical gases is considered and therefore external electricity demand for the blast furnace route is set at zero, on the assumption that this can be completely covered by the energetic use of the metallurgical gases.

6.2 Estimating the CO_2 reduction costs in order to set the contract price

The CO_2 reduction costs compared to the blast furnace route provide the basis for the definition of carbon contracts. These costs represent the quotient of the incremental costs of producing a tonne of raw material with low-carbon technology, and the verifiable CO_2 reduction, compared to the reference technology.

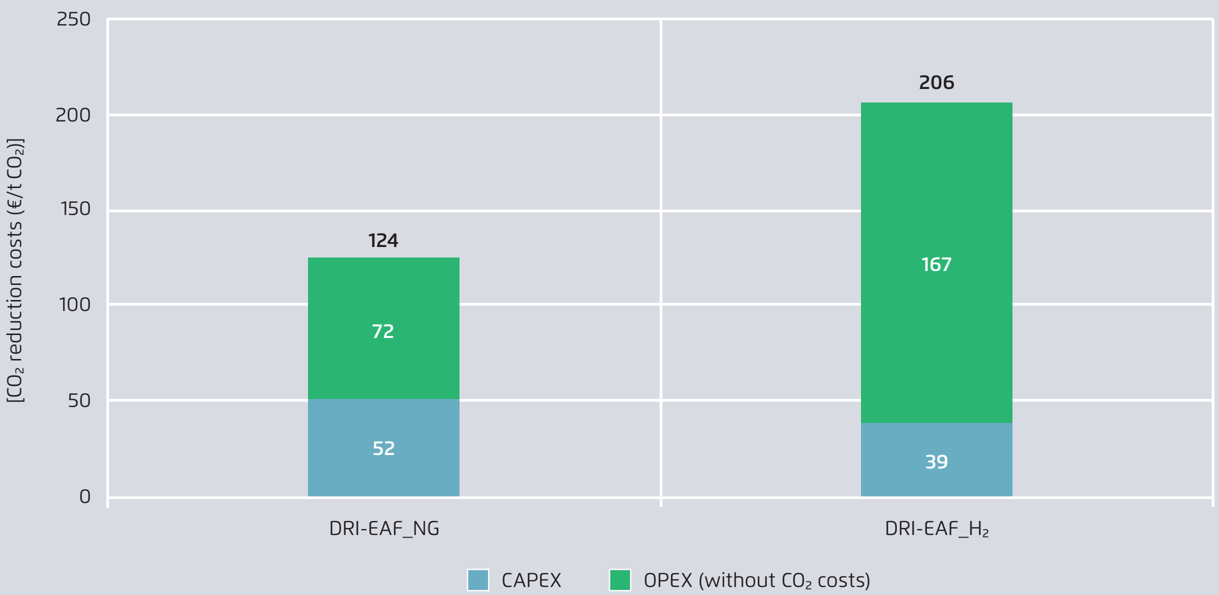
The expected reduction costs determine the contract price that must be achieved to compensate the incremental costs of production with the low-carbon technology. In the DRI-EAF_NG option, the contract price required is 124 euros per tonne of CO_2 under the prevailing assumptions, and 206 euros per tonne of CO_2 in the DRI-EAF_H_2 option. The different CO_2 emissions and reductions resulting from the different production routes and their comparison are summarised in Table 2. Figure 8 provides a comparison of the CO_2 reduction costs of steel production using natural gas and hydrogen-based direct reduction of iron. The results are calculated from the incremental costs of production relative to the blast furnace route and the resulting CO_2 reductions, as Table 2 shows. As Figure 8 shows, the operational CO_2 reduction costs dominate in the DRI-EAF_NG option due to the higher cost of DRI-pellets, electricity and natural gas. However, the annualised incremental investment costs are also relevant. These arise from the need to

CO_2 emissions and relative CO_2 reductions by primary steel route — Table 2

	Blast furnace route (Reference)	DRI-EAF_NG	DRI-EAF_H_2
Specific CO_2 emissions [tCO_2/t crude steel]	1.7	0.5	0.1
Specific CO_2 reductions [tCO_2/t crude steel]	–	1.2	1.6

Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

CO_2 reduction costs compared with the blast furnace route in € per tonne of CO_2 reduction — Figure 8



Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

invest in new plants with higher costs compared to the reference technology and from annualising with a relatively high, standard market capital cost rate of eight percent. This cost area can be mitigated by suitable investment support instruments.

In the case of the DRI-EAF_H_2 option, the investment costs related to CO_2 reduction are lower, resulting from a relatively higher CO_2 reduction.

In practice, however, the investment costs for a switch to natural gas and then hydrogen are only incurred once. If, as per the transformation path described in section 4, the DRI-EAF plant is initially operated with natural gas and then converted to hydrogen, these costs – apart from some minor adjustments – are incurred only for the initial investment. The hydrogen operation in the second step accrues only incremental operating costs. Thus, investing in DRI facilities is strategically important to enable the steel industry to use hydrogen and establish a demand anchor for renewable hydrogen. From this perspective, operating with natural gas plays an important role in safeguarding production in case hydrogen production is initially insufficient or variable. Consequently, investments in new DRI plants are a necessary condition for the transformation of the steel industry and the creation of flexible demand for the strategic production of renewable hydrogen.

Another aspect of investment costs is that they must be depreciated over a long period of time and that, especially for innovative technologies whose performance has not yet been tested, the capital costs on the financial market are quite high. It makes sense, therefore, to support strategic investments in DRI plants with suitable funding instruments.

Alongside the investment costs for DRI-EAF plants, operating costs (OPEX) are another decisive element for the competitiveness of the system. A sensible way to cover the incremental costs is the use of carbon contracts. We analysed the influence and variability of various operating cost components on CO_2 reduction costs in order to determine a suitable design for the contracts. We distinguish between three categories:

1) **No significant incremental costs for switching from the blast furnace route to a DRI-EAF system:** These costs are irrelevant for carbon contracts. Examples are general operating costs and alloys.

2) **Relevant but static incremental costs:** These costs are relevant for defining the contract price, and they can be easily determined and fixed. Examples are graphite electrodes, lime and oxygen.

3) **Relevant variable incremental costs subject to price fluctuations:** These costs are relevant for defining the contract price, but are hard to predict. It may thus make sense to use a price index in the carbon contract to allow for adjustments and avoid over- or under-compensation. Chapter 6.3 examines the influence of relevant variable costs drivers in more detail within the framework of a sensitivity analysis.

6.3 Sensitivity considerations with regard to price fluctuations

The costs discussed in category 3 include energy sources usually subject to strong price fluctuations. In the following section, the influence of historically observed price fluctuations will be discussed. The sensitivity diagrams illustrate how the fluctuation of a specific cost component affects the total operational CO_2 reduction costs. This shows the influence of the specific component.

Of relevance are the prices for energy carriers, which have risen sharply in 2022 because of the Russian war of aggression on Ukraine. The price of coking coal has risen from a long-term average of about 150 euros to over 500 euros per tonne at the upper limit. The price of natural gas has risen from an average of about 20 euros to over 130 euros per MWh at the extreme.

As these extreme values are short-term and crisis-related, there is a need for a reassessment of the prices to be expected for these commodities over the long term. Based on the report Climate Neutral Electricity System 2035 (Agora Energiewende, Prognos, Consentec, 2022), we assume that the price of natural gas will stabilise in the medium term at a level of 35 euros per MWh due to the development of sufficient capacities for LNG imports. As a more conservative assumption we also consider 50 euros per MWh.

For coking coal, we assume that a new market equilibrium of 200 euros per tonne will be reached, but we also calculate using a higher value of 378 euros per tonne.

We currently see no reason to revise the projected hydrogen prices, as the effects of an accelerated expansion of renewable energies and an increase in electricity costs due to the price of natural gas should roughly balance out in the longer term.

As DRI pellets are more expensive than standard ore, we are assuming a premium of 40 euros per tonne to take into account higher production costs as well as growing demand for this product.

6.3.1 Sensitivity of the CO_2 reduction costs in relation to the coking coal price

The coking coal price has a strong effect on the operating costs of the reference route (see Figure 9). Assuming a price development that leads to low prices for coking coal, as was observed at the beginning of 2016, the costs of the reference technology decrease and the relative CO_2 reduction costs of a DRI plant increase. Accordingly, high prices for coking coal, as observed in 2022, would lead to a decrease in

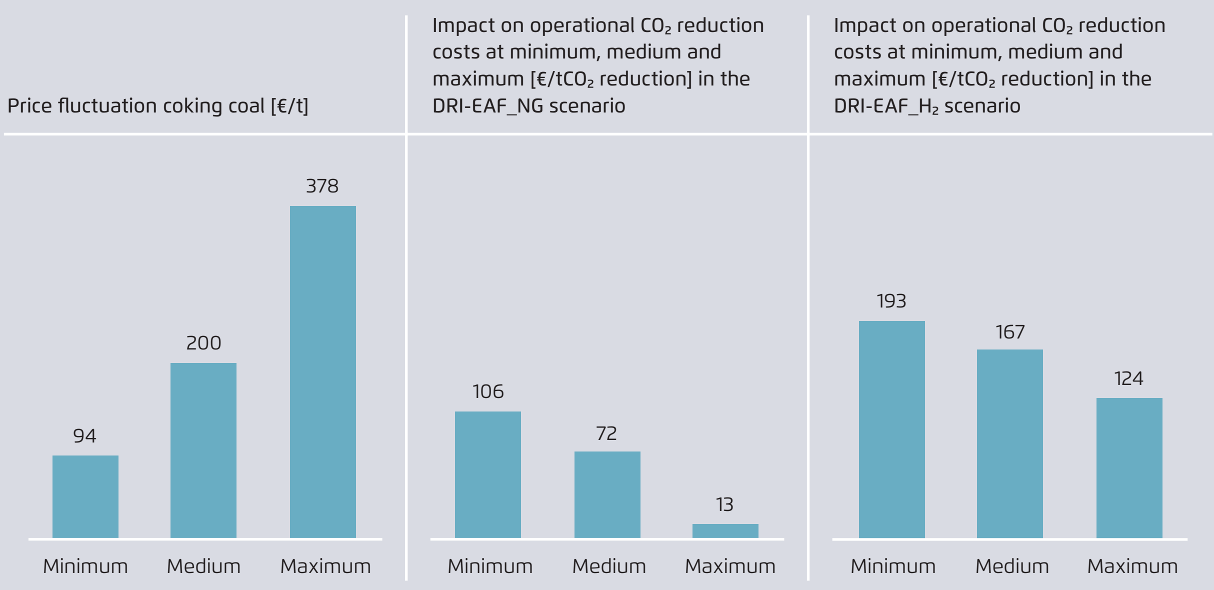
CO_2 reduction costs. For the DRI-EAF_NG option, for which we calculated average operational CO_2 reduction costs of 72 euros per tonne of CO_2, this results in a lower limit of 13 and an upper limit of 106 euros per tonne of CO_2. In the case of the DRI-EAF_H_2 option, for which we calculated mean operational CO_2 reduction costs of 167 euros per tonne of CO_2, limits of 124 and 193 euros per tonne of CO_2 result.

In both cases, the fluctuation of the coking coal price has a relevant influence on total CO_2 reduction costs for operation. However, this applies under the simplified assumption that other energy price parameters remain constant. However, there is a high correlation between the prices of energy sources, especially between coal and natural gas. This correlation reduces the influence of the general price fluctuations of these energy sources on the incremental costs and CO_2 reduction costs that result from a switch to a climate-friendly production method.

6.3.2 Sensitivity of the CO_2 reduction costs in relation to the natural gas price

The price development of natural gas also has a significant influence on the operating costs of a DRI plant, especially in the option using natural gas (see Figure 10). High natural gas prices lead to rising CO_2 reduction costs. Conversely, a downward trend in gas prices like the one observed in 2020 can significantly lower the reduction costs of the DRI plant. In the case of very high gas prices – as observed in 2022 – the operating costs increase accordingly. Assuming 35 euros per MWh as the long-term average for the purchase of natural gas, the average operating CO_2 reduction costs for the DRI-EAF_NG option are 72 euros per tonne of CO_2. If natural gas prices fall back to a historical minimum of 12 euros per MWh, this results in a lower limit of 19 euros. In the case of long-term high natural gas prices of 50 euros per MWh, this results in an upper limit of 106 euros

Influence of coking coal price fluctuation on CO_2 reduction costs — Figure 9



Australian Government (2021), Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022) per tonne of CO_2.[7] This analysis shows that the natural gas price has a relevant influence on the operational CO_2 reduction costs. In the case of the DRI-EAF_H_2 option, the influence is smaller, as natural gas is only used as an added reaction gas. When the calculated mean value of the operational CO_2 reduction costs is 167 euros per tonne of CO_2 the lower and upper limits are 166 and 171 euros per tonne of CO_2, respectively.

6.3.3 Sensitivity of the CO_2 reduction costs in relation to the hydrogen price

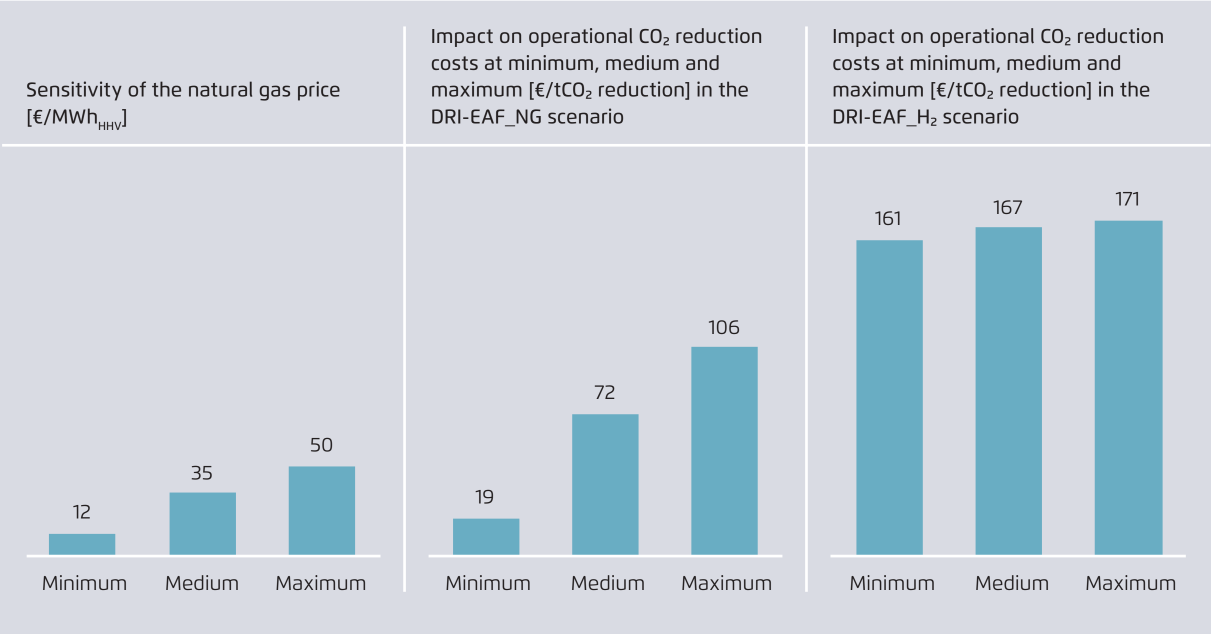
The development of the price for renewable hydrogen has a significant influence on the operating costs of the DRI plant in the DRI-EAF_H_2 option (Figure 11). The prices to be expected for renewable hydrogen in the future depend substantially on the electricity costs for operating the electrolysis and on the development of the costs for electrolysers. In the study "Climate-Neutral Germany 2045" (Prognos/Öko-Institut/Wuppertal Institut 2021a), a price level of 110 euros per megawatt hour of hydrogen (4.3 euros per kg) was forecast for 2050, based on a current price level of approximately 170 euros per megawatt hour of higher heating value (6.7 euros per kg). As a default value we consider 140 euros per megawatt hour of hydrogen (5.5 euros per kg). This value results in average operational CO_2-reduction costs of 167 euros per tonne of CO_2 when substituting the blast-furnace route with a DRI-EAF_H_2 plant. Based on the mentioned higher and lower hydrogen costs CO_2-reduction costs are projected with the limits of 131 euros and 203 euros per tonne of CO_2.

7 In reality, costs should be lower as high gas prices will partially be offset by high prices for coking coal.

6.3.4 Sensitivity of the CO_2 reduction costs in relation to the DRI pellet price

Since direct reduction of iron is a solid-state reaction, the iron ore must be used in the form of special DRI pellets. Due to the use of high-grade ore and the need

Influence of natural gas price fluctuation on CO_2 reduction costs — Figure 10



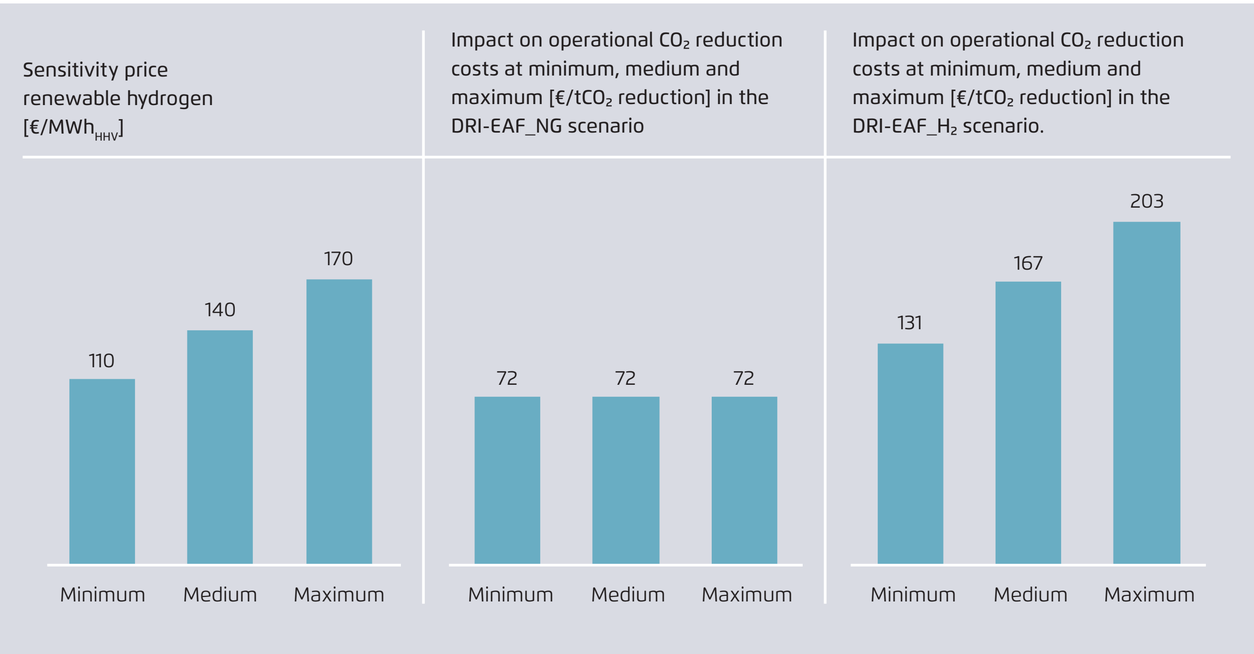
BDEW (2022); Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022) for an additional production step, these are more expensive than normal iron ore, which we estimate to cost 114 euros per tonne.[8] In addition, the supply is scarce and needs to be expanded to cater for a globally increasing DRI plant capacity. This explains why the price difference between DRI pellets and blast-furnace-quality iron ore is subject to strong fluctuations over time (see Figure 12).

At the beginning of 2019, this price difference was around 70 US dollars per tonne, while in the course of 2020 it fell below 30 US dollars per tonne.[9] In the long term, we assume a premium for DRI pellets of 40 euros per tonne compared to standard ore. This results in total costs of 154 euros per tonne of DRI pellets and thus average operational CO_2 reduction costs of 72 euros per tonne of CO_2 for the DRI-EAF_NG option. For the expected price fluctuations for DRI pellets between 134 euros at a premium of 30 euros per tonne and an upper limit of 174 euros at a premium of 70 euros per tonne, a lower limit of 59 euros and an upper limit of 200 euros per tonne of CO_2 are calculated. In the DRI-EAF_H_2-option, the influence is less. Deviating from the calculated mean value of the operational CO_2 reduction costs of

8 The absolute value of iron ore costs is less relevant, as it affects all primary steel routes equally and thus does not influence the incremental costs of climate-friendly production.

9 As part of the momentum that has developed around the steel industry transformation, prices for DRI Pellet Premium have also changed. For the year 2022, the pellet producer Vale has raised the prices for DRI Pellets, sometimes to over 60 USD/dmt (Argus, 2022). Even though this price level must be seen in the context of the current rise in energy prices and the Russian war of aggression on Ukraine, it can be assumed that prices will settle at a higher level for the long term due to the increasing demand for DRI pellets. Therefore, we assume a long term Pellet Premium of 40 euros per tonne.

Influence of different renewable hydrogen price assumptions on CO_2 reduction costs — Figure 11



Prognos, Öko-Institut, Wuppertal Institut (2020); Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

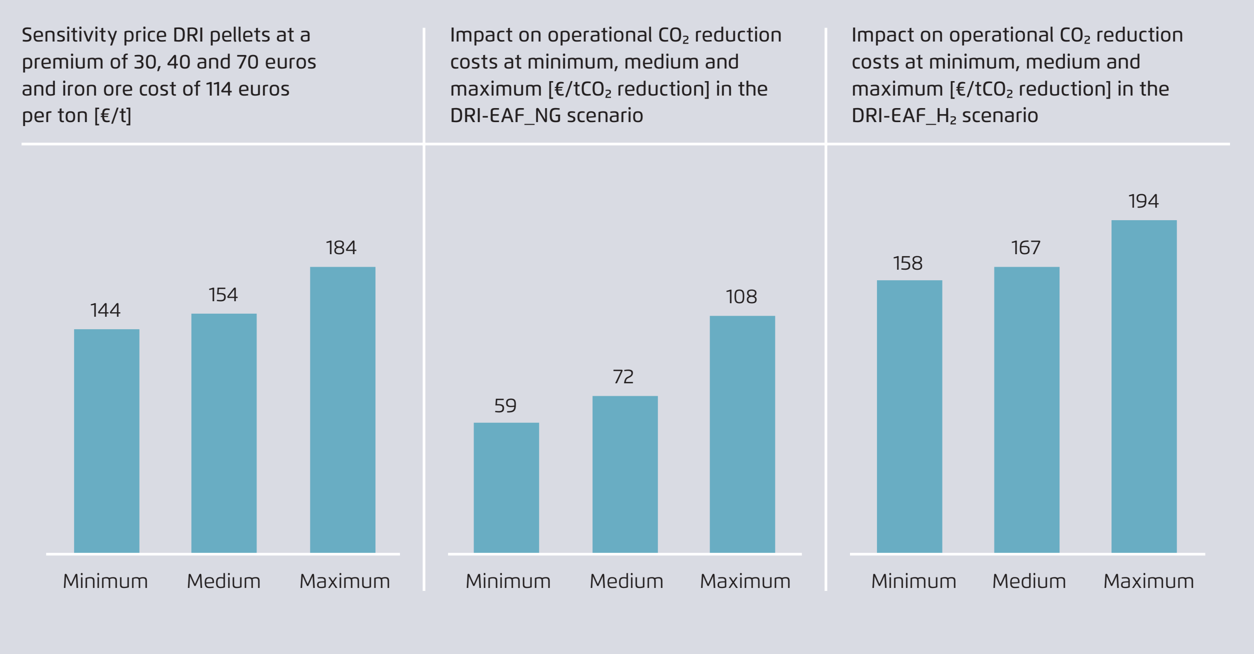
167 euros per tonne of CO_2, limits of 158 euros and 263 euros per tonne of CO_2 result.

6.3.5 Dynamic adjustment of carbon contracts to reflect fluctuating incremental costs

In order to deal with the large fluctuations in the incremental costs for the price premium for DRI pellets, the energy carriers coking coal and natural gas as well as hydrogen, the payments required by a carbon contract may need to be dynamically adjusted. This can be done by defining suitable formulas and price indices, which, in coordination with the contract price, are defined within the carbon contract. Based on the agreed contract price and the defined dynamic formulas, a corresponding carbon contract premium can be calculated for payment at the end of each settlement period.

In addition to the adjustments resulting from the dynamic adjustment of the operating costs, the CO_2 market price within the framework of a Carbon Contract for Difference (CCfD) can also be explicitly offset against the carbon contract premium. To determine the payments required by a carbon contract, the achieved CO_2 reduction must be verified at the end of each settlement period. These topics will be discussed in more detail in section 7.

Influence of DRI pellet price fluctuation on CO_2 mitigation costs — Figure 12



S&P (2022); Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

7 Design aspects and options for carbon contracts

As a basis for establishing general recommendations for the implementation of carbon contracts, this chapter discusses some key aspects of the steel sector. We focus on interactions with the EU ETS, the role of the steel industry for the market ramp-up of renewable hydrogen, the development of green lead markets, and dynamic hedging of incremental production costs.

7.1 Interactions between carbon contracts and the EU ETS

In order to protect industrial activities from the risk of carbon leakage, the EU-ETS offers free allocations of emission rights to trade-exposed industries, including steel production. The free allocation of emission rights lowers the effective CO_2 price for the sector and thus supports their competitiveness compared to production in countries without a CO_2 price.

Since the free allocations influence the relative competitiveness of reference and low-carbon plants, and thus the transformation costs discussed here, their effect on the costs of primary steel production with blast furnace and DRI plants must be analysed.

The free allocations for conventional plants are defined on the basis of specific benchmarks, summarised in Table 3.

The current benchmarks are tailored to conventional steel production. With the free allocations defined in this way, and subject to the efficiency of the plant, the emissions of the blast furnace-converter route can be largely offset, with a slight undercoverage of emissions as a rule. Due to the free allocations, the effective CO_2 price for production with the blast furnace route as the reference plant is thus low. The benchmarks defined for the blast furnace route ("hot metal," "iron ore sinter," and "coking coal") do not apply to DRI-EAF plants. Accordingly, the free allocation of emission allowances must be based on a combination of the following fall-back benchmarks (DEHst, 2019):

1) "process emissions" for natural gas/hydrogen as reducing agents; and

2) "fuel benchmark" for heating the reduction gas.

Product-related benchmarks of the EU ETS for the steel sector — Table 3

	Benchmark values 2013 – 2020	Forecast benchmark values 2026 – 2030
Hot metal	1.328 EUA/t	1.275 EUA/t
Iron ore sinter	0.171 EUA/t	0.152 EUA/t
Coking coal	0.286 EUA/t	0.194 EUA/t
EAF high-alloy steel	0.352 EUA/t	0.240 EUA/t
EAF carbon steel	0.283 EUA/t	0.192 EUA/t

Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

For EAF, the allocation takes places via the EAF product benchmark. Due to the interchangeability of electricity and fuel input, the free allocations decrease when the ratio of fuel to electricity input shifts.

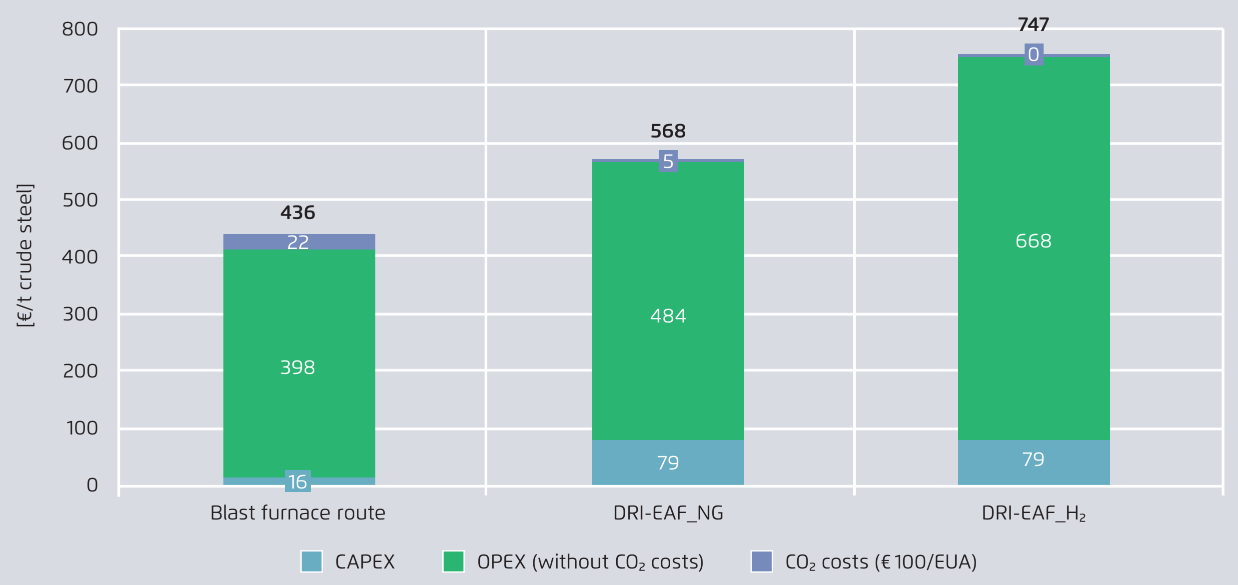
Due to the change in benchmarks, the free allocations for production with the DRI-EAF route are significantly lower than for the blast furnace route, corresponding to the lower emissions of direct reduction of iron. However, there is also some degree of undercoverage here, resulting in costs due to the purchase of missing emission rights. Where plants operate using renewable hydrogen, the use of fall-back benchmarks for process emissions further reduces the number of free allocations.

The number of free allocations, therefore, is significantly influenced by the technology change. This means that the effective impact of the CO_2 price on the production costs of the respective production processes is small (see Figure 13). Thus, the incremental costs of natural gas or hydrogen-based steel production relative to the blast furnace route are quite independent of the EU ETS price.

Based on the assumptions made, effective CO_2 costs remain around 22 euros per tonne of crude steel at a CO_2 price of 100 euros/EUA for the reference plant and taking into account the free allocations. The DRI-EAF_NG option results in effective CO_2 costs of around 5 euros per tonne of crude steel. When operating with a proportion of renewable hydrogen in the energy content of the reaction gas, 2 euros per tonne of crude steel are incurred (see Figure 13).

Contrary to expectations that free allocation based on uniform product benchmarks could contribute to financing the incremental costs of low-carbon production, emissions trading in its current form cannot – or only to a very limited extent – compensate for the incremental costs. Compared with primary steel production outside Europe, where

Costs in euros per tonne of crude steel under current rules for free EUA allocation — Figure 13



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there are generally no CO_2 or relatively low carbon costs, the prevailing rules actually make it necessary to purchase EUAs. This creates a further competitive disadvantage for DRI plants if they still use at least a proportion of natural gas.

Within the framework of existing allocation rules, the transformation costs will therefore have to be almost completely covered by carbon contracts. The differential costs to the CO_2 market price are then practically negligible. Even if the EUA price rose above the contract price, there would still be a need for additional compensation of incremental costs.

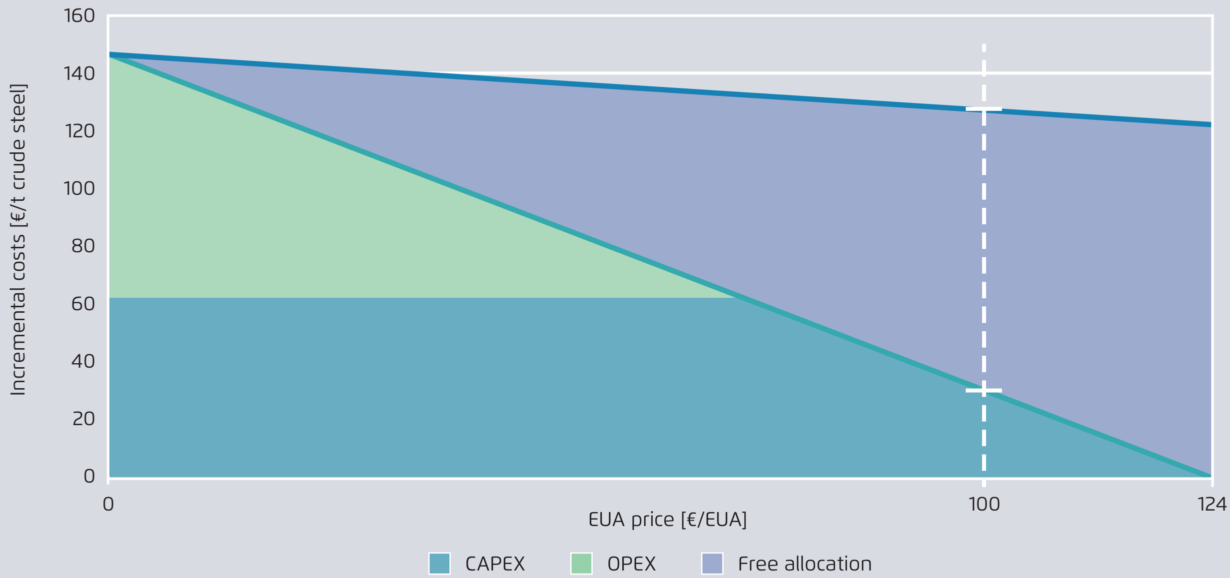
In order to better analyse the impact of the prevailing rules for free allocations on the construction and operation of natural gas-based DRI plants, the correlation between incremental costs in production, implicit CO_2 reduction costs and the effect of the EUA price is shown graphically in Figure 14.

Under our assumptions, the production of one tonne of crude steel using the natural gas-based DRI process is around 149 euros per tonne more expensive than with the CO_2-intensive blast furnace route. The annualised investment costs account for 63 euros of this and the incremental operating costs for the remaining 86 euros.

Based on a CO_2 reduction of 1.2 tCO_2/t of crude steel, the CO_2 reduction costs are 124 euros per tonne of CO_2, with 52 euros for annualised investment costs and 72 euros for incremental operating costs.

In a hypothetical scenario without free allocations or with the same amount of free allocations for the reference and low-carbon technologies, a CO_2 price of 72 euros per tonne of CO_2 would fully compensate for the incremental operational costs of natural gas-based direct reduction of iron. A CO_2 price of 124 euros per tonne of CO_2 can also finance the incremental costs for investment, represented by the green line in Figure 14. In practice, however, the free allocations for reference

Incremental costs as a function of the EUA price — Figure 14



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and low-carbon technologies result in a relationship symbolised by the red line in Figure 14. The influence of the CO_2 price is limited here to the effective CO_2 price, which affects the respective production paths through an undercoverage in the volume of cost-free allocations. The effect is illustrated by the white line. With an assumed CO_2 market price of 100 euros per EUA, the incremental costs for the production of natural gas-based DRI steel decrease from 149 euros to 132 euros per tonne of crude steel.

Based on this initial situation, we have identified four scenarios for the design of carbon contracts in relation to the EU ETS, which are presented below.

7.1.1 Scenario 1: carbon contracts

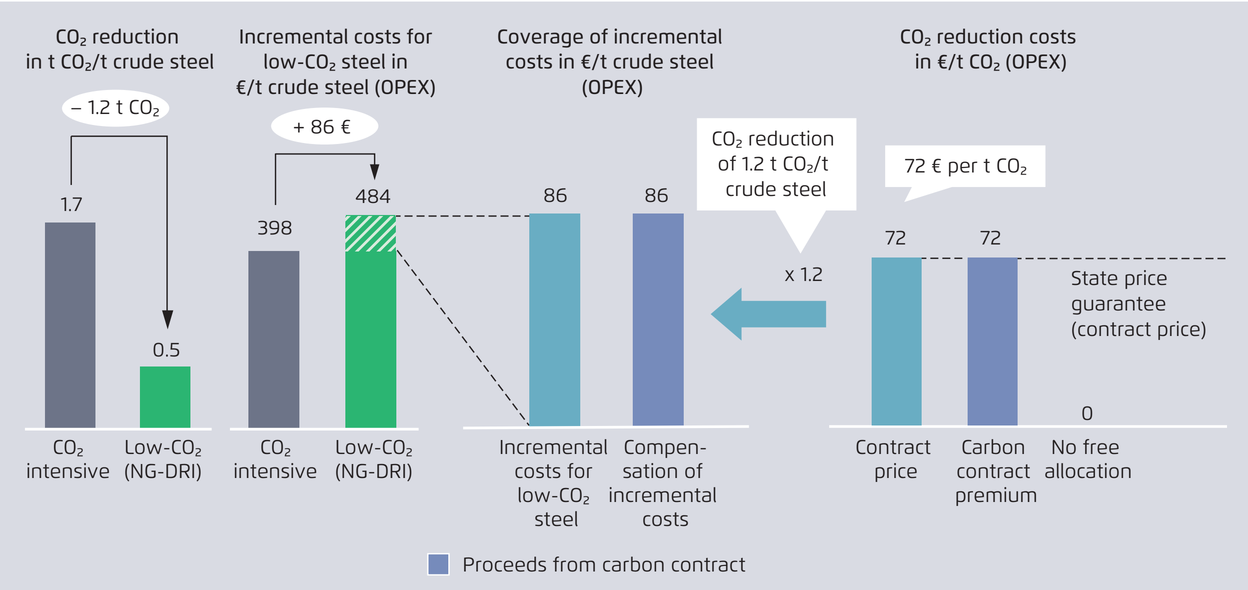
From the analysis in 7.1., we can conclude that the competitiveness of DRI systems is not enhanced by the prevailing practice of free allocations. Accordingly, the incremental costs for investing and operating these plants must be borne by other policy instruments. Since our focus here is on the compensation of incremental operational costs via carbon contracts, these[10] would have to offer a contract price of around € 72/t CO_2 to support the operation of a natural gas-based DRI-EAF-plant (see Figure 15). As explained in chapter 6, it makes sense to dynamically adjust the contract price by indexing the incremental costs resulting from the prices of coking coal , natural gas, and DRI pellets. The effective CO_2 price also plays a certain role, which can be taken into account when calculating the carbon contract premium.

Based on historical fluctuations in the costs of operating resources analysed in chapter 6.3, the

10 As we have shown, the economic effects of the incremental costs for low-carbon plants have to be assessed differently based on whether the costs are for investment or operation. We thus recommend promoting more investment via direct support and focusing carbon contracts on compensating incremental operating costs.

Carbon contract to hedge incremental operating costs (OPEX) of a natural gas-based DRI plant independent of the CO_2 price

Figure 15



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operational CO_2 reduction costs of natural gas-based DRI production can fluctuate within the parameters of 13 to 108 euros per tonne of CO_2. Depending on future prices and/or the possible correlation between prices for operating resources, this fluctuation range can even be exceeded under particular circumstances.

Despite these fluctuations, the operational CO_2 reduction costs are in a range that can be influenced by the EU ETS. The CO_2 market price has in some cases already exceeded 90 euros in 2022 and further price increases are to be expected. The incremental operational costs of natural gas-based DRI-EAF-plants could therefore be fully or largely covered by the CO_2 market price. For this to happen, however, the competitive disadvantage that arises for DRI systems with the prevailing practice of free allocations would first have to be eliminated. There are two options for this:

1) Setting a common product benchmark for blast furnace and DRI-EAF steel in the EU Benchmark Regulation;

2) Abolition of the free allocations for all steel production in combination with a Carbon Border Adjustment Mechanism (CBAM).

In both cases, the CO_2 market price has an effect on the respective production costs of the reference and low-carbon technologies and thus reduces or compensates for the incremental costs of low-carbon production. In both design variants, the result is a Carbon Contract for Difference (CCfD) in which the CO_2 market price has a direct effect on the calculation of the carbon contract premium. Both the EU Parliament and the EU Commission have recognised that the current practice of free allocations represents a competitive disadvantage for climate protection investments such as DRI plants. The EU Commission as well as the EU Parliament have proposed a combination of the above options, with the EU Parliament's proposal being more up-to-date. In the following section we will analyse the options as scenarios 2 and 3, at first individually and then, as scenario 4, in the combination proposed by the EU.

7.1.2 Scenario 2: CCfD in the case of equivalent free allocation

In this scenario, primary steel from both the blast furnace and the DRI-EAF routes would be given an – ideally – equivalent volume of free allocations, leading to a surplus of allocations for the DRI-EAF plant. Their sale then generates income that partially or fully compensates for the incremental costs of low-carbon production and can accordingly be offset against the carbon contract premium. This option is shown in Figure 16. To illustrate the principle, a CO_2 market price of 70 euros per tonne of CO_2 is assumed. If the CO_2 market price exceeds the contract price, no carbon contract payment is required.

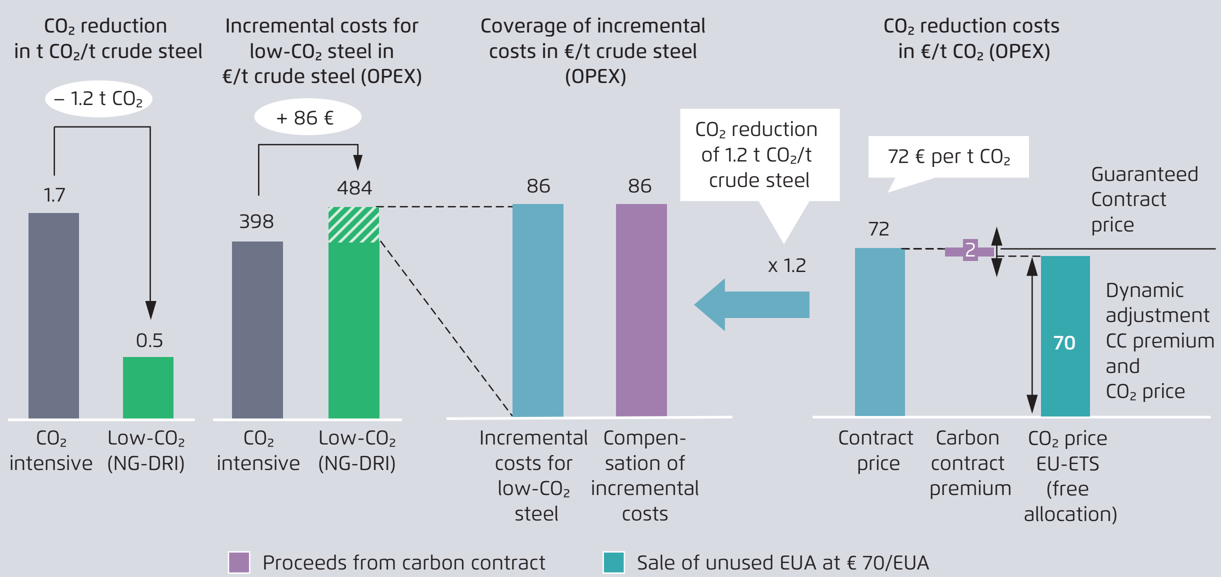
However, a specific extension of the scope of the blast furnace benchmark to DRI plants is subject to a number of factors which will be briefly outlined here for further analysis. In practice, there is no blast furnace benchmark, only a combination of the benchmarks for "hot metal," "iron ore sinter," and "coking coal".

It is unrealistic to expect that these can be applied in total to a DRI plant to establish effective equivalence of allocations. However, there is also the option of applying only the "hot metal" benchmark to the DRI plant, although this would not result in equivalence. To meet the objective of equivalent allocation, a process-independent uniform product benchmark would have to be defined. If free allocations are defined as a structural financing element for low-carbon plants, this conflicts with the objective of reducing free allocations in the EU ETS.[11]

11 In defining the *cross-sectoral correction factors,* it was stipulated that the share of free allocations for the industrial sectors may not exceed a share of around 45 percent

CCfD to support incremental operating costs (OPEX) of a natural gas-based DRI-EAF plant in case of equivalent free allocations

Figure 16



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If the DRI plants are included in the regular reviews and stricter benchmarking of a Top Runner approach, this leads to a faster reduction of allocations, including for conventional plants, which thus face a higher risk of carbon leakage.

Another problem with free allocations for both reference and low-carbon technologies is that they can result in competitive disadvantages for CO_2-efficient secondary steel production and other strategies aiming at material efficiency and substitution. To ensure that the policy instruments of free allocation and carbon contracts also support other aspects of a resource-efficient circular economy, either individually or in combination, they can be combined with a suitable climate levy on the use of CO_2-intensive raw materials in end products. In addition, suitable criteria and incentives for green marketing of products must be established.

of the EU ETS total cap. The problem must be addressed as part of the upcoming EU ETS reform.

7.1.3 Scenario 3: Introduction of a CBAM and abolition of free allocations

The introduction of a carbon border adjustment mechanism (CBAM) could create a uniform CO_2 price for all domestic production routes and imports. This would ensure efficient protection against carbon leakage for domestic production and fair competition between low-carbon primary production and resource-efficient circular economy approaches.

However, there are also a number of open questions regarding CBAM. They will be briefly outlined here and then discussed in more detail in chapter 9.

Even if a CBAM is implemented quickly and successfully, it is not expected to result in a CO_2 price at a level that can cover the full incremental costs of all low-carbon technologies. For the natural gas-based DRI route, it can be assumed that the incremental costs compared to the blast furnace route will be compensated. However, to cover the higher costs of operating with renewable hydrogen, payments via carbon contracts will remain necessary.

In addition, the risks with respect to future CO_2 prices as well as the costs of operating materials, which influence the incremental costs of climate-friendly production, are substantial, so that they can inhibit climate protection investments. These market risks can be offset by carbon contracts capable of responding dynamically to changing conditions.

The timing, design, and scope of a CBAM are uncertain. Carbon contracts must be implemented quickly and made compatible with a variety of possible circumstances in order to stimulate rapid industrial transformation.

7.1.4 Scenario 4: Gradual abolition of equivalent free allocations combined with the introduction of a border adjustment mechanism

This scenario looks at the introduction of a gradual reduction in the volume of free allocations in coordination with the introduction of a Carbon Border Adjustment Mechanism (CBAM), as proposed by the EU Commission in July 2021 as part of the Fit for 55 package (COM,2021) and presented in June 2022 in a modified proposal by the EU Parliament.

The EU Commission's proposal envisages a gradual introduction of the CBAM from January 2026. A transitional period of 3 years from 2023 should allow companies to adapt to the new requirements and implement a new regulatory system. Initially, the CBAM will be applied to a limited portfolio of products. In addition to cement clinker, fertilisers and aluminium, this also includes steel. From 2026, under this proposal, the CBAM would be introduced gradually by 10 percent per year in relation to the specific emissions of imported products, in inverse proportion to the reduction of the respective free allocations given to European production facilities. This means that the effective CO_2 price for reference plants will rise to 50 percent of the CO_2 market price in 2030 and to 100 percent in 2035. In the proposal now submitted by the EU Parliament, the free allocations for steel production are not to fall until 2027 and thus more slowly to 50 percent in 2030, and the CBAM is to be introduced in tandem. In 2031 and 2032, the transformation would then occur rapidly in two steps of 25 percent each. Under this proposal, free allocations for European production will cease from 2033. This results in full internalisation of the CO_2 price in combination with a CBAM to protect against CO_2-intensive imports from abroad.

Since, in the case of the steel sector, no equivalent free allocations are yet given for the low-carbon technology, a suitable uniform product benchmark would first have to be established, as discussed in Scenario 2. On this basis, the volume of free allocations then decreases annually with simultaneous phase-in of the CBAM. This means that the reference cost of production increases for the conventional technology. At the same time, however, the volume of free allocations – which can be sold by low-carbon plants to cover their incremental costs – also decreases. With the correct design, it can be assumed that these effects balance out overall. This again results in a CCfD where the CO_2 price directly affects the reference costs and the revenues of the low-carbon plant. Even in the context of an annual settlement, the CO_2 market price can thus in principle be added directly to the contract price to determine the carbon contract premium. At the end of the process, which is set for 2032 or 2035, depending on the proposal, Scenario 3 results, as described above.

Regardless of the year in which full internalisation is achieved, it is not expected that a CO_2 price will emerge at a level that can compensate for the full incremental costs of hydrogen-based direct reduction of iron. Therefore, carbon contracts remain an indispensable tool to spur the transformation of the steel industry, even in the context of the envisaged introduction of a CBAM. However, it remains important that carbon contracts are implemented quickly to stimulate the necessary investments independently of the complex political discussions on the details of a CBAM.

7.1.5 Overview of scenarios for implementing carbon contracts

In order to ensure the objective of a swift implementation of carbon contracts by member states, as well as their compatibility with future EU climate policy developments with regard to EU ETS reform and CBAM, these scenarios are presented together with their associated contract design options (see Figure 17).

Scenario 1 allows the short-term implementation of carbon contracts for DRI plants within existing rules for the free allocation of emissions allowances. In this case, the full incremental costs for production in low-carbon plants will be covered by the carbon contract payments.

In the case of natural gas-based DRI-EAF plant, this compensates for the misaligned incentives under the current allocation rules. In the case of the DRI-EAF plant with renewable hydrogen, significant incremental costs must also be borne. Since the CO_2 price plays a subordinate role in this arrangement, the instrument is not a CCfD, but a carbon contract. The reduced effect that the effective CO_2 price has on the incremental costs of low-carbon production can be accounted for by a dynamic contract price.

The implementation of scenario 2) requires a change in the allocation rules in order to create a level playing field between the blast furnace and DRI-EAF routes. Depending on the level of the benchmark, the cost burden for the blast furnace route and the additional income resulting from the sale of the surplus certificates for the DRI-EAF plants can be managed.

Either way, the incremental costs of low-carbon production decrease. In the case of direct reduction of iron based on natural gas, it can be assumed that the incremental operating costs will be completely compensated by the CO_2 market price.

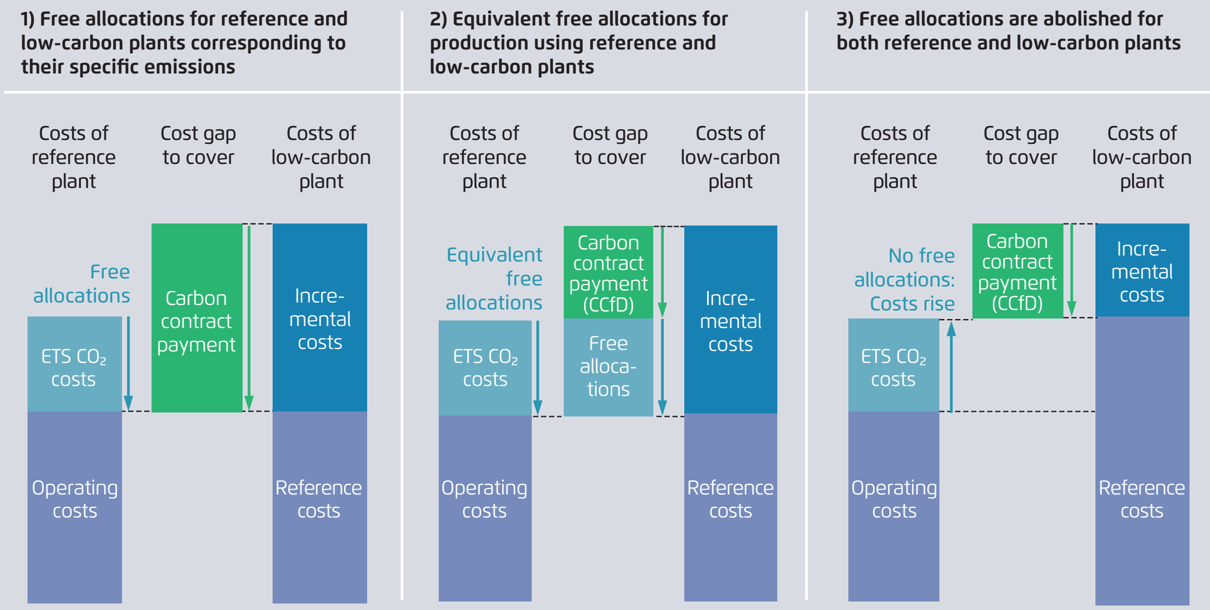
In this case, a carbon contract would only have the purpose of hedging the CO_2 market price signal. In the case of renewable hydrogen, this scenario reduces the incremental costs to be borne by the carbon contract. However, given the expected CO_2 prices, it can be assumed that substantial payments will still be necessary.

As shown in Figure 17, this scenario results in a CCfD, in which the CO_2 market price is deducted from the contract price to calculate the carbon contract premium. Thus, the payments under the CCfD vary with the EU ETS price. Alternatively, free allocations can be handed over to the state if linked to the agreement of a contract price that is independent of the CO_2 market price.

In scenario 3, the introduction of a CBAM results in the abolition of free allocations for blast furnace and DRI-EAF plants. As a result, the production costs of both routes are strongly influenced by the variations in the CO_2 market price and the incremental costs of low-carbon production fluctuate significantly. As in the second scenario, it can be assumed that the incremental costs of the natural gas-based direct reduction of iron will be compensated by the CO_2 market price. In the case of operating the DRI-EAF plant with renewable hydrogen, however, substantial payments under the carbon contract would probably still be necessary.

The fact that the CO_2 market price affects both the reference technology and low-carbon technology can be taken into account in a CCfD. Since the transformation costs are influenced by variations in the prices of other input materials (see chapter 6.3), the adjustment of the carbon contract premium with the

Scenarios for the design of carbon contracts as a function of different rules for free allocations — Figure 17



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CO_2 market price can also be seen as part of a more dynamic contract price.

Scenario 4) corresponds to the proposal from the European Commission and the European Parliament to ensure equivalent free allocations for reference and low-carbon technologies in a first step, which is equivalent to a change from scenario 1) to 2). The proposal to gradually reduce these cost-free allocations over ten or seven years and at the same time to introduce a CBAM corresponds to a gradual substitution of scenario 2) by 3). With this combination, the Commission and the Parliament have presented an interesting proposal with which the requirements identified here can be met:

1) Setting a uniform product benchmark for crude steel before 2026 would compensate for the incremental costs entailed by the natural gas operation of the DRI-EAF plants.

2) The effective CO_2 price would reduce the incremental costs for the hydrogen-based operation of DRI-EAF plants and thus the refinancing requirements of carbon contracts.

3) The gradual reduction of free allocations increases the reference price for steel products, which encourages alternative mitigation strategies such as substitution, material efficiency and steel recycling.

4) The rising reference price of steel products also reduces the incremental costs for green steel, which strengthens the demand and willingness to pay for climate-friendly steel.

Conversion of *carbon leakage* protection from free allocations to CBAM using the example of the steel sector

Figure 18

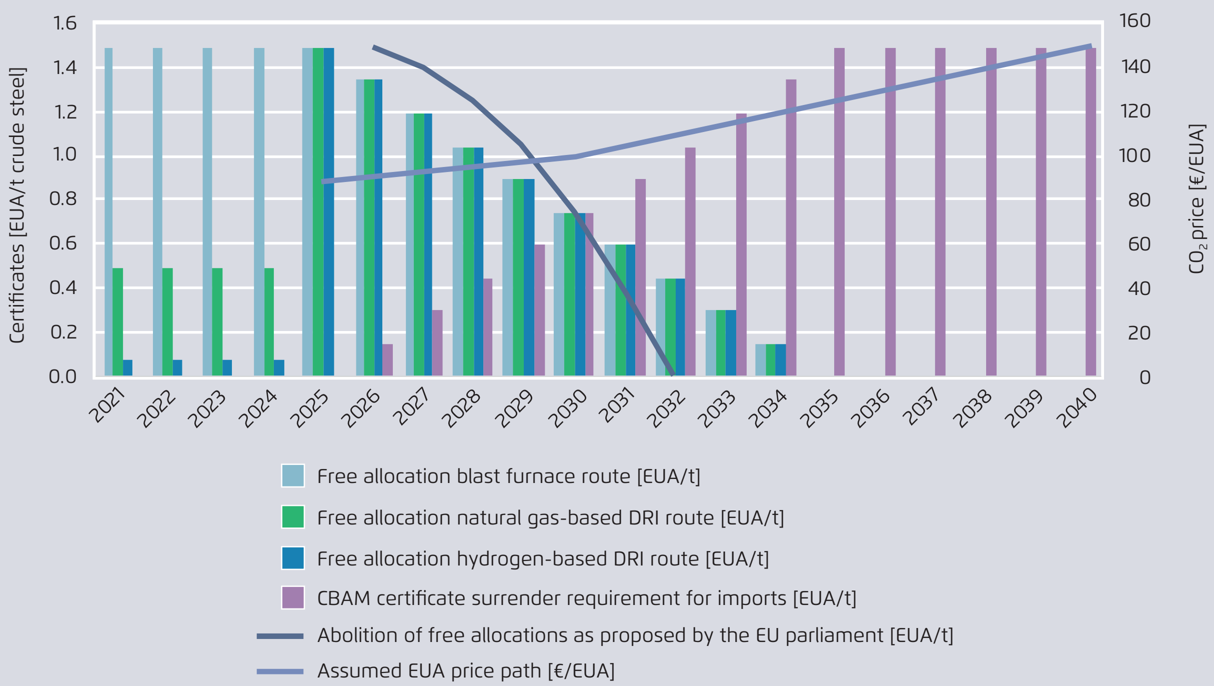

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Figure 18 illustrates both the original proposal from the EU Commission to introduce carbon leakage protection for the steel sector and the more recent proposal from the EU Parliament. Furthermore, the graph illustrates the costs of different steel production routes under the EU Parliament's proposal.

7.2 Market ramp-up of hydrogen

A key feature of DRI plants is that they can initially be operated using natural gas and subsequently use increasing proportions of hydrogen. This feature is strategically important for several reasons:

→ Natural gas-based DRI plants can already replace blast furnace plants today, thus saving significant CO_2 emissions quickly and cost-effectively. This opportunity for significant reductions in the period up to 2030, when the supply of renewable hydrogen must be developed, is essential for the implementation of the sectoral targets discussed in the amendment to the Climate Protection Act.

→ While the supply of renewable hydrogen remains insufficient and inconsistent, DRI plants can be operated with CCS-based hydrogen. CCS-based hydrogen can either be supplied from outside the system or the CO_2 can be captured directly at the plant and then transported to a geological storage site. Under both variants, DRI plants can support the establishment of the appropriate infrastructure for the transport of H_2 and CO_2. The capture of CO_2 at the DRI plants represents a first step for a possible future operation with biogenic reaction gases to provide a CO_2 sink capacity.

→ The fact that DRI-EAF plants can use both natural gas and hydrogen interchangeably makes them the ideal demand anchor for the gradual ramp-up of renewable hydrogen. It is important that the expansion of renewable energies, the development of electrolysis capacities for production, and the development of infrastructure for the storage and transport of hydrogen are all coordinated with one another. The flexibility of DRI-EAF plants makes it possible to produce hydrogen in a system-reinforcing manner to support the expansion and efficient use of renewable electricity.

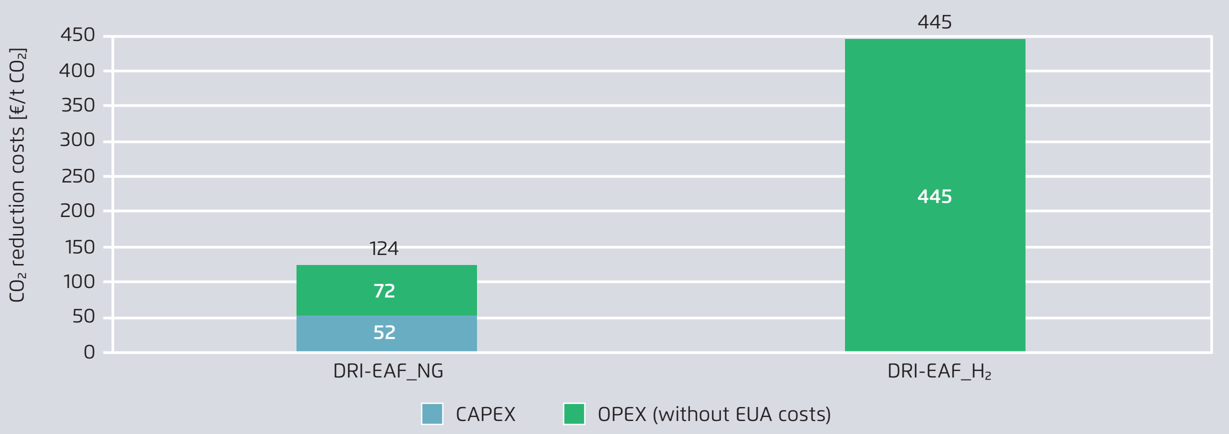
→ The system-reinforcing operation of electrolysis plants when the share of renewable energy in the power grid is high and the CO_2 intensity of the electricity is low is also mentioned by the EU Commission as a condition for the approval of state aid. As part of the approval of the Dutch SDE ++ mechanism from December 2020 (EU Commission, 2020), the full-load hours of electrolysers are initially limited to 2000 hours per year. In addition, the option of flexible renewable hydrogen use is defined as a condition for participation in the aforementioned funding regime.

For these reasons, it seems sensible to first support the development of natural gas-based direct reduction of iron and then to support the use of hydrogen in the established DRI-EAF plants with specific carbon contracts. In this case, the incremental costs of the hydrogen-based compared to the natural gas-based DRI-EAF route are decisive for the design of the carbon contract. Since the CO_2 savings when switching from natural gas to hydrogen amount only to approx. 0.4 tCO_2 per tonne of crude steel, the high initial reduction costs are particularly apparent. With a hydrogen price of 140 euros per MWh[12] and a natural gas price of 35 euros per MWh, this amounts to 445 euros per tonne of CO_2 avoidance.

On the basis of these assumptions, Figure 19 presents a comparison of the CO_2 reduction costs during the first (natural gas-based) and second (hydrogen-based) steps. This shows that the incremental operat-

12 The hydrogen costs result from an average electricity price of 62 euros per kWh, specific investment costs of 500 euros per kW for electrolyser capacity, 3 500 full-load operation hours with an efficiency of 72 percent and an interest rate of 6 percent.

Comparison of CO_2 reduction costs when switching from the blast furnace to the natural gas-based DRI-EAF plant in the first step and switching to hydrogen-based production in the second step — Figure 19



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ing costs in the first step are dominant, but that the investment costs for setting up the DRI-EAF plant are also significant. In the second step, the investment costs of the DRI-EAF plants no longer play a role and only the higher costs of hydrogen compared to natural gas are responsible for the incremental costs.

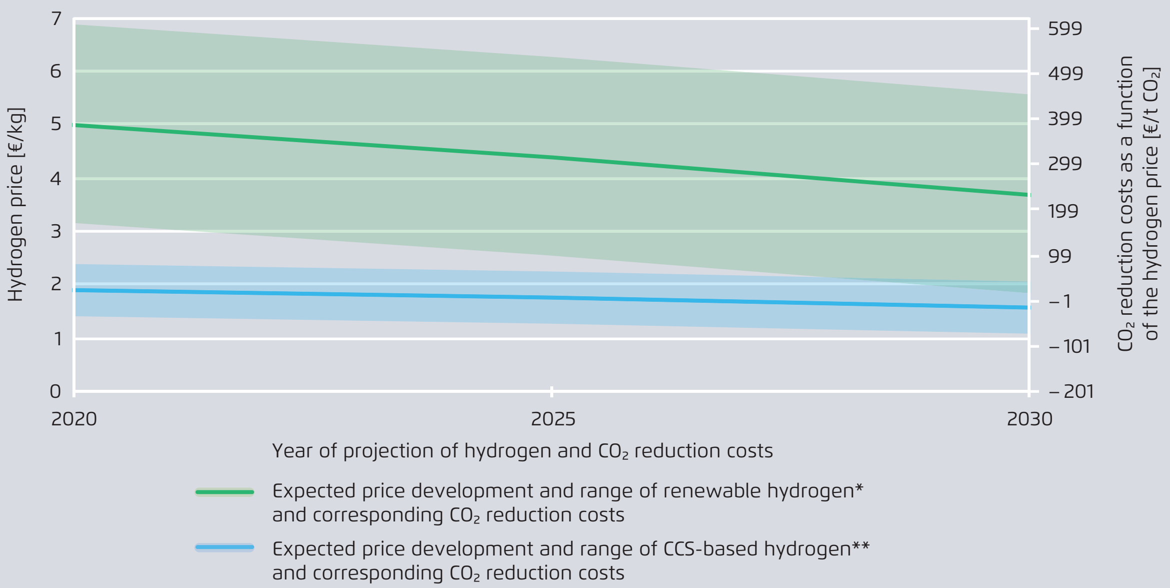
As already discussed, the CO_2 price hardly plays a role under the existing allocation rules, since the free allocations are lost when switching from natural gas to hydrogen-based direct reduction of iron. But even if the allocation rules were changed, the CO_2 market price would probably not cover the very high CO_2 reduction costs. To lower the costs of hydrogen-based direct reduction of iron, the focus must be on an efficient market ramp-up.

Figure 20 illustrates the CO_2 reduction costs when switching from natural gas to hydrogen-based steel production as a function of the hydrogen price. It also presents forecasts for minimum, medium, and maximum costs for renewable and CCS-based hydrogen for the years 2020, 2025, and 2030. The comparison shows both the potential and the uncertainty of the expected cost reduction. The uncertainty of the projections is not surprising given the very early stage of the market ramp-up for the production of renewable hydrogen. Ultimately, the path for the development and expansion of renewable energies, hydrogen production, infrastructure and technology development, and thus for the cost reduction, will depend on the success of the policy measures under discussion today. With this in mind, we discuss how the steel industry can stimulate the development of an efficient hydrogen economy through the design of appropriate carbon contracts.

There are a number of strategies and policy instruments for promoting hydrogen-based technologies

CO_2 reduction costs of hydrogen-based iron ore reduction depending on the hydrogen price and relevant forecasts for the years 2025 and 2030

Figure 20



* Guidehouse on the basis of BNEF (2021), Prognos/Öko-Institut/WI (2020), Hydrogen Europe (2020), Gas for Climate (2020); 2030 range is based on Prognos/Öko-Institut/WI (2020) and Agora/AFRY (2021)
** Based on ETC (2021)

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that can be combined in a suitable way. The wider question here is whether the use of renewable hydrogen in production should be subsidised to make it available to industry at a reasonable price, or whether the incremental costs for industrial production using renewable hydrogen along the entire value chain should be covered through carbon contracts. A key aspect of this is ensuring that hydrogen is used primarily to decarbonise industrial processes for which there are no other renewable alternatives. It is also important to ensure that electrolysis sites are strategically located to minimise grid bottlenecks.

Another issue is the requirement that electrolysis should only take place at times when there is enough renewable electricity in the system. Various applicable criteria are under discussion, but all aim to limit the full-load hours for carrying out hydrogen electrolysis to periods when there is a high proportion of renewables in the grid.

In view of these system-relevant goals, targeted support for the use of hydrogen in the steel industry makes sense. Carbon contracts must be coordinated and designed together with other funding instruments in such a way that an effective market ramp-up and benefits for the development of a comprehensive hydrogen economy can be achieved. With this aim in mind, some related principles are proposed here for further discussion on the design of carbon contracts.

a) **Creation of DRI capacity as a necessary first step:** In view of the strategic relevance of DRI-EAF plants, the investment in the technology should be directly supported. The necessary investment support must cover the higher capital requirement compared with the reference plant. In compensating the incremental operational costs for natural gas, the main aim is to compensate for the perverse incentives under the existing allowance rules until such time as these are abolished. An additional aim is to cover risks affecting the competitiveness of low-carbon plants – which result from the variability of operating costs and thus create incremental costs – by designing the carbon contracts in a suitably dynamic way. Even if the focus in the first step is on building DRI-EAF plants, the transformation can be designed to include an expandable proportion of renewable hydrogen from the outset.

b) **An option to use CCS-based hydrogen as an intermediary step:** This option enables a rapid short-term reduction of CO_2 emissions and the creation of central infrastructure for the transport of H_2 and CO_2, as well as the storage of CO_2 in geologically suitable locations. Moreover, CCS-based hydrogen is ideal for complementing the variable production and use of renewable hydrogen.

c) **Key elements of an efficient market ramp-up for renewable hydrogen:** To support increased hydrogen production and the resulting cost reductions, it seems sensible to gradually increase the volume of hydrogen used in DRI plants and to source it via a series of carbon contracts that are subject to increasingly competitive auctions. Such a step-by-step procedure may enable first cost reductions.

d) **Prioritising the selection of system-reinforcing sites:** The system-reinforcing nature of a site results from the interaction of production, transport and the use of renewable hydrogen. It thus makes sense for carbon contracts to support concerted value chains. The selection process should ensure that a) system-reinforcing sites for electrolysis and b) positive transfer effects for the creation of a hydrogen-based infrastructure and industrial networks are given preference.

e) **Principles for system-reinforcing electrolysis:** The flexible use of hydrogen in natural gas-based DRI plants is ideal for the use of renewable hydrogen from electrolysers that initially still operate with low full-load hours, in order to accompany the gradual expansion of renewable energies. To reach this goal efficiently, it makes sense to decouple the support for investment for electrolysers from compensation for operating costs in carbon contracts. This will minimise costs for carbon contracts and set them at a level suitable for the strategic expansion of electrolysis. This principle also satisfies the demand from the EU Commission that the operation of electrolysers should not lead to an increase in energy system emissions (EU-Commission, 2020).

f) **Coherence of and synergy between financial support instruments:** The number and variety of the instruments to subsidise the production and transport of hydrogen are certain to grow rapidly. It is therefore important that their effects are fully taken into account when defining the carbon contract.

Possible developments with regard to the regulatory framework and to factors that influence the cost of hydrogen production can be taken into account within the dynamic approach. We will discuss this in detail in chapter 7.4.

7.3 The contribution of carbon contracts to the expansion of green markets

The transformation of primary steel production is a necessary and urgent step to allow public and private consumers to make and purchase climate-friendly infrastructure investments and products. Building sustainable demand for climate-friendly steel products offers the opportunity to set international standards and to help to transform the global steel industry towards climate neutrality.

However, the transformation of the steel industry entails challenges that will not be overcome solely through an incipient and uncertain demand for low-CO_2 steel. In addition to the transformation costs already mentioned, the limited market power of the steel industry must also be considered. Steel products are a basic material that displays little differentiation and is subject to further processing by numerous manufacturers. The lack of differentiation and the complex value chains make it difficult for steel producers to justify higher prices for climate-friendly steel products across an often very diversified customer portfolio.

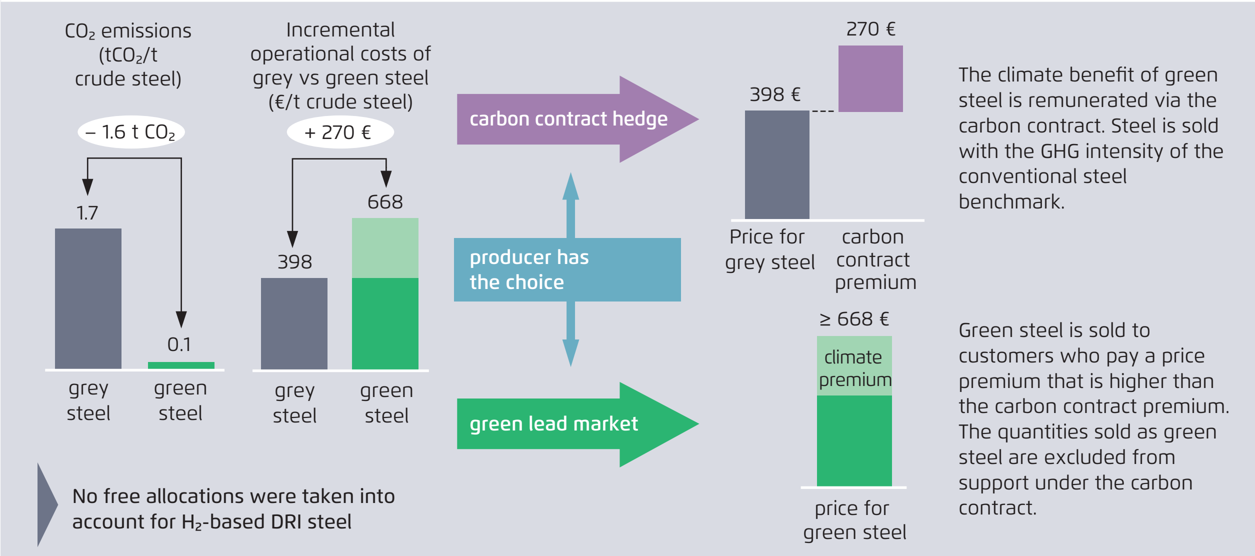
Carbon contracts, which cover the incremental costs of climate-friendly production, are an ideal instrument for creating an initial supply of low-CO_2 steel products. In cooperation with progressive companies in the manufacturing industry, steel producers can use carbon contracts to grow demand and to increase willingness to pay across the entire value chain. In addition, carbon contracts provide an initial benchmark for the definition of “green” steel products for targeted marketing.

To create the confidence needed for transformative and future-proof investments and at the same time to stimulate demand for climate-friendly steel, carbon contracts need to be designed accordingly. Steel producers need the certainty that the incremental costs of low-carbon production will be covered for as long as these are not borne by the market. At the same time, they need the freedom to market their products as “green” when there is a corresponding demand.

In order to meet both conditions and to lay the foundation for the development of sustainable green lead markets, carbon contracts can be designed as a hedging instrument, as shown in Figure 21.

In order to implement the concept visualised here, carbon contracts are designed as a put option without a fixed delivery obligation, which gives steel producers the freedom to choose the marketing method. As such, carbon contracts would ensure the competitiveness of climate investments and incentivise companies to sell their “green” steel products with a climate premium that goes beyond the payment offered by the carbon contract. This allows the incremental costs of low-carbon production to be offset or even for that production to generate higher margins.

Illustration of the interplay between carbon contracts and green lead markets — Figure 21



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The detailed design of this form of carbon contract must cover a number of aspects:

a) **A clear definition of what counts as "green":** In order to ensure that the "green steel" label is credible, its climate benefits must be clearly defined and marketed. The quality of steel in relation to the climate can be quantified by comparing its production-specific emissions with the benchmark provided by the reference technology. From this definition it follows that there must be different categories. These range from the CO_2 intensity of the blast furnace as the reference technology to natural gas-based DRI-EAF production to almost climate-neutral steel based on DRI-EAF production using hydrogen as well as scrap-based steel recycling. There are currently various initiatives to define what counts as "green". In addition, the definition of "green steel" in carbon contracts would represent an important reference point for the development of these concepts.

b) **A clear accounting and ownership of CO_2 reduction:** For a sustainable growth in demand for green steel, its green attribute must be demonstrated and transferred to the customer with specific and verifiable emissions data. With this information, manufacturing industry can manage its supply chain and verify and declare the CO_2 emissions of their value chain and products.

Steel supported by carbon contracts should not, therefore, simply be marketed as a "green" product. As long as the incremental costs of climate-neutral production compared with the reference technology are compensated by the carbon contract, its products must indicate the CO_2 intensity of the reference technology. The arguments around this concept were discussed in detail during the project workshops and are briefly summarised here:

1) The sale of green steel supported by a carbon contract would lead to an oversupply in the absence of higher costs. This undermines the willingness of customers to pay for more expensive climate-friendly production. In addition, such a subsidy for green primary products has a market-distorting effect, because it discriminates against alternative GHG abatement strategies such as steel recycling.

2) Double crediting and the possible remuneration of the "green attribute" is also problematic from the perspective of EU state aid law. Applicable law prohibits the marketing of the green attribute and the implicit CO_2 reduction if it has already been financed by the state or another social group.

3) By clearly pricing the green attribute through the carbon contract, primary steel producers gain the market power to enforce appropriate price premia. It also provides certainty to manufacturers that their efforts to market the green attribute as a differential will not be undercut by subsidised and less differentiated alternatives.

c) **Verification and adjustment of carbon contract payments:** The carbon contract must define clear criteria based on the principles of accreditation and marketing of the green attribute. How the steel supported by the carbon contract was sold must be verifiable. Batches that were explicitly marketed as green steel must be deducted from the volume supported by the carbon contracts as part of the periodic settlement. The latter reduces the carbon contract payment, while the green attribute is passed on to customers.

   Steel products that cannot achieve a climate premium must demonstrate that they are sold as conventional steel. The benchmark used for calculating the contract price in the carbon contract also defines a steel product's specific CO_2 emissions for this purpose.

d) **Encouraging demand for green steel:** A complementary measure to the hedging through carbon contracts and the support of climate-friendly steel production is the encouragement of demand for green steel products. Adjusting the regulations governing public procurement is one key lever. It is important that the criteria and definitions for green steel in public procurement are consistent with those of the carbon contract.

Moreover, private demand can be encouraged by establishing instruments for monitoring and reporting CO_2 emissions along the entire value chain. These guarantee transparency and decision-making power for consumers. In this context, it is important to develop clear and convincing product labels that communicate the complex aspects of the climate footprint of products in a scientifically consistent, but simple and convincing manner.

Finally, the discussion of criteria and standards for green steel products must also take place at the international level to promote a transparent and level global playing field for competition for the production and sale of climate-friendly products and strategies.

The various aspects of the development of green lead markets were analysed in the study "Tomorrow's Markets Today" (CISL and Agora Energiewende, 2021).

In summary, carbon contracts are an ideal instrument to hedge the incremental costs for the construction and operation of low-carbon plants in the industrial sector. In the case of steel it gives producers and their clients the opportunity to market green steel as a differentiated material and to produce and advertise accordingly a wide range of climate-friendly products, from small appliances, machines, and vehicles to real estate and infrastructure. It is important to emphasise that these markets are not limited to Europe, but that the opportunity arises to finance the transformation of industry through the sale of climate-friendly products on the world market and at the same time to create global standards and markets for climate-neutral products as well as the facilities for their production.

7.4 Summary of dynamic carbon contracts

As shown in the previous sections, it is difficult to determine the effective incremental costs of low-carbon production over multiple years. This is primarily due to unpredictable fluctuations in operating costs.

In addition, not only the CO_2 market price, but also regulatory developments with regard to free allocation play a role. Although the definition of a suitable contract price is essential for the selection and the contractual definition of project support, the effective funding must be settled dynamically on the basis of suitable formulas and price indices.

This goal can be achieved by defining appropriate advance payments, settlement periods, and processes. Over the course of the settlement period, regular advance payments can be set on the basis of the contract price. At the end of the settlement period, the CO_2 reductions achieved in practice are verified and the actual CO_2 reduction costs are determined using a dynamic carbon contract premium. A suitable adjustment of the effective payments of the carbon contract can thus avoid risks for companies and the possibility of over-compensation.

In addition, the requirement that steel products marketed as "green" should be excluded from receiving financial support through the carbon contract means that the volume of these products sold along with the associated CO_2 reduction is deducted accordingly.

A proper design of carbon contracts must thus take into account dynamic incremental operating costs, regulations on free allocation, and the free marketing of green steel. Concepts that meet these requirements are now presented here.

7.4.1 Definitions of terms required for a dynamic design and the settlement of incremental operating costs:

As the fundamental variable of the carbon contract, the contract price must be set on the basis of a transparent calculation of the average CO_2 reduction costs. It must be paid to compensate for the incremental costs of low-carbon production through a payment for the CO_2 reductions. Since these incremental costs fluctuate, the contract price must be converted into an effective carbon contract premium using suitable and contractually defined formulas and price indices. In the case of direct reduction of iron, the focus is on the variable surcharge for DRI pellets and the incremental costs resulting from the replacement of coal with natural gas or hydrogen. To adjust these costs dynamically, either public price indices or project-specific contractual agreements can be used.

Contractual agreements are important if the construction and long-term operation of a DRI-EAF plant also require corresponding hedging for the purchase of operating materials. A long-term contractual agreement is especially important for hydrogen in order to secure the investment in and operation of the electrolysers.

7.4.2 Definitions of terms required for a dynamic design and the accounting of the effective CO_2 price:

As shown in Figure 17, the influence of the CO_2 price on the incremental operating costs depends largely on the regulations for free allocation. There are specific requirements for each of the four scenarios.

Scenario 1: Technology-specific free allocations for reference and low-carbon plants: This scenario represents the status quo. Under existing rules, both the blast furnace and the natural gas or hydrogen-based DRI-EAF routes receive roughly the allowances required for their operation. If the best available technology is used for the relining of the blast furnaces and for the new construction of DRI-EAF plants, the volume of free allocations obtained should generally be close to covering real expected emissions. In this case, the effective CO_2 price would then be close to zero and the incremental costs of low-carbon production are not significantly influenced by fluctuations in the CO_2 market price.

However, if there is a shortfall in free allocations for the reference or climate protection technology, possibly due to a lowering of the applicable benchmarks over time, there will be an increasingly effective CO_2 price that is influenced by the CO_2 market price and the development of the respective free allocations. As a rule, this effect is small and can be mapped within the scope of the dynamic approach defined in 7.4.1.

In addition, it is important that a carbon contract is geared towards a more fundamental reform of the regulations for free allocations, as described in the following scenarios.

Scenario 2: Equivalent free allocations based on a uniform product benchmark: In this case, the CO_2 price does not have a direct impact on the operating costs of the reference or low-carbon plants. However, there is a surplus of free allocations for low-carbon production, which can be sold to cover part of the incremental costs. The resulting contribution must be set in such a way so that it can be directly deducted in the context of a dynamic approach to determine the climate protection premium. This results in a Carbon Contract for Difference (CCfD), in which the CO_2 market price can be subtracted directly from the contract price to calculate the carbon contract premium in combination with the dynamic adjustment defined in 7.4.1.

Scenario 3: Abolition of free allocations: Here, the production costs for the reference system increase and the incremental costs of low-carbon production decrease to the same extent. Consequently, the CO_2 reduction costs decrease as the CO_2 market price rises. As part of the dynamic approach, the CO_2 price can thus be deducted directly to determine the carbon contract premium. This, in turn, results in a CCfD in which the CO_2 market price can be subtracted directly from the contract price in order to calculate the carbon contract premium in combination with the dynamic approach defined in 7.4.1.

Scenario 4: Abolition of equivalent free allocations and introduction of a CBAM: This scenario corresponds to the proposals from the EU Commission and the EU Parliament to ensure equivalent free allocations for reference and low-carbon technologies in a first step, which corresponds to scenario 2. In a second step, the free allocations are gradually reduced over ten and seven years, respectively, and at the same time a CBAM is introduced until scenario 3 is realised. The carbon contract must be designed in such a way that it can deal with the annual evolution of these parameters in the context of a dynamic approach.

7.4.3 Accreditation of green steel sold on the free market

In order to clearly distinguish low-carbon steel products that were supported by carbon contracts from green steel for sale on the free market, it is necessary to quantify the volume marketed as "green steel" and exclude it from the supported volume. This requires defining a number of criteria for marketing and accounting of grey and green steel in the carbon contract.

In principle, a company can market all or part of the product volume produced in a low-carbon plant as grey or green. If the steel is marketed as a conventional, grey product, it must be sold with a reference to the specific emissions benchmark of the reference system defined in the carbon contract. This means that this steel and the CO_2 reduction achieved as a result may not be taken into account in the context of voluntary or regulatory targets for CO_2 management in the supply chain. When marketing green steel, this can be done on the basis of the specific CO_2 emissions from low-carbon production. The total volume of steel products sold as grey and green in each settlement period must be documented accordingly. To determine the settlement volume, the volume sold as green steel must be deducted from the production volume. The total verified CO_2 reduction to be supported is obtained by multiplying the verified specific CO_2 reduction by the settlement volume. Multiplying the verified CO_2 reduction to be funded over a settlement period by the dynamic carbon contract premium results in the compensation to be paid out for the settlement period, i.e. the carbon contract payment.

In summary, pragmatic dynamic carbon contracts are an important instrument to account for fluctuations in the CO_2 market price and in operating costs, and developments in ETS regulations and green lead markets.

8 Scenarios for calculating the transformation costs of the German steel sector

As demonstrated above, carbon contracts are a suitable instrument to secure the investments and incremental operating costs for low-CO_2 steel production. In addition, they can be implemented quickly, which is also facilitated by the fact that the concept was established by the new federal government within the framework of the Immediate Climate Protection Programme 2022. This programme sets out how carbon contracts to cover the incremental costs of climate-friendly production are to be implemented and financed. Complementary to this support for operating costs, an investment programme was set out for the steel industry for the construction of DRI-EAF plants to supplement the IPCEI hydrogen funds.

Furthermore, a programme for the definition of green lead markets was set out in order to promote the demand for climate-friendly steel products via demand-side instruments (BMF, 2022).

Responsibility for the elaboration and implementation of these funding programmes is located in the BMWK. As a first step, the BMWK has initiated an expression of interest procedure with industry in order to develop a funding guideline for carbon contracts (BMWK, 2022). After the submission of a corresponding notification at the EU level, the first tenders for the funding of projects in the primary industry are to take place before the end of 2022.

Furthermore, carbon contracts can be designed in such a way that they remain compatible with future changes in free allocation, in the CO_2 market price and in the demand for green steel products.

With the aim of shedding light on these aspects for the transformation path described in Chapter 5, assumptions for various scenarios are defined and modelled below and the results are presented and discussed.

8.1 General assumptions for projecting transformation costs

In order to make a meaningful estimate of the transformation costs, the general assumptions for the development of DRI-EAF capacities must be defined. In addition, variable assumptions must be made for the future development of the rules for free allocations, the costs of climate-friendly hydrogen and the role of green lead markets.

The general assumptions include a linear build-up of DRI-EAF capacities of 2 Mt p.a. over 6 years from 2025 (see Table 4). This means that a total of 12 Mt of DRI-EAF capacities can be put into operation by 2030. The incremental investment costs for this amount to around 1.2 billion euros per year. This amount must be mobilised in combination with the conclusion of a suitable carbon contract approximately three years before commissioning, so that the companies can make an investment decision with regard to the plant construction. Furthermore, we assume that the plants will initially be operated largely with natural gas, with the share of hydrogen rapidly increasing from 13 percent in 2025 to almost 80 percent in 2030.

The incremental costs for the additional annual volumes of hydrogen are covered by carbon contracts with a duration of 10 years each. Furthermore, we assume that the CO_2 market price will develop linearly from today's level to 88 euros per EUA in 2025, to over 100 euros per EUA in 2030 and to 150 euros per EUA in 2040, whereby its impact on the incremental costs

General assumptions for the projection of transformation costs — Table 4

General assumptions	Assumptions for the market ramp-up
Build-up of DRI-EAF capacity of 12 Mt by 2030. Operate plants at 90 percent capacity utilisation rate	Linear ramp-up through commissioning of 2 Mt p.a. of DRI-EAF capacity over six years from 2025 to 2030
Incremental investment for DRI-EAF plants compared to relining blast furnaces totalling € 7 billion (580 €/t DRI annual capacity)	Incremental investment of € 1.2 billion p.a. for DRI plants compared to blast furnace relining over six years from 2025 to 2030. Capex must be funded and available 3 years before commissioning
Linear increase in the energy share of hydrogen for the operation of the DRI-EAF plants to 77 percent in 2030	Increase in the energy share of hydrogen in the operation of the DRI-EAF plants from 13 percent in 2025 to 77 percent in 2030
Issue of carbon contracts with a term of 10 years to cover the incremental operational costs	Carbon contracts compensate the incremental costs of producing with natural gas and an increasing proportion of climate-friendly hydrogen. The hydrogen proportion increases over 6 years to 77 percent. Each batch is hedged for ten years
Increase in the CO_2 market price from € 88/EUA in 2025 to € 150/EUA in 2040	The effective CO_2 price depends on the assumption regarding free allocations (see Table 5)

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of low-carbon production depends on the development of the regulations for free allocations.

8.2 Scenarios and results for projecting transformation costs

Based on the general assumptions regarding the market ramp-up of hydrogen-based direct reduction of iron discussed above, we have defined both a reference scenario for the projection of transformation costs and analysed four different scenarios for the development of hydrogen costs, of market-driven demand for green steel and the rules for free allocation (see Table 5). The four scenarios analysed are: 1) low hydrogen costs; 2) development of green lead markets; 3) equivalence of free allocations; 4) and a combined scenario. These four scenarios are discussed in this chapter along with the reference scenario.

8.2.1 Reference scenario

We have used the reference scenario to define the maximum applicable transformation costs. In this scenario, we assume that the transformation of the steel industry will be supported with carbon contracts while the rules for free allocations will stay the same. Furthermore, we assume hydrogen prices of 6 euros per kg in 2025 with a linear decrease to 3.7 euros per kg in 2040 (see Table 5 and Figure 19). In addition, no steel is labelled as green in this scenario and the entire transformation costs must therefore be borne through a sequence of carbon contracts.

The results of this scenario are summarised in Figure 22. When analysing the data, the cost of building the DRI plants in the years 2023 to 2028 stands out. These are investments that go beyond the usual relining of blast furnaces and that aim to transform the steel industry with DRI-EAF plants as

Scenarios for projecting the transformation costs in the steel industry			Table 5
Variable for the definition of scenarios	**Assumptions for the reference scenario**	**Assumptions for scenarios 1 – 3**	**Assumptions for the combined scenario**
1) Development of hydrogen costs	High hydrogen costs of € 6/kg in 2025 with linear decrease to € 3.7/kg in 2040	Low hydrogen costs of € 2.8/kg in 2025 with linear decrease to € 1.5/kg in 2040	Average hydrogen cost of € 4/kg in 2025 with linear decrease to € 2/kg in 2040
2) Development of green lead markets	No sale of green steel	Sales of green steel for 30 percent of production in 2030 and 60 percent in 2040	Sales of green steel for 50 percent of production in 2030 and 100 percent in 2036
3) Regime for granting free allocations	Status quo: Free allocations for reference and low-carbon plants corresponding to their actual emissions	Equivalent allocations or abolition of free allocations for reference and low-carbon plants	

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low-carbon technologies. Since these investments play an important strategic role for the market ramp-up of hydrogen, we assume that they will receive separate support. Because the capital for this has to be made available around 3 years prior to commissioning, around 3.5 billion euros in funding will be required for the 2022–2025 legislative period. A similar amount will be required for the following legislative period.

The amount of these investments and thus the incremental expenditure that is eligible for funding are independent of the general conditions discussed above. Therefore, in the following section, we focus on discussions around the compensation of incremental operating costs.

In order to cover the incremental operating costs, our model calculation assumes a gradual ramp-up of hydrogen use in combination with natural gas. In 2025, when the first 2 Mt of DRI-EAF capacity go online, the share of hydrogen in the total energy requirement of the plant will be 13 percent. In combination with the linear ramp-up of the DRI capacities by 2 million tonnes per year, the hydrogen share also increases by 13 percent per year.

In 2030, the total capacity of the DRI plants will thus reach 12 million tonnes operating with an average utilisation rate of 90 percent. The share of hydrogen in the total energy requirement of these systems is then 77 percent. In order to safeguard our assumption regarding a gradual ramp-up of hydrogen through carbon contracts, we assume that each additional tranche receives a contract with a term of 10 years each. This assumption results in the run-up of incremental costs to be covered annually as depicted.

For the entire period up to 2039, the operational transformation costs total almost 28 billion euros. Around half of the necessary funding commitments would have to be made during the ongoing legislative period (LP 20). Most of the actual expenditures however would not be due until the next legislative period and beyond.

8.2.2 Alternative scenarios

In order to put the costs presented in Figure 22 into perspective, we can model their effects on the transformation costs and their financing in the analysis of the four remaining scenarios. The results are presented in Figure 23.

Scenario 1) Low hydrogen costs:
The first scenario presents a situation where the costs for climate-friendly hydrogen are lower than assumed in the reference scenario. This situation can be caused by a faster cost regression for the production of renewable hydrogen or by the use of CCS-based hydrogen.

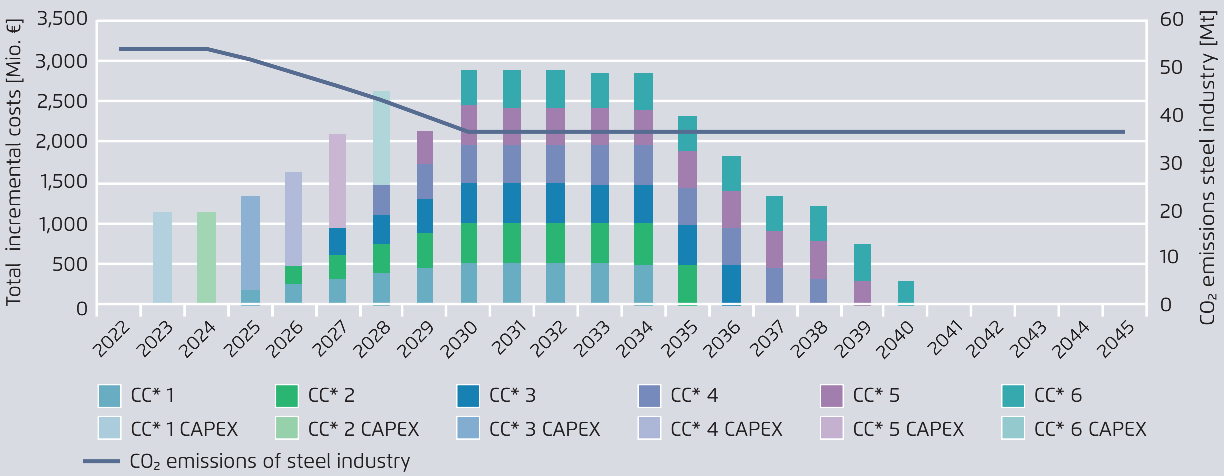
The combination of the use of system-reinforcing renewable hydrogen alternating with CCS-based hydrogen can lead to significantly lower hydrogen costs. In the scenario presented here, the effective financing costs for carbon contracts are reduced to 11.1 billion euros.

Scenario 2) Development of green lead markets:
The second scenario assumes that a growing share of low-carbon steel production can be sold on the market as green steel with a corresponding climate premium. A share of 30 percent was set for 2030, which corresponds to sales of around 3.3 Mt of green steel. For the year 2040 we assume that this volume will double. Under this assumption, the effective financing costs for the carbon contracts will drop to 17 billion euros compared with the reference scenario.

Scenario 3) Equivalence in free allocations:
The third scenario assumes that there will be a reform of the rules on free allocations, which establishes an equivalence between reference and low-carbon technology. In this case, part of the transformation

Projection of transformation costs for the reference scenario

Figure 22



Total costs in billions of euros	LP 20	LP 21	Total
Incremental investment costs (DRI plants)	3.5	3.5	7.0
Carbon contract financing commitments to cover the incremental operational costs as the total of carbon contract 1–6	13.0	14.5	27.5

* CC = Carbon contract

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Projection of transformation costs for the alternative scenarios

Figure 23

* CC = Carbon Contract

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costs is borne by the CO_2 market price. Given the assumptions of a CO_2 price of 88 euros in 2025 with a linear increase to 100 euros in 2030 and 150 euros in 2040, the effective financing costs for carbon contracts fall to just under 10 billion euros.

Scenario 4) Combined scenario: Finally, the fourth scenario combines the other assumptions in a realistic way. It assumes an equivalence between the free allocations and the development of a market- or policy-driven demand for green steel. However, it assumes only a moderate price reduction of 4 euros per kg in 2025 to 2 euros per kg in 2040 for hydrogen.

Based on this combination of assumptions, the effective financing costs for carbon contracts fall to a total of 1.3 billion euros relative to the reference scenario. The transformation costs for operation and thus the necessary funding commitments for the reference scenario and the four alternative scenarios are shown in Table 6.

8.3 Analysis of the results of the projected transformation costs

In summary, the transformation of primary steel production proposed by the study "Climate-Neutral Germany 2045" can be implemented with suitable carbon contracts. With a CO_2 reduction of almost 18 million tonnes in 2030, this measure is also key for achieving the envisaged sectoral target for the industry. The transformation costs for this are potentially significant, at a total of up to 35 billion euros, but can

Refinancing requirements for carbon contracts to fund incremental operational costs in different scenarios

Table 6

Scenario	Description of assumptions	Need for financing commitments in € billion		
		LP 20	LP 21	Total
Reference scenario	1a) high hydrogen costs (€ 6/kg_{2025} falling to € 3.7/kg_{2040}) 2a) no sale of green steel 3a) maintenance of the current rules on free allocations	13.0	14.5	27.5
1) Low hydrogen costs	1b) low H_2 costs (€ 2.9/kg_{2025} falling to € 1.5/kg_{2040}) 2a) same as reference scenario 3a) same as reference scenario	5.9	5.2	11.1
2) Development of green lead markets	1a) same as reference scenario 2b) sale of green steel (from 30 % in 2030 to 60 % in 2040) 3a) same as reference scenario	8.6	8.4	17.0
3) Equivalence of free allocations	1a) same as reference scenario 2a) same as reference scenario 3b) introduction of equivalent free allocations as of 2026	5.5	4.3	9.8
4) Combined scenario	1c) average H_2 costs of € 4.5/kg_{2025} and € 2/kg_{2040} 2c) sale of green steel: 50 % of production in 2030 and 100 % in 2036 3b) introduction of equivalent free allocations as of 2026	1.0	0.3	1.3

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be broken down and reduced through appropriate measures. In the following section we will briefly address the central aspects of the analysis.

a) **Investment for the construction of DRI plants:** The construction of DRI plants with an annual capacity of 12 million tonnes by 2030 requires investments of approx. 9 billion euros and represents a fundamental measure for the future viability of the German steel industry. The investment in DRI is around 7 billion euros greater than the costs of relining existing blast furnaces. Half of that investment must be mobilised over the next legislative period.

   To enable companies to make these investment decisions, the incremental investment costs as well as the incremental operating costs must be funded and hedged. The investment costs can be covered by a suitable combination of capital funding instruments. Possible components for this funding are the EU Innovation Fund and funding from the IPCEI (Important Project of Common European Interest). Ideally, these European mechanisms will be combined with funding from the German federal government and, if necessary, the federal states, in order to achieve the funding quota required for effective implementation.

   In addition, the detailed design of the investment funding plan and the carbon contracts should reduce the investment risks in order to lower the capital costs of the necessary equity. To this end, the development and use of green or transition bonds can be helpful.

b) **Hydrogen cost reduction:** As outlined in this study, DRI systems are an ideal anchor for building a hydrogen economy. The aim is to reduce the costs for the provision of hydrogen through expansion and technological development in the production of renewable energies, electrolysis, and in the transport and storage of hydrogen. This goal must be achieved through an optimised market ramp-up that focuses on the climate impact and economic efficiency of the energy system as a whole. The results of the ongoing discussion on the development and promotion of system-reinforcing electrolysis, as well as on the role of CCS-based hydrogen in order to cover a fluctuating and limited supply of renewable hydrogen, are pivotal for that purpose. In the event of an optimal market ramp-up, it can be assumed that the costs for renewable hydrogen will decrease significantly relative to the reference scenario, which would lead to a reduction of the transformation costs.

c) **Development of green lead markets:** The development of a market-driven demand for green steel products is a strategic measure to establish the low-carbon production of raw materials and the resulting products, first as a differential for higher value creation and ultimately as a general standard. With this goal in mind, carbon contracts must be designed accordingly and combined with policy instruments to promote green lead markets from the outset.

d) **Adjusting the rules for free allocation:** Through an adjustment of the rules for free allocation, as discussed in chapter 7.3, part of the transformation costs can be covered by emissions trading. In the event that free allocations are abolished altogether, rising reference costs would be passed on to all consumers. This scenario is best realised within the framework of the CBAM proposed by the EU Parliament to ensure appropriate protection against carbon leakage for conventional plants. This scenario results not only in a reduction in the costs of the carbon contracts, but also in a spur to market-driven demand, since the necessary climate premium decreases due to rising reference costs.

   An alternative is the equivalent allocation to both the reference and the low-carbon technologies. In this case, the reference costs remain unchanged, but part of the incremental costs can be covered through the sale of the free allocations. The question of how to deal with free allocations in the case of selling the product as green steel would need to be addressed, as this also influences the level of the necessary climate premium. Another element that can be combined with this design is the setting of a climate levy for refinancing the costs of the carbon contracts and shifting the relative prices of the end products.

In conclusion, however, a detailed discussion of the advantages and disadvantages of the options goes beyond the aim of this background study. In any case, carbon contracts must be designed in such a way that they remain compatible with both scenarios, as well as with the combination scenario proposed by the EU Parliament.

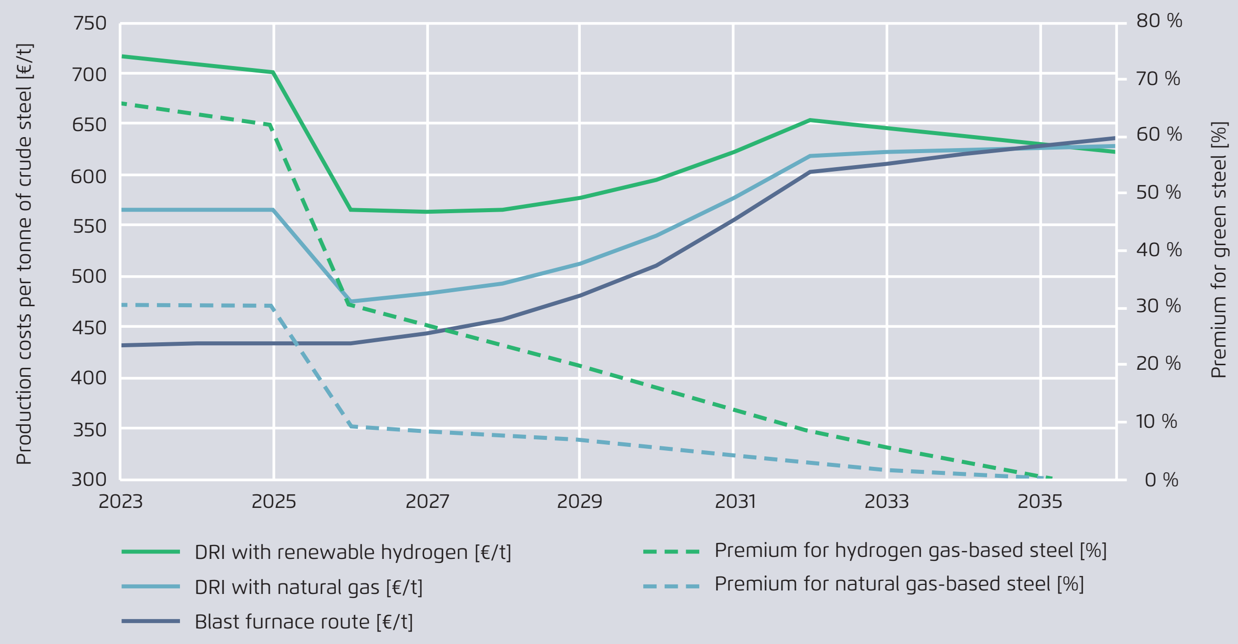
e) **The combination and evolution of the scenarios:** The scenarios analysed show that the theoretical transformation costs are relatively high, but that there is also a large number of concrete policy instruments and options to reduce these costs. A rapid implementation of carbon contracts is the necessary first step. At the same time, the market ramp-up and the resulting cost reduction for hydrogen must be constantly optimised, green lead markets must be supported and the concept of carbon contracts must be addressed as part of EU ETS reform.

Under optimal conditions, the costs of carbon contracts can be significantly reduced through a coordinated development of policy instruments.

8.4 The path to green steel as a reference product

A comparison of the results presented here shows how important the interaction of policy instruments is for an efficient transformation of the steel sector.

Projection of the costs of different steel production routes in the case of a combined scenario — Figure 24



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As illustrated in Figure 24, the incremental costs of natural gas- and hydrogen-based primary steel production are initially still high compared to the blast furnace route but can be quickly and significantly reduced by a reform of EU emissions trading. An equivalent allocation of free allocations for all primary production routes initially lowers the incremental costs of the climate-friendly alternatives and thus makes green steel affordable for the market.

As part of the gradual introduction of a border adjustment mechanism from 2027, the allocation of free allocations for all production routes can be reduced in return. As a result, reference costs will rise, and the market will have to pay increasing prices for both CO_2-intensive and climate-friendly steel products through the internalisation of the CO_2 price.

In the context of this price adjustment, however, indirect economic effects and impacts on consumers must also be considered. For socially disadvantaged groups, the resulting price increases can add to the already rising cost of living. Since the reduction of free allocations will lead to increased revenues from the auctioning of emission rights, these social distortions can be compensated for if necessary.

An economic advantage from the adjustment of market prices results from the upgrading of the secondary steel route. Due to the low emissions involved, steel recycling gains a growing cost advantage. The resulting additional revenues can be used to expand and optimise reverse logistics and the processing of scrap in such a way that energy and resource consumption decreases, and value creation increases through the use of high-quality scrap as a domestic raw material.

In this way, a coherent package of policy measures can promote the transformation of the steel industry towards climate neutrality as a whole. As shown in the scenario presented here, this transformation must start with the build-up of climate-friendly direct reduction of iron supported by carbon contracts. In the context of a broader reform of CO_2 pricing, the incremental costs of climate-friendly production then fall continuously. Under the assumptions made, hydrogen-based steel will then become price-setting from around 2035 and can then establish itself as the standard.

9 Summary and outlook for the implementation of carbon contracts

In summary, the transformation of primary steel production through the replacement of existing blast furnaces with DRI-EAF plants is an urgent and sensible step for the reduction of CO_2 emissions in the short term, for an efficient market ramp-up of the hydrogen economy, and for the long-term climate neutrality of Germany. In addition, it enables the steel industry, the downstream processing industry and plant manufacturers to develop climate-friendly products and establish them as standards on the international market.

Carbon contracts are a suitable instrument to hedge the risks of this transformation. They can be implemented quickly and relatively unbureaucratically and flexibly coordinated with the still uncertain development of relevant framework regulations. These include, above all, the definition and promotion of renewable hydrogen and green lead markets as well as carbon leakage protection in the EU ETS.

In the following section, we briefly summarise the central principles for a rapid implementation and selection. Moreover, we also shed light on the relevance of a strategic coordination with the relevant framework conditions described above.

9.1 Principles for a rapid implementation

As has already been outlined, the construction of DRI-EAF systems is a necessary step for the transformation to climate-neutral primary steel production. In order to minimise the costs of this transformation, framework conditions have to be created in the near term that enable the industry to forego relining blast furnaces as scheduled and instead to build plants for direct reduction of iron. Ideally, these investments will be secured by a combination of funding instruments:

a) **Supporting incremental investments:** Investments above and beyond relining existing blast furnaces are ideally financed by a combination of existing and new funding instruments. The aim is to promote more investment while keeping it as separate as possible from the incremental costs of operation. This will reduce investment risks and decrease capital costs.

b) **Hedging incremental operating costs via coordinated carbon contracts:** Depending on the operating concept, incremental costs for the operation of DRI-EAF plants must be quantified and covered by a carbon contract. The contract must be dynamically adjusted to relevant variations and developments in the incremental operational costs, the regulations on free allocation in the EU ETS and demand in the context of green lead markets. In addition, carbon contracts must be defined in such a way that they can be combined over time and, if necessary, replaced. It must be possible, for example, to first secure the operation of the DRI-EAF system using natural gas and then to replace this fuel with increasing shares of renewable hydrogen.

9.2 Principles for the selection process

Combined funding for incremental costs for the investment and operation of low-carbon plants can be awarded via a two-stage selection process organised by the state and open to all companies seeking to establish DRI-EAF systems in Germany.

In the first stage, the participating companies must define an operating concept and the incremental costs within a project outline to apply for funding. Since concepts and implementation in the context of existing systems can vary greatly, it is important to create comparability through the definition and use of uniform principles and a suitable transformation cost calculator. A clear calculation of the CO_2 reduction costs plays a central role here. They are not only the basis for the discussion and setting of a suitable contract price, but also represent a central principle for project selection.

Alongside cost efficiency, further principles should be identified for the selection of projects, for example:

a) **Setting out a path to climate neutrality:** The construction of a DRI plant is usually only a first step on the path to climate neutrality. To ensure that companies have a complete and actionable strategy for achieving climate neutrality, the entire transformation path should be coherently outlined as part of the selection process. It is important to ensure that the low-carbon plant cannot only be operated with natural gas or CCS-based hydrogen, but is also suitable for long-term operation with renewable hydrogen – possibly in combination with renewable carbon carriers.

b) **Positive transfer effects:** In order for DRI plants to be selected and funded based on their key contribution to the development of climate-neutral production networks and the strategic infrastructure for Germany's climate neutrality, it makes sense to evaluate these aspects in the selection process as well, using suitable criteria.

Based on such principles, a competitive selection can be made in the first step of the process in order to ensure that projects are funded that are compatible with the goal of climate neutrality, but also offer low reduction costs and high positive spill-over effects.

In the second step of the selection process, a project-specific carbon contract can then be negotiated to cater for particular features of the plant and the concept. The proposed operating concept should be checked and the generic transformation cost calculator transferred to a project-specific financial model. This model and the CO_2 reduction costs it identifies will then form the basis of the carbon contract. The mechanisms for dynamic adjustment, verification and settlement of all contract parameters must also be specified in a suitable way. For the first projects, a business audit should also be carried out in the course of regular settlement periods.

Based on the initial experiences, the tender model can be furthered elaborated and simplified if needed.

9.3 Relevance of framework conditions

As described in this study, market conditions and the regulatory framework play a central role in the effective development of climate-friendly production. This includes first and foremost the definition and promotion of renewable hydrogen, the demand for climate-friendly products on green lead markets and the CO_2 price in combination with the development of protection against carbon leakage in the EU ETS. It is precisely the uncertainty of these developments that is the main argument for the need to quickly hedge the upcoming reinvestments in the steel industry with suitable carbon contracts. Ideally, however, the short-term implementation of carbon contracts will be brought into line with a strategic development of the framework conditions from the outset. We briefly summarise the relevant aspects below for further analysis in subsequent studies:

a) **Criteria for the promotion and sustainable use of renewable hydrogen:** Discussions on how to define the criteria for the operation and funding of plants for hydrogen electrolysis are in full swing. The fact that economically and ecologically viable production of renewable hydrogen depends on a rapidly increasing share of renewables in our electricity system suggests that this discussion and the resulting criteria will develop accordingly. It is important, therefore, to create carbon contracts and, if necessary, to stagger them so that they can support and hedge this evolution. Due to their flexibility when operating with natural gas and climate-friendly hydrogen, DRI plants allow the system-reinforcing operation of electrolysis systems in coordination with an increasing supply of renewable energies. In the context of progress in the production, transport and, if necessary, import of hydrogen, this development can also be mapped by purchasing different batches. In this context, a staggered portfolio of carbon contracts must also be brought into line with other funding instruments. For example, it is crucial for the contract price whether the investment in an electrolysis system is funded separately, so that only the electricity for electrolysis and other operating costs are relevant for the hydrogen costs.

The role of CCS-based hydrogen also needs to be addressed. Its ability to complement the system-reinforcing operation of electrolysis plants will be of great importance for combining the rapid decarbonisation of steel production with the gradual expansion of renewables and thereby for accelerating the development of the necessary infrastructure.[13]

b) Building green lead markets and international standards for green steel products: The goal of the industrial transformation should be to build a robust international demand for climate-friendly products, which in turn will require securing the necessary investments with carbon contracts. However, to leverage demand for green steel products, the climate benefits of these products must be scientifically defined and marketed in an sensible way. The definition of climate-friendly steel as eligible for support through carbon contracts is a first step in this direction. In addition, appropriate demand instruments such as public procurement requirements or quotas must be identified. In addition, policies are needed to influence the behaviour of manufacturers and consumers. This can be done through product labelling requirements or the definition of product standards. In each case, care must be taken to avoid distortions between different steel grades that are equivalent from an environmental perspective.

c) Reform of the EU ETS and refinancing of carbon contracts: A rising CO_2 market price is a key element for achieving medium- and long-term climate goals, but it also requires a reform of the EU ETS and its mechanisms to protect against carbon leakage. The fact that the existing regime for free allocations as carbon leakage protection for conventional production processes cannot promote the switch to low-carbon technologies must be compensated for by means of an appropriate design of carbon contracts. The carbon contract model, in which the full incremental costs of climate-friendly production are borne, is particularly useful in the short term, since a reform of the current carbon leakage regime cannot be implemented quickly. However, this arrangement may also be relevant in the long term if the establishment of a CBAM regime should fail and the aim is to reduce the volume of free allocations and to remove low-carbon plants that are to be operated in a climate-neutral manner from the EU ETS as a result. However, the costs for this model are high over the long term and would have to be funded through a climate levy in the medium term. This should be designed in such a way as to offer

13 Depending on the operating concept, this could include pipelines for the import of climate-neutral hydrogen or infrastructure for transporting carbon captured at DRI plants. In both cases, the concept can be expanded to BECCS when using biogas or pyrolysis gas.

consumers an incentive to forego CO_2-intensive products or to choose climate-friendly substitutes.

An alternative is to reform the carbon leakage protection system so that low-carbon plants also receive an equivalent volume of free allocations relative to the reference system. In this case, the volume of free allocations in the EU ETS would remain constant[14] in the long run, but the costs for refinancing carbon contracts would decrease. The reference method remains exempt from CO_2 costs. In addition, part of the incremental costs of low-carbon plants is compensated through the sale of free allocations. In this model, it would also make sense to define a climate surcharge in such a way as to refinance the costs of carbon contracts while generating adequate price signals for consumers.

Another option is the complete abolition of free allocations within CBAM. In this case, the reference costs and the prices for CO_2-intensive input materials increase. This creates a corresponding price signal for the avoidance, substitution or recycling of CO_2-intensive primary production. In addition, the incremental costs for low-carbon primary production decrease, which also promotes the creation of a corresponding demand for green products. Nevertheless, costs remain for the refinancing of carbon contracts. These can now no longer be financed by a climate levy, as the CO_2 costs have already been internalised under the EU ETS and cannot legally be levied twice. However, the abolition of the free allocations would result in an increased volume of emission rights for auctioning. The resulting income could be used to refinance carbon contracts.

Last but not least, the proposal from the EU Parliament is the main focus of discussion (COM, 2021). The short-term equivalent allocation of free allocations would quickly support the impact and financing of carbon contracts. The gradual phasing out of free allocations and the introduction of a CBAM would then increasingly internalise the CO_2 market price, which would promote the market-driven demand for green steel products and for the alternative reduction strategies of a resource-efficient circular economy in equal measure.

9.4 An appeal for rapid implementation

Precisely because of the uncertainties outlined above, the rapid implementation of carbon contracts is an important and necessary step in bringing about the transformation of the steel industry. In this context, it is important to create the right conditions for suitable investment decisions as quickly as possible, since the downstream approval procedures and plant construction take around three years. This means that the relevant decisions about which investments and commitments should be used to cover the incremental costs of operating these systems must be made at the beginning of the next legislative period.

To successfully initiate and further develop this process, the focus should lie on pragmatic action, but also on strategic development of the framework conditions. Carbon contracts can quickly be introduced to hedge the necessary investments. Their strategic design and integration with the framework conditions will be pivotal in establishing green steel as the standard in global competition.

14 The question of the extent to which this option is compatible with a declining total volume of allocations was addressed in the publication Breakthrough Strategies for Climate-Neutral Industry in Europe (Agora Energiewende and Wuppertal Institute 2021)

Annex I: Transformation cost calculator

The goal of the transformation cost calculator (TCC) is to provide an initial, qualified estimate of the CO_2 reduction-related incremental costs of a climate-friendly production compared to the conventional reference plant. The overarching goals here are:

1) Identification and universally valid quantification of the main cost drivers for the transformation of a typical primary steel production process based on the specific CO_2 reduction costs.

2) Creation of a tool for the initial assessment and analysis of specific projects, perhaps as a first step towards awarding carbon contracts.

3) Creation of a transparent basis for the analysis of the costs and benefits of the transformation of the steel industry and its associated infrastructure.

4) Creation of a basis for estimating the total investment and financing requirements for the transformation of the steel sector to climate neutrality.

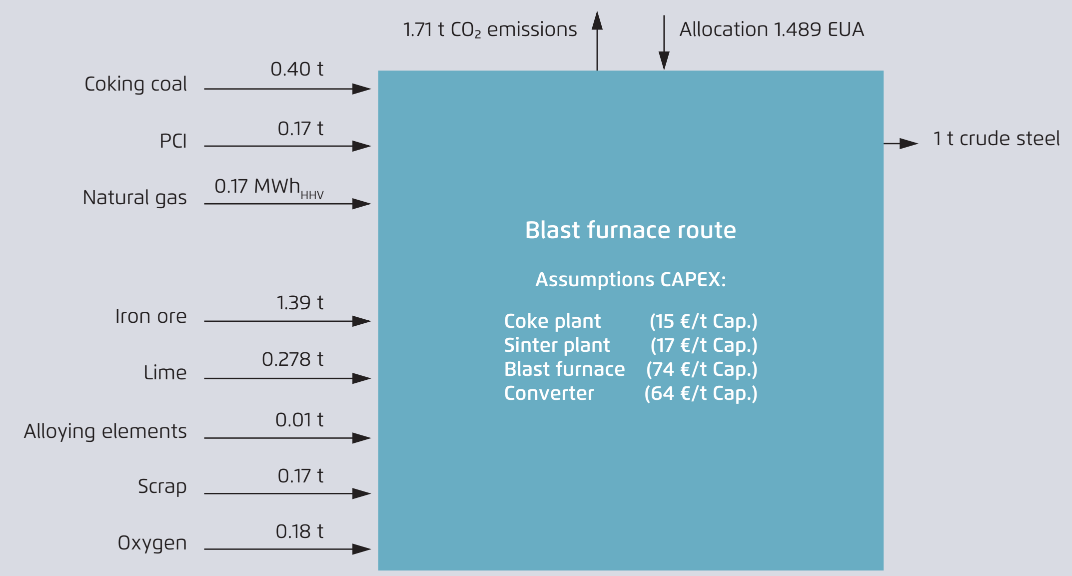
This version 1 of the TCC is a preliminary version that will be further developed, if necessary, to reflect progress on the estimation of the general transformation costs. Its use for the evaluation of specific projects is possible at the responsibility of the stakeholders, but cannot substitute for a specific investment analysis.

The structure of the transformation cost calculator in Excel is designed in such a way that, on the basis of default values, individual manual entries can be made both with regard to the price assumptions and the specific consumption quantities.

The production of one metric tonne of crude steel without further processing is taken as the system boundary. Internal material flows within the system boundary are not taken into account for reasons of simplification.

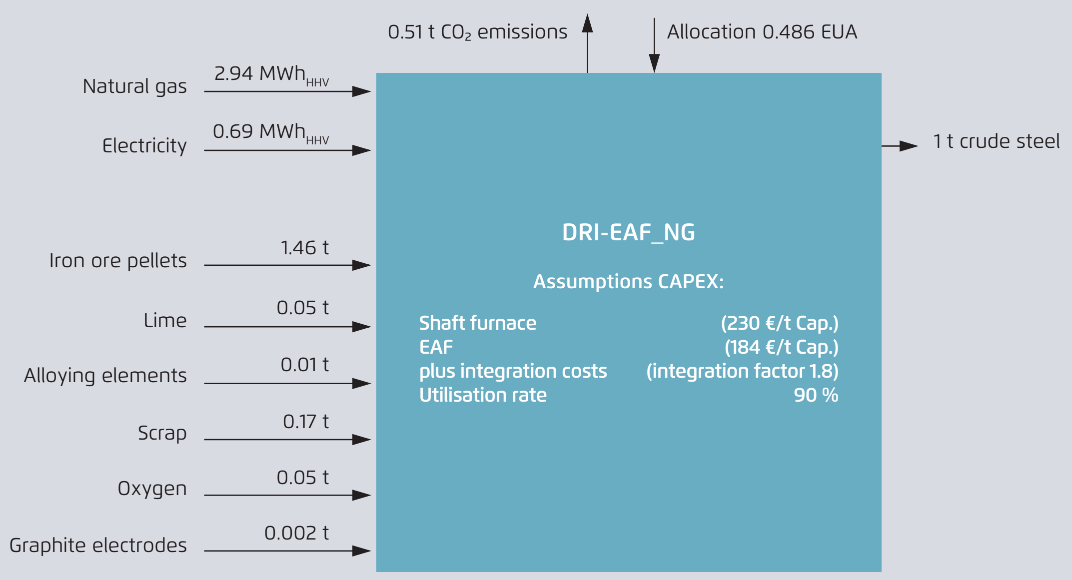
The system boundaries of the production routes considered and the default values for the production of one ton of crude steel are shown below. The assumptions and references for the default values can be found in Annex II.

System boundary and default values of the blast furnace route — Figure 25



Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

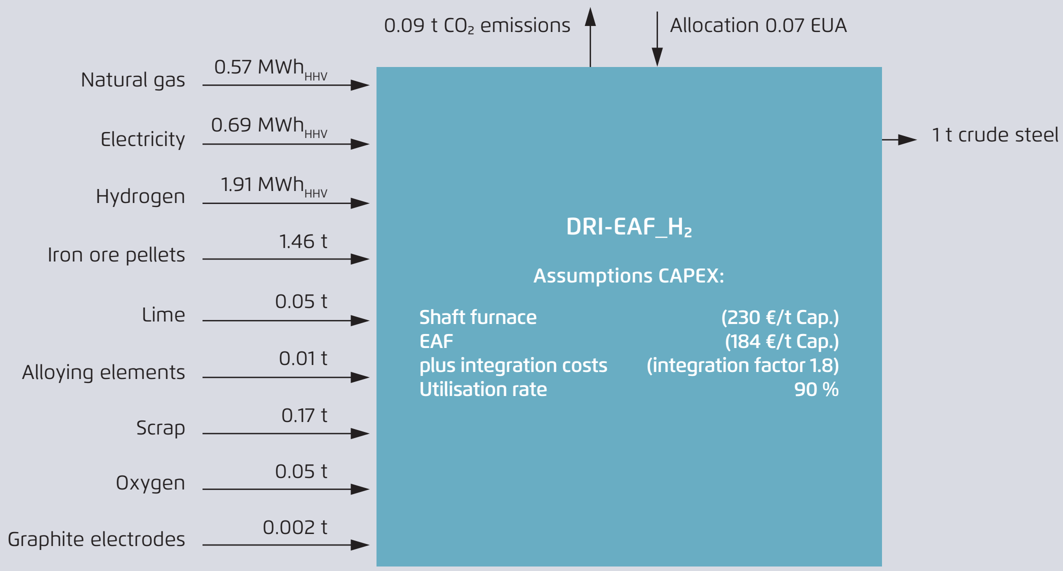
System boundary and default values of the DRI-natural gas route — Figure 26



Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

System boundary and default values of the hydrogen route

Figure 27



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Annex II: Assumptions regarding prices and calculation parameters

Price assumptions — Table 7

Prices of energy sources and material flows	References	Unit	2020	2030	2040	2050	Default values	Comments
Natural gas	Prognos et al. (2020)	€/MWh		35			35	Value 2030 as default; reference value calorific value
Biomethane	Schneider et al. (2019)	€/MWh				51	51	Reference value calorific value
Renewable hydrogen	Prognos et al. (2020)	€/kg		5.5			5.5	Value 2030 as default
Electricity	Schneider et al. (2019)	€/MWh		60–70		50–60	60	Mean value 2030-2050 as default
Coking coal	VDKI (2020)	€/t	143				143	Prime Hard Coking Australia 2019/2020; 10 % markup on FOB (estimate)
Injection carbon (PCI)	VDKI (2020)	€/t	110				110	Assumption for steam coal based on source and stakeholder estimates; 10 % markup on FOB (estimate)
Lime	Vogl et al. (2018)	€/t	100				100	
Iron ore	Fischedick et al. (2014)	€ 2010/t	114	123	133	143	114	Average 2020 as default
Pellets	S&P (2022)	€/t					154	Calculated on the basis of iron ore plus assumption: € 40/t DRI grade premium
Scrap	Vogl et al. (2018)	€/t	180				234	Mean value 2020
	Fischedick et al. (2014)	€/t	287	324	365	411		
Alloying elements	Vogl et al. (2018)	€/t	1,777				1,777	
Graphite electrodes	Vogl et al. (2018)	€/t	4,000				4,000	
Oxygen	Vogl et al. (2018)	€/t	61				61	
EUA prices	**Assumptions Agora (2022)**	**€/EUA**	**50**	**100**	**150**		**100**	

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Assumptions for investment cost calculation — Table 8

Profitability parameters	References	Unit		Default values	Comments
Depreciation periods					
Depreciation period shaft furnace	Vogl et al. (2018)	a	20		
Depreciation period EAF	Vogl et al. (2018)	a	20		
Depreciation period general	Wörtler et al. (2013)	a	**15**	**18**	Rounded-up mean; Vogl/Wörtler
Capital costs	Vogl et al. (2018)	%	5		
	Wörtler et al. (2013)	%	**10**	**8**	Rounded-up mean; Vogl/Wörtler

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Assumptions regarding free allocations — Table 9

Free alloca-tion	References	Unit	2013–2020	2021–2025	2026–2030	Default values calculator
Crude steel	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t crude steel	1.328	1.288	1.275	1.275
Sinter	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t sinter	0.171	0.157	0.152	0.152
Coking coal	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t coking coal	0.286	0.217	0.194	0.194
EAF high alloy steel	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t high alloy steel	0.352	0.268	0.240	0.240
EAF steel	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t EAF steel	0.283	0.215	0.192	0.192
Fuel	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/MWh	0.20196	0,15336	0.137	0.137
Process emissions	Decision 2011/278/EU and EU Allocation Regulation (EU Allocation Regulation) (EU) 2019/331	EUA/t CO_2	0.97	0.97	0.97	0.97

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Assumptions regarding input quantities and CO_2 emissions of the blast furnace route — Table 10

Production (crude steel)	References	Unit [/t crude steel]	Specification	Comments
Moeller mix				
Pellets	Wörtler et al. (2013)	Proportion used in DE 2010	27 %	94 kg CO_2/t product
Lump ore	Wörtler et al. (2013)	Proportion used in DE 2010	14 %	41 kg CO_2/t product
Sinter	Wörtler et al. (2013)	Proportion used in DE 2010	59 %	41 kg CO_2/t product
Iron ore	UBA (2012)	t	1.39	
	WSA (2018)	t	1.37	
	Sprecher et al. (2019)	t	1.41	
	Mean value	**t**	**1.39**	
Coal	**UBA (2012)**	**t**	**0.56**	
Natural gas	**Weigel (2014)**	**MJ**	**611.3**	Converted from calorific value to heating value
Injection coal (PCI)	Sprecher et al. (2019)	t	0.13	
	UBA (2012)	t	0.14	
	Brunke (2017)	t	0.23	Maximum
	Mean value	**t**	**0.17**	
Oxygen	**Weigel (2014)**	**t**	**0.18**	
Lime and aggregates	UBA (2012)	t	0.29	
	WSA (2018)	t	0.27	
	Mean value	**t**	**0.28**	
Scrap	WSA (2018)	t	0.125	
	Sprecher et al. (2019)	t	0.21	
	Schlemme et al. (2019)	t	0.25	Maximum
	UBA (2012)	t	0.19	
	Mean value	**t**	**0.19**	
CO_2 emissions reference	**Schneider et al. (2019)**	**t**	**1.71**	

Agora Industry, FutureCamp, Wuppertal Institute and Ecologic Institute (2022)

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