Wuppertal Institut

Providing a knowledge base for decarbonizing the Kazakh metals industries

Published by:

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Supported by:

Federal Ministry for Economic Affairs and Climate Action

INTERNATIONAL CLIMATE INITIATIVE

on the basis of a decision
by the German Bundestag

As a federally owned enterprise, GIZ supports the German Government
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Published by
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

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Project description
Capacity Development for Climate Policy in the Countries of
Southeastern and Eastern Europe, Southern Caucasus and Central Asia

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This report was elaborated by the experts of the Wuppertal Institut für Klima, Umwelt, Energie gGmbH within the individual measure “Towards Carbon Neutrality Strategy implementation in the private sector of Kazakhstan” of the IKI regional project “Capacity Development for Climate Policy in the Countries of Southeastern and Eastern Europe, Southern Caucasus and Central Asia” (CDCPIII), implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on behalf of the Federal Ministry for Economic Affairs and Climate Action (BMWK).

On behalf of
Federal Ministry for Economic Affairs and Climate Action (BMWK)

Germany 2025

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This report is the result of the project "Providing a knowledge base for decarbonizing the Kazakh metals industries (DeKaMe)" which was granted to Wuppertal Institut by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in the context of the GIZ project "Capacity Development for climate policy in the countries of South East, Eastern Europe, the South Caucasus and Central Asia, Phase III' (CDCPIII). This project is part of the International Climate Initiative (IKI). The Federal Ministry for Economic Affairs and Climate Action (BMWK) supports this initiative on the basis of a decision adopted by the German Bundestag. For more information: www.international-climate-initiative.com

Please cite the report as follows:

Holtz, G., Jülich, A., Knoop, K., Leipprand, A., Acosta-Fernandez, J., Bilici, S., Viebahn, P. (2025). Providing a knowledge base for decarbonizing the Kazakh metals industries (DeKaMe) – Final Report. Wuppertal Institute.

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List of Abbreviations

CCS	Carbon Capture and Storage
DRI	Direct Reduced Iron
QIC	Qazaqstan Investment Corporation
HBI	Hot Briquetted Iron
BF	Blast Furnace
BOF	Basic Oxygen Furnace
EAF	Electric Arc Furnace
MOE	Molten Oxide Electrolysis
NG	Natural Gas
Fig.	Figure
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
R&D	Research and development
WI	Wuppertal Institute for climate, environment, energy gGmbH
GIZ	German International Cooperation Society
SAF	Submerged Arc Furnace
RE	Renewable Energy
PFC	Perfluorocarbons
PV	Photovoltaic
IP	Iron Plate
HM	Hot metal
CHPP	Combined Heat and Power Plant
OSBF	Open Slag Bath Furnace
CBAM	Carbon Border Adjustment Mechanism
ESF	Electric Smelting Furnace
CS	Crude steel
LHV	Lower Heating Value
CCfD	Carbon Contracts for Difference
PGH	Process Gas Heater
PCI	Pulverized coal injection
JSC	Joint stock company
ERG	Eurasian Resources Group
CIS	Commonwealth of Independent States
PPA	Power Purchase Agreement
EU-ETS	European Union-Emission Trading System
KZ-ETS	Kazakh-Emission Trading System
LT	Low Temperature
HaHe	Hall-Héroult
IPCEI	Important Project of Common European Interest

List of Units and Symbols

$	US dollar
₸	Tenge
%	Percentage
€	Euro
°C	Degrees Celsius
CO_2	Carbon dioxide
$CO_{2\text{-eq.}}$	Carbon dioxide equivalents
g	Gram
h	Hour
H_2	Hydrogen
H_2O	Water
HF	Hydrogen fluoride
CF_x	Carbon fluorides
SO_2	Sulfur dioxide
Na_3AlF_6	Sodium hexafluoroaluminate (cryolite)
Al_2O_3	Aluminium oxide (Alumina)
AlF_3	Aluminium fluoride
CF_4	Carbon tetrafluoride
C_2F_6	Hexafluoroethane
Al	Aluminum
C	Carbon
H_2	Hydrogen
O_2	Oxygen
kg	Kilogram
H_2O	Water
NaOH	Natrium hydroxide (caustic soda)
$Al(OH)_3$	Aluminium hydroxide
a	year/annum
$NiFe_2O_4$	Nickel iron oxide
Ni	Nickel
Fe	Iron
Cu	Copper
MWh	Megawatt hour
Mtpa	Megaton per annum
Mt	Megaton
km	Kilometer
kt	Kiloton
kW	Kilowatt
kWh	Kilowatt hour
Mil.	Million
MJ	Megajoule
Nm^3	Normal cubic meter
t	Ton
vol.%	Percentage by volume
m.%	Percentage by mass
ppm	Parts per million
CO	Carbon monoxide

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1 Introduction

Steel and aluminium are metals which are extensively used in various sectors of the global economy, ranging from the automotive industry to the building sector. Their production currently generates significant amounts of greenhouse gas (GHG) emissions. Conventional primary steel production is a highly emission-intensive process that includes various steps from the reduction of iron ore to pig iron and further processing this to crude steel, and, finally, to finished steel products. Today it is primarily done by the integrated coal-based blast furnace-basic oxygen furnace (BF-BOF) route, which globally accounts for around 70 % of today's steel production. The remaining 30 % is mainly produced by recycling steel scrap in electric arc furnaces (scrap-EAF) and only minor shares are produced via various other production routes (World Steel Association, 2024). Primary aluminium production includes the refining of bauxite to alumina and the subsequent reduction of alumina to aluminium in a smelting electrolysis. The energy-intensive smelting process requires large amounts of electricity – which is nowadays typically associated with significant scope-2 emissions from electricity production – and is also responsible for process emissions from burning carbon-based anodes in the electrolysis process (MPP 2022).

Kazakhstan is one of the world's largest producers of metals such as uranium, iron, steel, copper, zinc and aluminium. These resources form the basis for the country's most important economic sectors. Metallurgy accounts for 43% of total manufacturing production and is therefore of great economic importance. Metallurgy, in particular the iron and steel industry, is also one of the largest GHG emitters in Kazakhstan's industrial sector. A large proportion of metallurgy plants in Kazakhstan are outdated and energy inefficient and the share of renewable energies in the energy mix of metallurgy is still low.

Kazakhstan has set itself the goal of achieving a climate-neutral economy by 2060 and created the "Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan by 2060", which was approved by Decree of the President of the Republic of Kazakhstan No. 121 of 2 February 2023 (Government of the Republic of Kazakhstan 2023). The strategy includes the transformation of the Kazakh steel and aluminium industries to almost GHG neutral production. Given the long economic lifetimes of industrial plants of at least 20 years and their technical lifetime which even can be substantially longer, all future investment decisions – including those made in the near future –need to take into account the long-term target of climate neutrality.

Against this background the overarching objective of the project “Providing a knowledge base for decarbonizing the Kazakh metals industries (*DeKaMe*)” was to provide a knowledge base on which Kazakh policy makers and stakeholders can draw to define technological pathways towards deep decarbonisation[1] of steel and aluminium industries in Kazakhstan and for the design of supportive policy instruments.

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[1] The term “deep decarbonization” is used to describe production processes that allow steel and aluminium production with (almost) zero GHG emissions.

More specifically, the project had the following objectives:

- **O1:** Identify and describe technological options for decarbonising the iron and steel industry and summarise their advantages and disadvantages in the Kazakh context.
- **O2:** Identify and describe technological options for decarbonising the aluminium industry and summarise their advantages and disadvantages in the Kazakh context.
- **O3:** Identify and describe policy instruments for decarbonizing the iron and steel as well aluminium industries including best-practice examples and international activities on green lead markets as a menu of policy options for Kazakh authorities.
- **O4:** Facilitate the provision of relevant and up-to-date knowledge about decarbonizing the iron and steel and aluminium industries to Kazakh' policy makers and stakeholders.

The work was carried out in 3 work packages (WP). WP 1 addressed objectives O1 and O2 and created an overview of the technological decarbonization options, their advantages and disadvantages as well as possible opportunities and obstacles for their introduction in Kazakhstan. For gathering data and validation of findings three stakeholder interviews of 1h length were conducted as part of WP1 in November 2024. The interviewees were the Eurasian Resources Group (ERG)[2], Quarmet JSC[3] and Ecojer Association[4]. The findings of WP1 are presented in sections 2-4 of this report. WP 2 covered objective O3 by creating an overview of the status quo of financing instruments in Germany and the EU. Section 5 of this report includes the results of WP 2. Objective O4 was dealt with in WP 3 by conducting one webinar with Kazakh stakeholders on November 25, 2024 and providing input to another webinar with Kazakh stakeholders on December 10, 2024. Furthermore, 1-pagers describing deep decarbonisation technologies for steel and aluminium will be created and distributed to stakeholders by GIZ.[5]

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[2] https://www.eurasianresources.lu

[3] https://qarmet.kz/en/

[4] https://ecojer.kz/en

[5] At the time of writing of this report, the 1-pagers are still under development

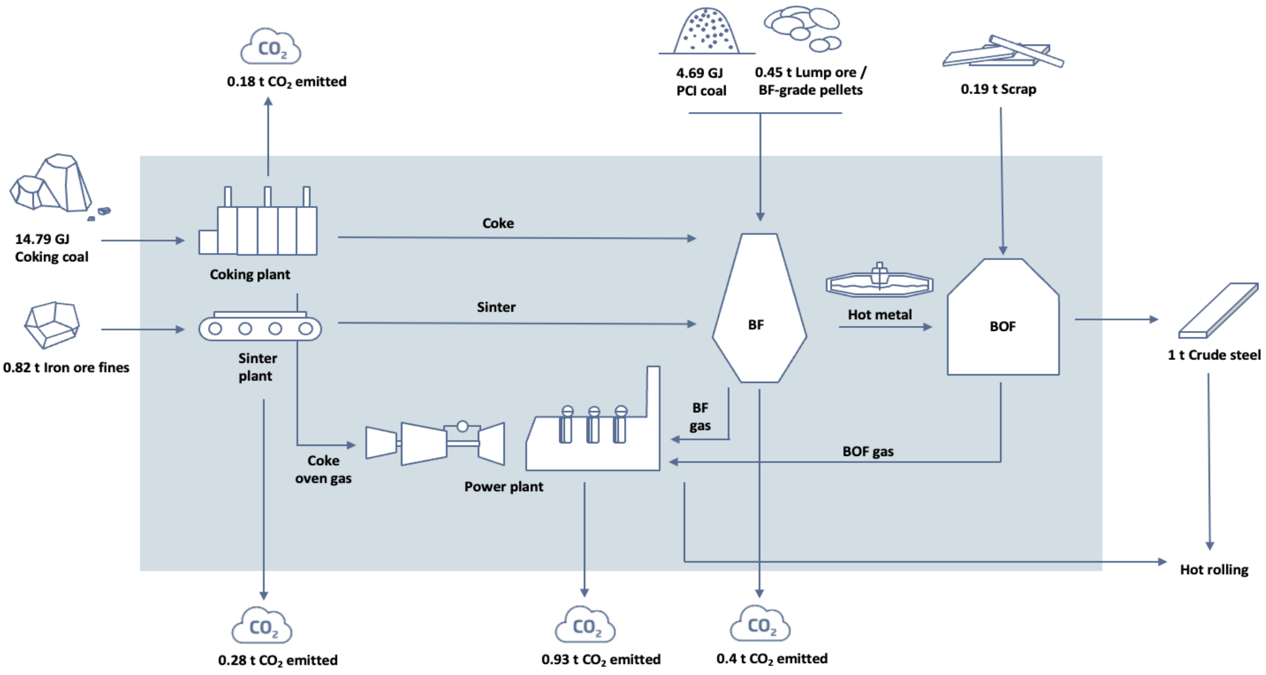
2 Technological options for decarbonizing steel and aluminium production

2.1 Options to considerably reduce CO2 emissions of iron and steel production

Today, conventional primary steel production is mostly done by the integrated coal-based blast furnace-basic oxygen furnace (*BF-BOF*) route, which globally accounts for around 70% of today's steel production. Recycling of steel scrap in electric arc furnaces accounts for most of the remaining 30%. Other production routes contribute only minor shares (World Steel Association 2024).

In the dominant *BF-BOF* route, displayed in Figure 2-1, iron ore is sintered and then melted in blast furnaces along with coke and limestone. The carbon rich coke serves both as a reducing agent and energy carrier, leading to the release of high amounts of CO_2. Besides coke, pulverized coal (PCI coal) is injected as additional energy carrier and adds to CO_2 emissions. In the subsequent basic oxygen furnace, the molten iron (pig iron) is further refined, which also produces CO_2 emissions. In total, the BF/BOF route consumes about 19.5 PJ of coking coal and PCI coal and emits about 1.8 t of CO_2 per ton of crude steel produced.[6]

Figure 2-1: The blast furnace-basic oxygen furnace (BF-BOF) route for primary steel making



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[6] Direct emissions only and including some counter-balance for the use of off-gases for hot rolling.

Future green steel production technologies could reduce CO_2 emissions through new disruptive approaches and increased recycling. As part of this project, the following options were examined:

- Blast furnace-basic oxygen furnace route (BF-BOF) equipped with carbon capture and storage (CCS)
- Direct reduced iron (DRI) using hydrogen, biomass or natural gas
- Electrolysis processes: Electrowinning and molten oxide electrolysis (MOE)
- Increasing recycling rates and secondary steel production in the electric arc furnace (EAF)

These options are described in the following and analysed and compared specifically for the Kazakh context in section 1.1.

2.1.1 Blast furnace-basic oxygen furnace route equipped with Carbon Capture and Storage (CCS)

In this CO_2 abatement measure, point sources in the *BF-BOF* route that release CO_2 into the atmosphere are retrofitted with post-combustion CO_2 capture technology. Captured CO_2 will then be transported to a CO_2 storage facility that pumps the CO_2 to fully depleted oil and gas deposits or saline aquifers for permanent storage.

In theory, retrofitting existing steel production facilities with CCS technology could provide steel companies an option for near-zero crude steel production without the need for making structural changes to the production process itself. In principle, the CCS technology might reduce the CO_2 emissions that are released to the atmosphere by up to 90 %. However, applying CCS to the *BF-BOF* route poses challenges (see below) that decrease the actual techno-economical potential to reduce CO_2 emissions. Current global low-carbon steel capacity announcements seem to show that the risks outweigh the benefits: only 1 Mtpa capacity of the *BF-BOF-CCS* route is announced globally to be realized until 2030, whereas 94 Mtpa DRI capacity is announced to be realized in the same time period (Agora Industry 2023).

A main challenge for the *BF-BOF-CCS* route lies in the feasibility of achieving a high capture rate for the processes as a whole. The integrated *BF-BOF* route has several point sources of emissions with different CO_2 concentrations in the waste gas streams. Considering the fact that the CCS technology operates more efficiently with higher CO_2 concentration in waste gas streams, retrofitting CO_2 point sources with low CO_2 concentrations would result in higher energy consumption of CCS units. A techno-economically feasible approach for the BF-BOF-CCS route, which is displayed in Figure 2-2 seems to be retrofitting major CO_2 point sources with a CO_2 concentration higher than 15 % only, namely the coke oven underfiring stack of the coking plant, the hot-blast stoves of the blast furnace and the onsite combined heat and power plant (CHPP). Other CO_2 point sources, namely the sinter plant and smaller point sources not shown in Figure 2-2 (venting flares and oxygen heaters) have either very low CO_2 emissions or low CO_2 concentration in the flue gasses, which makes equipping CCS technology techno-economically unfeasible for these processes (Agora Industry, Wuppertal Institute and Lund University 2024).

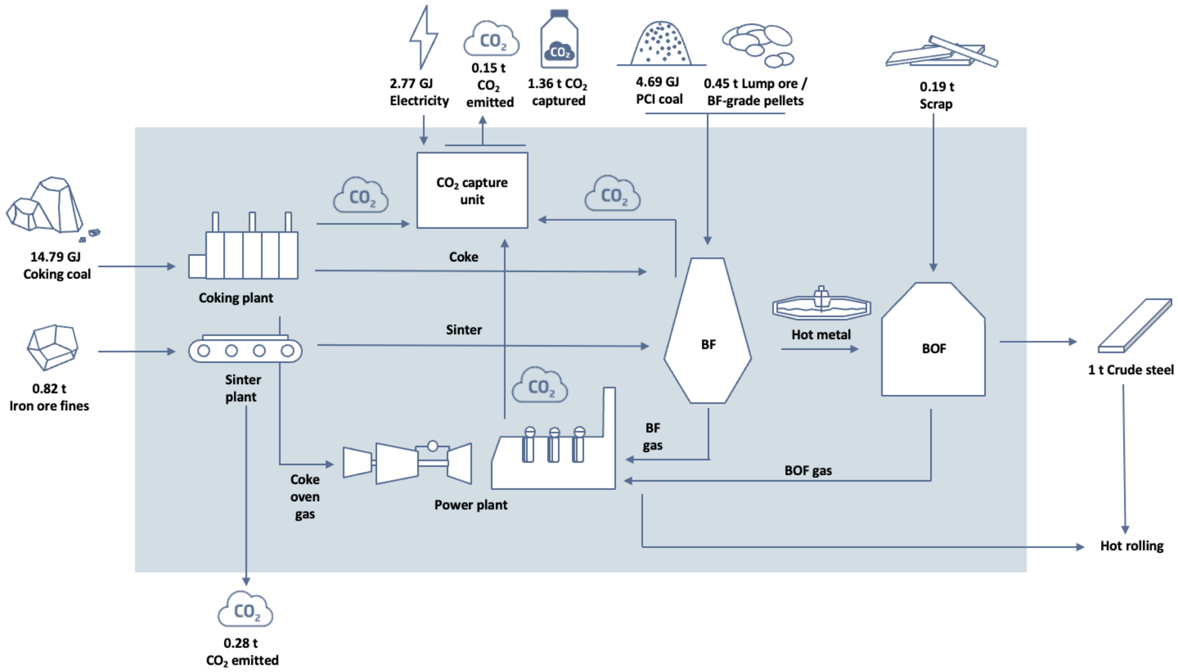
In total, the CCS process (as proposed here) can reduce the CO_2 emissions by 77%, compared to the BF-BOF route.[7] For doing so, an additional 770 kWh of electricity per ton of crude steel is required.

2.1.2 Direct reduced iron (DRI) using hydrogen, biomass or natural gas

The direct reduction (DR) of iron ore to iron is an alternative to traditional BF ironmaking that is commercially available. Annual global DRI production increased from 44 Mt in 2000, 70 Mt in 2010 and 105 Mt in 2020 to 135 Mt in 2023, with Middle East/North Africa, Asia and North America being the biggest DRI producing regions so far (MIDREX 2023).

The conventional direct reduction of iron ore takes place in a vertical shaft furnace using syngas[8] as reducing agent at temperatures below the melting point of iron. As iron ore raw material, mainly iron ore pellets or, to a lesser extent, lump ore is used, as the uniform size of iron ore pellets and their specific properties make pellets best suited for the DRI process.

Figure 2-2: Blast furnace-basic oxygen furnace route (BF-BOF) equipped with Carbon Capture and Storage (CCS)



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[7] The system boundary for the comparison is up to crude steel and the usage of off-gases for hot-rolling has been considered by a counter balance in both cases.

[8] A mixture of carbon monoxide (CO) and hydrogen (H_2) containing gasses

The resulting product of the direct reduction technology is a solid state of iron known as direct reduced iron (DRI) and is also called “sponge iron” due to its spongy, porous appearance.

The flexibility of producing syngas for the process from different sources allows a wide range of reducing gasses to be used, including natural gas, coal-derived syngas[9], gasified biomass or hydrogen. Today, natural gas and coal-derived syngas are used in industrial-scale plants, while the use of pure hydrogen is still being tested and may require some minor adjustments. However, the choice of reducing gas used determines the CO_2 emissions of the process, which will decrease with increasing hydrogen content in the reducing gas, since hydrogen only produces H_2O as by-product instead of CO_2.

Today, there are two main competing technology providers with different processes, with Midrex holding the lion's share of the DRI market with over 70 % and HyL-Energiron being second with around 25 %. In the conventional natural-gas-based Midrex process, natural gas first passes through a reformer, where it is split into CO and H_2 to produce a suitable reforming gas, which is then fed to the shaft kiln, where both CO and H_2 can act as reducing agents. However, the reformer requires additional natural gas for heating. In contrast, in the conventional natural-gas-based Energiron ZR[10] process, the reforming reaction of the natural gas takes place in-situ in the shaft kiln itself, so no additional reformer is required, but natural gas is still needed to heat the reducing gas and maintain a constant operating temperature. When hydrogen is used as the reduction gas, no major preparation is required in both technologies other than preheating the hydrogen to suit the operating conditions. For the operation with biomass, a biomass gasifier can provide the shaft kiln with a suitable bio-syngas. Although biomass gasification (IEA Bioenergy 2020) and direct reduction are both proven technologies with numerous projects around the globe, there are no use-cases to the author’s knowledge that combined direct reduction technology with biomass gasification on a commercial scale.

DRI-based crude steel production routes

Similar to the hot metal from the blast furnace, the DRI is processed into crude steel in a subsequent process step. As DRI exits the shaft furnace in a solid state, it first needs to be melted in order to be further processed. This can, on the one hand, be achieved by charging DRI directly into an electric arc furnace in its solid state. This *DRI-EAF* route has become the current commercial process route for producing crude steel from DRI. In this route, DRI is charged together with a flexible proportion of scrap to be processed into crude steel. As the iron ore is not melted in direct reduction and therefore no slag is formed to facilitate the removal of impurities from the iron in the *DRI-EAF* route, it is necessary to use special high-quality DR-grade iron ore pellets with a high iron content of typically at least 66% Fe (Nicholas and Basirat 2022).

Alternatively, DRI can be smelted in specific smelting furnaces which are available on the market as Electric Smelting Furnaces (ESF). The product of these ESF is a liquid metal with properties similar to the hot metal from the BF, which can be fed directly into existing BOF units for further steelmaking without any modification of the steelmaking process. ESF are able to remove impurities in the iron ore through slag formation on top of the molten metal. In the *DRI-ESF-BOF* route lower grade pellets (BF

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[9] The coal-based DRI process is even more CO_2 intensive than conventional blast furnace reduction, resulting in specific emissions of over 2.2 t/t CS.

[10] ZR stands for Zero Reformer

grade pellets) can therefore be used, which – compared to DR grade pellets – offer higher market availability but suffer from lower iron content, typically in the range of 61 to 65%. This route also allows to use existing equipment (the BOF) and thus to avoid stranded assets. However, in contrast to the EAF – which allows a flexible scrap charge in addition to DRI from 0% to 100% – the scrap addition to the BOF is limited to a maximum of around 30%. Hence, the *DRI-ESF-BOF* route provides less operational flexibility, compared to the *DRI-EAF* route.

Figure 2-3 displays the two routes for the case of using hydrogen as reduction gas. In the case of a hydrogen-based direct reduction (H_2-DRI), the preheating of the hydrogen in a process gas heating unit (PGH) is required to suit the operating conditions. This can be done using the same gas as for reducing. For achieving a fully climate neutral *DRI-EAF* production, the preheating can therefore also be done using hydrogen as a fuel. The *DRI-ESF-BOF* route has the advantage that waste gas from the smelting unit and basic oxygen furnace can be used for preheating, leading to a reduced need for hydrogen as a fuel for preheating. However, the use of these waste gas streams for heating results in CO_2 emissions, as these streams contain CO, which is formed by the addition of carbon in the smelter or BOF.

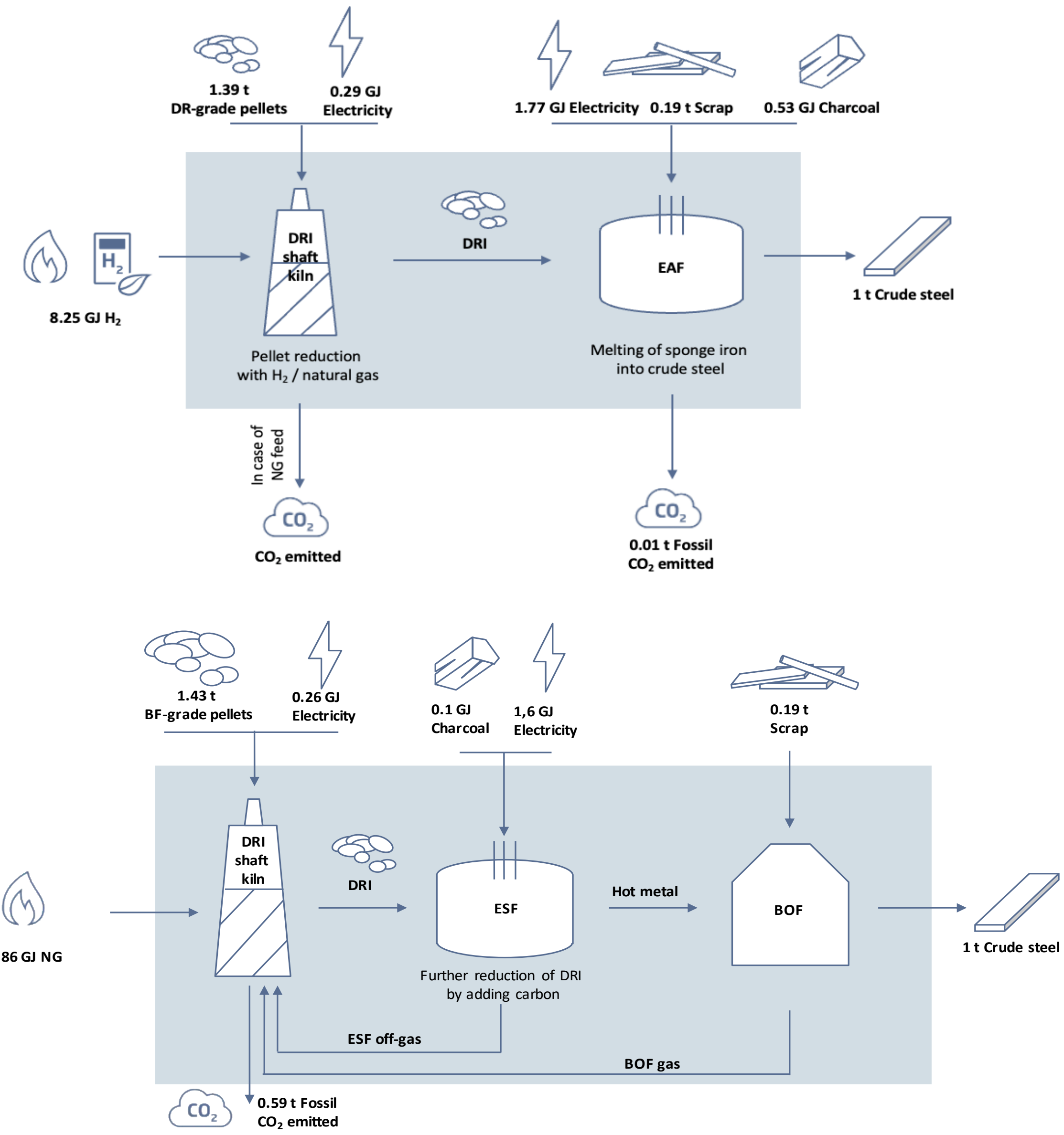
Excursus: Combining DRI with CCS

The DRI process can also be combined with carbon capture and storage (or use) if carbon-containing reduction gases such as natural gas and biogas are used. Using amine (MEA) scrubbing as capture process, CO_2 in the waste gas stream of the shaft kiln can be captured with 90% efficiency. Since only the shaft kiln would be combined with the CCS technology, this results in a total emission reduction of 64% in crude steel production compared to DRI-EAF without CCS. The capture is cost-efficient as the CO_2 stream from the reduction process is comparably clean. But additional energy is needed to operate the CCS technology, which leads to an additional electricity consumption of 170 kWh/t CS, according to our calculation based on Agora Industry, Wuppertal Institute and Lund University (2024). The need for CO_2 transport and storage must be also considered when combining DRI with CCS.

Excursus: DRI/HBI as possible Export Option

The solid state of DRI makes it a favourable commodity for transport, if the highly porous DRI is further prepared by compaction to avoid re-oxidation and self-ignition. This compaction is usually carried out directly after the shaft kiln discharge in a hot state and results in uniform briquettes, which are then referred to as hot briquetted iron (HBI). The fact that DRI can be transported in the form of HBI allows steelmakers to decouple the ironmaking process from the steelmaking process and opens up the possibility of separating ironmaking and steelmaking geographically. Hence, steelmakers can decide to produce DRI in geographical locations with optimal conditions for the provision of reducing gas and export HBI to the steel production facility where it can be processed further into steel (Bilici et al. 2024). The spatial decoupling of DRI production and steel making comes with an energy penalty, though. Briquetting requires an additional 12 kWh/t of DRI (Orre et al. 2021). In addition, due to cooling after discharge, briquetting and transport, reheating of HBI is required for further processing it to steel, resulting in an energy penalty of 120-140 kWh/t crude steel, compared to directly feeding hot DRI to a subsequent melting unit (Duarte & Pauluzzi 2021).

Figure 2-3: DRI-based steel production routes (top: H2-DRI-EAF; bottom: H2-DRI-ESF-BOF)



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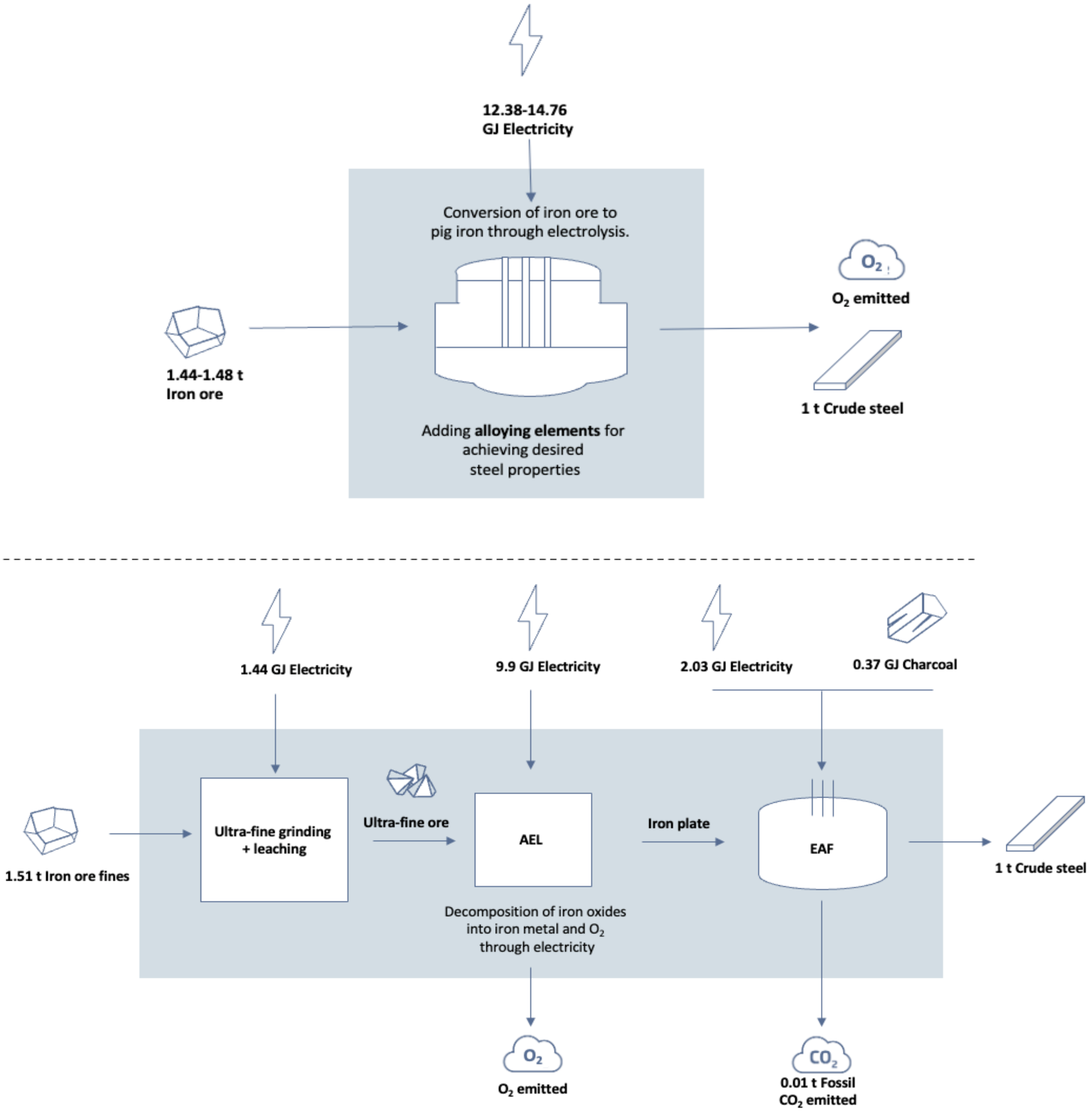
2.1.3 Iron ore electrolysis

In electrolysis processes, iron ore is reduced by putting it into a solution and passing an electric current through it. Currently, two routes are explored, the molten oxide electrolysis (*MOE*) route and the electrowinning of iron in an alkaline electrolysis process with subsequent processing in an electric arc furnace (*AEL-EAF*), see Figure 2-4. Both types of electrolysis processes generate almost no direct CO_2 emissions since no carbon-based reducing agents are required (Agora Industry, Wuppertal Institute & Lund University 2024)

Figure 2-4: Iron ore electrolysis routes (top: MOE; bottom: AEL-EAF)



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In the molten oxide electrolysis (*MOE*) route, the iron ore is directly processed into a liquid metal. In the electrolytic cell, the iron ore is dissolved in an electrolyte solution with a temperature above the melting point of iron. An electric current is then passed through the solution in order to reduce the iron ore. The process allows the production of various steel properties in the electrolytic process itself by adding alloying elements.

In the electrowinning or alkaline electrolysis (*AEL-EAF*) process, iron ore fines are grinded and leached and the resulting ultra-fine iron ore grains are processed in the electrolysis cell into a solid iron plate, which is then processed into steel in the EAF. In the electrolysis cell, the ground iron ore grains are reduced in an alkaline solution at around 110°C by an electric current. At the comparably low operating temperatures of the alkaline electrolytic cell the iron does not melt. In this route, some small residual emissions occur in grinding and leaching of the iron ore, as well as in the EAF steelmaking step.

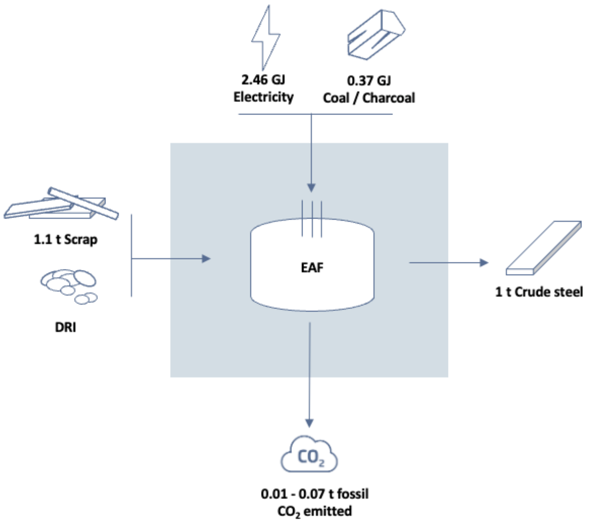
It is important to notice that both electrolysis processes have so far only been proven in pilot plants and not in commercial scale production facilities, yet. We estimate that the *MOE* could be technologically ready to produce steel on a commercial scale by 2035 and the *AEL-EAF* by 2040[11].

2.1.4 Recycling and secondary steel production

Today, roughly 30 % of global steel production is based on scrap (World Steel Association 2024). The scrap is melted in an electric arc furnace (EAF), which is operated with electricity. In this route, no reduction of iron ore is required and consequently no carbon-based reducing agents are used, which leads to specific direct CO_2 emissions of below 0.1 t CO_2 per tonne of crude steel produced, which is significantly lower than the specific emissions of conventional primary steel production. Secondary steel production can be an important lever for reducing CO_2 emissions of the steel sector in the long term as it is projected that globally the available scrap amounts will increase, compared to overall steel demand (IEA 2020a).

Steel scrap includes impurities besides the pure iron. These impurities currently limit the use of secondary to the production of low value steel grades, such as bar steel in construction. Steel properties can be improved during the secondary steel making process by adding a small amount of coal and lime in the EAF in order to produce slag that removes the impurities. However, this approach is limited, because copper contamination in steel scrap cannot be removed with existing technologies and finished steel products allow only certain levels of copper content, depending on their intended use. Better product design, scrap sorting and most importantly flexible charging of shares of DRI/HBI in the EAF in addition to scrap could improve the suitability of scrap-based steel for use in higher-value steel products. For example, the US steel production system shows that these levers facilitate an increased use of scrap for the production of high-value steel products. In the US, the scrap share of metallic inputs into the steel making processes was over 70% in 2019, which is mainly due to high scrap utilization in the DRI-EAF route of around 90% (IEA 2020a).

Figure 2-5: Secondary steel production route



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[11] see section 5.4 and 5.5 in Agora Industry, Wuppertal Institute and Lund University (2024).

2.2 Options to considerably reduce GHG emissions of aluminium production

Aluminium (Al) is the most abundant metallic element (approx. 8 w-%) in the earth's crust (WEF 2021). In nature, however, aluminium never occurs as a pure metal, but in a variety of natural minerals, e.g. in combination with oxygen, silicon or other metals. The most important mineral of commercial aluminium production is bauxite, which typically contains between 40 and 60 w-% of aluminium (hydr)oxides with small amounts of iron, silicon and titanium compounds as well as many other trace impurities (BGR 2020; Georgitzikis et al. 2021).

However, bauxite ore, which is usually mined in open pits, cannot be processed directly into aluminium because the mineral impurities must first be removed, resulting in the formation of aluminium oxide (Al_2O_3) – also known as alumina – as an intermediate product. This pre-processing stage is carried out in an alumina refinery using the *Bayer* process, where bauxite is treated with caustic soda (NaOH) by digestion and heated to precipitate aluminium hydroxide ($Al(OH)_3$). Next, the precipitated but watery $Al(OH)_3$ is calcined in rotary or fluidized bed reactors to remove excess water and produce a white solid alumina powder. In order to obtain pure aluminium, the alumina powder is melted by a smelting electrolysis – the *Hall-Héroult (HaHe)* process – where it is dissolved in molten cryolite[12] (Na_3AlF_6), decomposed and resulting in liquid pure aluminium (>99 w-%) at the bottom of the cell, where it is periodically siphoned off. Figure 2-6 shows an overview of the aluminium production process.

The overall electrochemical reaction for the production of aluminium in the electrolysis cell is:

$$1/2\ Al_2O_{3\ (dissolved)} + 3/4\ C_{\ (s)} \rightarrow Al_{(l)} + 3/4\ CO_{2\ (g)} \qquad \text{(Eq. 1)}$$

As Equation 1 shows, the carbon anode is consumed in the electrolysis process and forms CO_2 by oxidation with the oxygen from alumina. Therefore, the anode must be replaced periodically. In addition, this electrochemical reaction produces a large amount of GHGs and other harmful gases, which mainly includes three parts: (1) carbon compounds (CO_2 and a small amount of CO) from the electrochemical reaction (2) perfluorocarbons (PFC's) released with the appearance of an anodic effect[13] and (3) hydrogen fluoride (HF) produced by raw material containing H_2O reacting with the fluoride electrolyte.

However, due to the high binding energy of aluminium and oxygen in the form of alumina, the smelting process is quite energy intensive, consuming about 13–16 MWh_{el} per ton of aluminium produced with a world average of about 14,1 MWh_{el} (International Aluminium Institute 2024). Emissions from aluminium electrolysis are mainly from the anode reaction, which produces approximately 1.5 t CO_2/t Al. In addition, there are 0.4 t CO_2-eq/t Al from PFC's[14] (Kortes & van Dril 2019; Zore 2024) produced by the anode effect as well as indirect emissions associated with electricity

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[12] A fluorine-containing salt that lowers the melting temperature of Al_2O_3 from normally 2050°C to 950 -970°C (Zore 2024)

[13] Anode effect is a characteristic phenomenon in molten salts electrolysis leading to emissions of perfluorocarbons (PFC) (Zore 2024) – This effect is characterized by a sudden increase in cell voltage accompanied by a decrease in current efficiency and causing the carbon from the anode to react with the fluorine in the molten cryolite bath leading to the generation of PFCs (MPP 2023; Zhu-Xian et al. 2016)

[14] When anodic effect occurs, the PFC's emissions are mainly CF_4 and C_2F_6, whose global warming potentials (GWP) are a multi-fold of that of CO_2, reaching up to 7380 and 12400 on a 100-year time scale respectively (IPCC 2023)

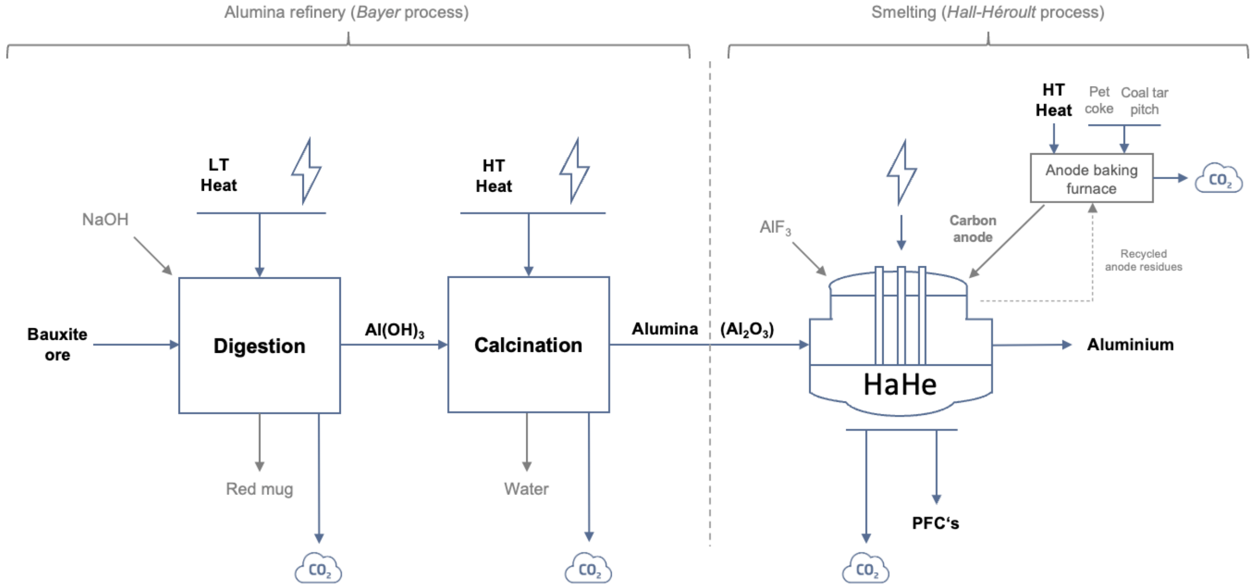
consumption, which depend on the CO_2 intensity of the electricity used.

In contrast to the decarbonization of the iron and steel industry, there are no disruptive processes for the production of low-carbon aluminium and therefore no overarching transformation of current plant layout is envisioned to reduce GHG emissions. However, in the absence of such processes, other measures are required. The following description of approaches to lower GHG emissions from aluminium production focusses on the aluminium smelting step and includes the following options:

- Use of inert anode materials
- Aluminium electrolysis in combination with CCS
- Increasing recycling rates
- Use of low-carbon electricity

These options are described in the following and analysed and compared specifically for the Kazakh context in section 4.2

Figure 2-6: Overview of the aluminium production process, including aluminium refining and smelting



Source: own figure

2.2.1 Use of inert anode materials instead of carbon

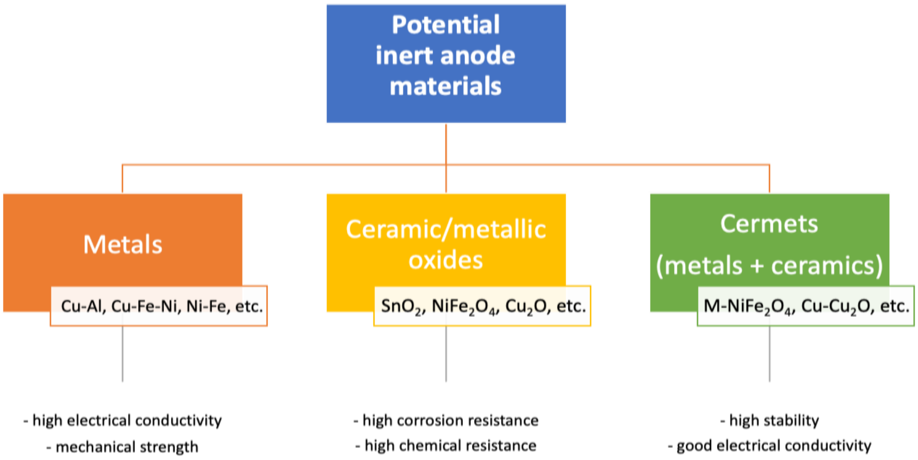
In today's aluminium smelters, carbon-containing anodes are used, which can be divided into a discontinuous type (pre-baked anodes) and a continuous type (self-baking Søderberg anodes). The former are the most widely used in the aluminium industry and account for up to 90% of global primary aluminium production. In a Søderberg cell, the anode is produced in situ, whereas in a pre-bake cell, the anodes are produced in a separate anode baking furnace, which is often integrated into the primary aluminium plant. Pre-baked anodes mainly consist of carbon and are usually produced on-site in a multi-step process. Petroleum coke (pet coke) serves as the main raw material and is first crushed and screened to achieve the desired particle size. Coal tar pitch, used as a binder, is then heated and mixed with the crushed pet coke to form a homogeneous paste. This paste is moulded or extruded into specific shapes to produce the characteristic anode geometry. The shaped anodes are then baked in furnaces at temperatures of approximately 1000 to 1200°C in a reducing atmosphere (oxygen-free environment). This baking process hardens the anodes, giving them the necessary mechanical strength and high electrical conductivity.

Irrespective of the anode type, the carbon in the anodes can be regarded as a raw material for aluminium electrolysis, as it is consumed as a reducing agent (see Equation 1) during the anode reaction to dissolve the oxygen from the aluminium. As described before, the combustion of these anodes, resulting in the reaction of carbon with free oxygen to form CO_2, is the main source of direct emissions in the aluminium smelting process – responsible for approximately 1.5 t CO_2-eq/t Al. One of the main options for reducing GHG emissions from primary aluminium production is therefore the use of new, innovative anode materials to replace conventional carbon anodes. Ongoing research aims to use inert materials for anodes that do not have a tendency to burn and, because they do not contain carbon, do not produce CO_2 emissions nor PFC's (He et al. 2021). Inert anode materials do not react chemically or electrochemically during electrolysis, i.e. they are not consumed (or are consumed very slowly) by the anode reaction. With inert anodes the total electrolysis cell reaction will be:

$$Al_2O_3\,_{(dissolved)} \rightarrow 2\,Al_{(l)} + 3/2\,O_2\,_{(g)} \quad \text{(Eq. 2)}$$

As Equation 2 shows the only by-product will then be O_2 with no climate relevant effects.

Figure 2-7: Potential materials for inert anodes



Source: own figure, based on Padamata et al. (2023)

However, most materials, with the exception of precious metals, carbon materials and very few ceramic materials, have high solubility due to severe corrosion at the high operating temperatures in the electrolytic cell (typically 950–970°C). Potential inert anode materials must have low solubility and low reactivity in the electrolyte and also show good chemical resistance against the anodically produced hot oxygen gas. In addition, the anode material should be physically stable at the operating temperature, mechanically robust and resistant to thermal shock. Proving materials with these necessary properties is quite challenging today.

Figure 2-7 gives an overview of potential materials for inert anodes. These have different properties and it is not yet clear which type will ultimately prevail on an industrial scale. While metallic variants have high electrical conductivity and mechanical strength, oxide combinations have high corrosion and chemical resistance, whereas Cermets (composite materials made of ceramic materials in a metallic matrix) show high stability with good electrical conductivity.

Today, there are two main challenges in the development of inert anode materials. First, the aluminium produced must be of sufficient purity. The level of impurities in the aluminium can be very significant for customers and the need to produce pure aluminium will become more stringent in the coming years. The corrosion products caused by the dissolution of the anode material in the electrolyte will mainly end up in the metallic phase and thus contaminate the aluminium produced. Therefore, anode corrosion should be low enough to produce impurity levels that meet current specifications for smelter grade aluminium. Second, anodes should last as long as the cell life, which can now be up to 5 years or more (Kvande & Drabløs 2014). There would then be no need to replace anodes after the cell has been commissioned. However, it is a chemical fact that all materials have a finite solubility in the highly corrosive cryolitic melts at around 960°C, so a totally inert anode will probably never be found for use in these electrolytes (He et al. 2021).

Several companies and research institutions have been actively involved in the development of inert anode materials in recent years. There is no doubt that significant progress has been made, with regard to these two main challenges. However, the operation of inert anode cells will certainly remain a challenge (Solheim 2019). The commercial aspects of inert anodes have not yet been proven. There are currently a number of technical issues to be resolved and it is impossible to say when, or even if, this will be a proven technology. In any case, it is likely to be several years before the above issues are satisfactorily resolved. It may be that cell retrofitting will not be the preferred development path in the future and that a completely new cell design will be required.

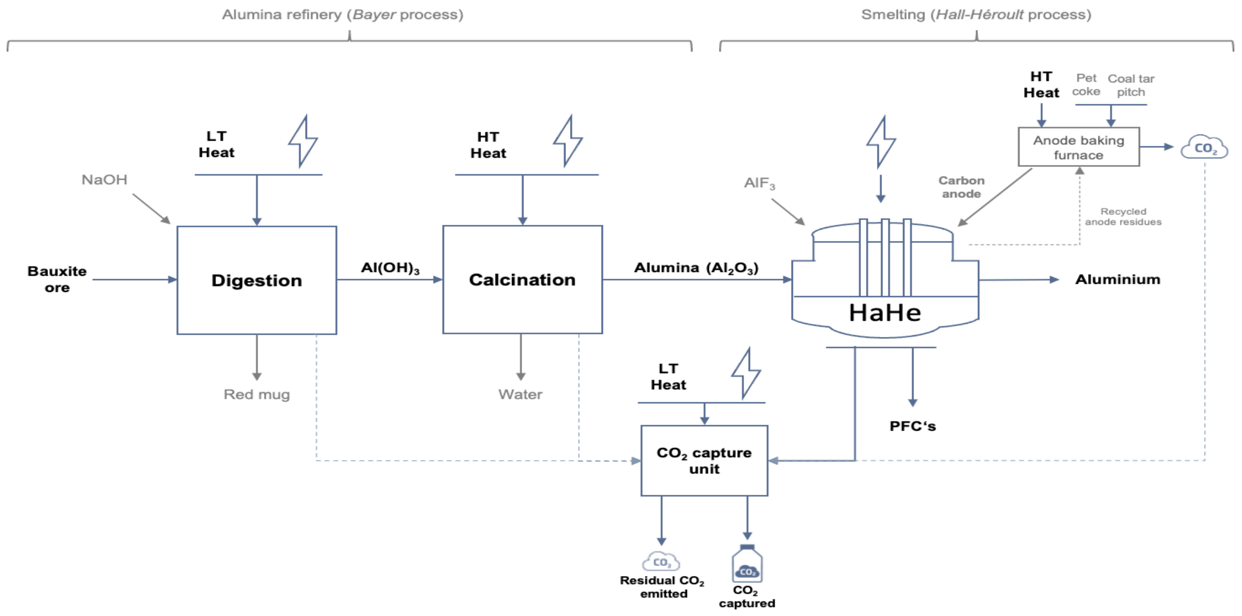
2.2.2 Aluminium electrolysis with CCS

Another option for cutting emissions from primary aluminium production is to retrofit the electrolysis cell with carbon capture systems and storing the CO_2 permanently (CCS), see Figure 2-8. However, the capture of the aluminium smelter off-gases hasn't been widely studied, raising questions about its technical feasibility. The way modern aluminium electrolysis cells are designed, a large amount of air must pass through the system to cool process equipment and prevent fugitive emissions from escaping into the potroom during operation. As a result, the CO_2 concentration leaving the system through the ducts is reduced to about 1 vol.% (MPP 2023; Zore 2024). However, to date, most CCS technologies have been developed from fossil power generation and industries with higher CO_2 concentrations, typically above 4 vol.%, which research has shown would be appropriate to make the cost of using CCS a worthwhile investment (Saevarsdottir et al. 2023). In addition to the low CO_2 concentration, aluminium smelting off-gases contain a number of pollutants that challenge compatibility with existing capture technologies, so many current off-gas treatment systems are typically limited to dry scrubbers and bag filters used to remove hydrogen fluorides and recycle fluorides back into the system.

Furthermore, CCS systems can only capture the CO_2 emissions from the smelter off-gas stream, but no PFC emissions. Thus, a significant portion of the relevant GHG associated with the electrolysis process cannot be reduced by CCS. Also, CCS systems typically operate at only 90% efficiency[15], resulting in residual CO_2 emissions of at least 10% for the smelter off-gas (MPP 2022) and an overall GHG mitigation of about 70%, including PFC's.

In principle, the capture of CO_2 from off gas streams can take place not only at the smelting furnace, but also at other points in aluminium production where carbon-containing energy sources are used as fuel, e.g. during calcination. However, the individual streams are each small and differ in their composition, so that a separate, adapted CCS unit would have to be built for each stream, which would probably be far too expensive in relation to the CO_2 reduction potential and would prevent economical operation. The option to capture CO_2 from the alumina refinery is not therefore further analysed here.

Figure 2-8: Overview of CCS applied to the aluminium production process



Source: own figure

2.2.3 Increasing recycling rates

Aluminium can well be recycled. Recycling scrap aluminium instead of producing primary aluminium from raw material highly cuts energy demand to only about 5% of primary production and does not include process emissions (Wang 2022).

Aluminium is already one of the most recycled materials worldwide reaching up to 90% recycling quotes. Large quantities are already today produced via recycling (MPP 2022). But

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[15] Standard capture rate for amine scrubbing (MEA) capture process

aluminium scrap availability is a reasonable constraint limiting the share of secondary production related to total aluminium production. On the one hand, a significant proportion of all the aluminium produced ever – approximately 75% – is still in use today (International Aluminium Institute 2023). If recycled, this readily available stock, mainly from post-consumer scrap, can significantly reduce the need for primary aluminium production in the future.

On the other hand, despite technological advances in the recycling industry, challenges remain, including metal losses during the recycling process. While some sectors, such as automotive, building or construction, have high scrap collection rates, others, such as packaging, have varying levels of recycling due to factors such as product life and local market conditions (Raabe et al. 2022; Stacey 2015; Zore 2024). A comprehensive approach is needed to maximize the benefits of aluminium recycling. This includes increasing collection rates, improving scrap sorting, minimizing pre-consumer scrap and reducing metal losses. By implementing these strategies, the industry can significantly reduce the demand for primary aluminium, leading to significant reductions in GHG-emissions and contributing to a more sustainable future.

2.2.4 Use of low-CO_2 electricity

The energy-intensive smelting process requires large amounts of electricity – 14.1 MWh_{el}/t of Al, in the global average – which can be associated with significant *scope-2* emissions from electricity production, depending on the CO_2-intensity of the used electricity. Consequently, in the global aluminium industry, in the year 2023 the larger share (60%) of the sector's total emissions stemmed from indirect emissions associated with the electricity consumed in the smelting process.[16] According to the International Aluminium Institute, the use of hydroelectric power in aluminium electrolysis was increased significantly between 2018 and 2022, which reduced the industry's carbon footprint by 0.7 t CO_2-eq/t Al over this period.[17] Most of this improvement is due to a significant increase in the use of renewable energy in China, by far the world's largest aluminium producer.

If renewable electricity with virtually no scope-2 emissions is used, the overall GHG intensity of aluminium production can thus be significantly reduced. The availability of and access to renewable energy sources will always be crucial to the success of this measure. As the development of the electricity infrastructure is typically not in the hands of the aluminium plant operators, it is primarily up to governments to create the right framework conditions for the electricity system to become climate-neutral. Power Purchase Agreements (PPAs) – long-term contracts between a renewable energy plant operator and an electricity consumer – have become a key instrument in the energy transition in recent years. Especially for energy-intensive industries such as aluminium production, PPAs offer an attractive opportunity to meet their electricity needs with renewable energy on a stable cost basis.

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[16] https://international-aluminium.org/statistics/greenhouse-gas-emissions-primary-aluminium

[17] https://international-aluminium.org/aluminium-industry-reports-decline-in-greenhouse-gas-emissions/

3 Boundary conditions for decarbonising steel and aluminium in Kazakhstan

3.1 The Kazakh economy: characteristics, challenges and opportunities

The Kazakh economy is heavily dependent on the extraction and export of raw materials, with fossil fuels such as coal and oil playing a prominent role. Kazakhstan is also one of the world's largest producers of metals such as uranium, iron, steel, copper, zinc and aluminium. These resources form the basis for the country's most important economic sectors. The country's dependence on raw materials has led to considerable economic growth in the past, but also harbours the risk of fluctuations in global market prices (Kazenergy Association 2021; Global Factor International Consulting 2024).

3.1.1 Important economic sectors

The most important economic sectors are briefly described in the following.

Extraction of fossil energy resources (coal, crude oil, natural gas)

Kazakhstan is rich in fossil fuels and is one of the world's leading producers of coal and oil. The extraction of these energy resources is an important economic sector and contributes significantly to value creation. The energy sources extracted are used both to meet domestic demand and for export. In 2020, oil production accounted for 54.9 % of total energy production, followed by coal with 27.9 % and natural gas with 16.6 %. In 2020, 31% of total final energy consumption was covered by oil, followed by coal with 22%. The export of oil and gas makes a significant contribution to government revenue (IEA 2022a).

The extraction of fossil fuels creates jobs in various sectors, from exploration to transport (Handrich et al. 2023). The extraction and utilization of these energy products also contribute to the country's high CO_2 emissions (IEA 2022a).

Mining for metallic and non-metallic minerals

In addition to fossil fuels, Kazakhstan has rich deposits of metallic and non-metallic minerals. The mining of minerals such as iron, copper, zinc and aluminium contributes significantly to gross domestic product (GDP). In 2024, Kazakhstan was among the top 20 countries in terms of proven reserves of various minerals.

Mining for metallic and non-metallic minerals provides jobs in the mining areas and in further processing (Global Factor International Consulting 2024). These minerals are raw materials for various industries, including the metal industry, the construction industry and the chemical industry.

Metal industry

The metal industry, especially iron and steel production, is a mainstay of the Kazakh economy. Kazakhstan is a major exporter of metals and metal products. The metal industry is an important exporter and thus contributes to

GDP. In 2022, metallurgy generated over 9 trillion KZT.

The metal industry provides jobs in production, but also in upstream and downstream areas such as mining and logistics. The metallurgy sector is responsible for around 26% of total industrial production in Kazakhstan (Government of the Republic of Kazakhstan 2023) and supplies important materials for the construction industry, mechanical engineering and other industries.

Energy sector

Fossil fuels are the most important source of energy for power generation, heat supply and the transport sector in Kazakhstan. Kazakhstan has large and easily exploitable coal reserves. Coal is therefore the country's most important source of energy and accounts for around 50 % of the total energy supply and over 20 % of final energy consumption.

The electricity industry, which is responsible for the generation and distribution of electricity, ensures the energy supply for the entire economy and is therefore an important factor for economic growth. Coal-fired power plants account for around 57 % of total installed electricity generation capacity, while gas-fired power plants account for around 25 %. Over 70 % of electricity is generated using coal (IEA 2022a). Hydropower contributes about 10% to electricity generation, while variable renewables provided about 5% of electricity in the year 2023 (Agora Energiewende 2024).

Agriculture

Agriculture plays an important role in the economy and contributes to the food security of the country and the Central Asia region. Kazakhstan is a major producer of grain and other agricultural products and ranked 9th in the world ranking of wheat exporters in 2020 (Government of the Republic of Kazakhstan 2024).

Other industries

In addition to the sectors already mentioned, Kazakhstan has a large number of other economic sectors that contribute to GDP and employment. These include the food industry, the chemical industry, oil refining, rubber and plastics production and the construction industry.

3.1.2 Challenges for sustainable development

The Kazakh economy is facing various challenges for its sustainable development. The impact of mining on the environment is a major concern. The vast availability of domestic fossil fuels as well as the favourable prices of fossil fuels domestically make it difficult to deviate from traditional energy sources and heavy reliance on coal for power generation leads to high CO_2 emissions (IEA 2020b; Global Factor International Consulting 2024).

Kazakhstan's dependence on commodity exports also makes it vulnerable to price fluctuations on the global markets (Kazenergy Association 2021; 2023). Diversification of the economy is crucial for long-term, stable growth. The government is endeavouring to diversify the economy and promote new sectors such as renewable energy, tourism and information technology (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan 2022; IEA 2022a).

But Kazakhstan's energy infrastructure is outdated and geared towards the use of fossil fuels. It needs modernisation to increase efficiency and enable the transition to renewable energies (Agora Energiewende 2024). The modernisation of the electricity grid and the expansion of renewable energies require considerable investment (Government of the Republic of Kazakhstan 2024; Kazenergy Association 2023). But there is limited access to funding and financing decarbonisation projects is a major challenge, especially for small and medium-sized enterprises (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan 2022). Currently, there are inadequate political and regulatory framework conditions and a lack of clear political guidelines and incentives for the decarbonisation of the economy (Kazenergy Association 2021) as well as a lack of awareness and commitment to decarbonisation among stakeholders, including the public, industry and policy makers (Global Factor International Consulting 2024).

3.1.3 Opportunities for sustainable development

The possibilities of transforming the Kazakh economy by climate-neutral economic growth are supported by its great potential for wind and solar energy. Due to its great renewables conditions, Kazakhstan also has the potential to become a major producer of green hydrogen. The use of green hydrogen could drive the decarbonisation of industry and the transport sector (Kazenergy Association 2023; Tleubergenova et al. 2023). The development of a green hydrogen industry would reduce Kazakhstan's dependence on fossil fuels and create new industries and jobs in the fields of renewable energy, electrolysis, hydrogen transport and storage. Kazakhstan, being located between Europe and Asia could benefit from increasing demand for clean energy in these regions by exporting green hydrogen to these countries.

Kazakhstan also has great potential for the geological storage of CO_2, particularly in the Precaspian Basin, as well as in the Mangyshlak, South Torgay and Ustyurt basins. The well-developed infrastructure of the oil and gas industry in these regions offers favourable conditions for the implementation of CCS projects (Abuov et al. 2020).

3.2 The Kazakh steel and aluminium industries

Metallurgy accounts for 43% of total manufacturing production and is therefore of great economic importance. Metallurgy, in particular the iron and steel industry, is also one of the largest CO_2 emitters in Kazakhstan's industrial sector. In terms of greenhouse gas emissions, metallurgy contributes 58% of emissions from industrial processes and product use (Global Factor International Consulting 2024).

Metallurgical processes are inherently energy-intensive as they require high temperatures and pressures. But the high energy consumption and CO_2 emissions of metallurgy are due to several additional factors (Government of the Republic of Kazakhstan 2024): a large proportion of metallurgy plants in Kazakhstan are outdated and energy inefficient and the share of renewable energies in the energy mix of metallurgy is still low. So far, there is a lack of experience and expertise in implementing measures to reduce CO_2 emissions.

The increasing demand for low-carbon metals and metal products on international markets requires adaptation to new rules and standards. Kazakhstan's metallurgical companies must reduce their emissions and introduce cleaner processes in order to remain competitive on the international markets (Government of the Republic of Kazakhstan 2023; Kazenergy Association 2023).

3.2.1 Iron and steel

In Kazakhstan, today's steel production is split between two steel mills, an integrated blast furnace-basic oxygen furnace (BF-BOF) steel mill operated by *QIC Qarmet* in Temirtau with a capacity of 6 Mtpa and an electric arc furnace (EAF) based steel mill operated by *KSP Steel* in Pavlodar with a capacity of 0.8 Mtpa (Global Energy Monitor 2023). However, total crude steel production in 2023 only reached about 4 Mtpa as one out of three BOFs at the *Qarmet* steel mill were undergoing major overhauls at that time[18]. But with the completion of these maintenance works in the first half of 2024, production is expected to return to up to 5 Mtpa. In addition, two new BF-based steel plants were announced in the Aktobe region with a total capacity of 1.4 Mtpa of crude steel and one plant for direct reduced iron (DRI) with a capacity of 0.3 Mtpa of DRI or 1 Mtpa of crude steel[19]. However, these plants are still not operational and it is unclear if and when they will produce their first steel. Furthermore, there are plans from the *Eurasian Resources Group (ERG)* to implement a hot briquetted iron (HBI) plant dedicated to exports that is expected to produce 2 Mtpa of HBI by 2026 in a first stage and additional 2 Mtpa by 2028[20].

3.2.2 Aluminium

Kazakhstan's aluminium industry today is focused only on the primary production of aluminium and consists of a fully integrated enterprise[21] in the region of Pavlodar, divided into *Aluminium of Kazakhstan JSC* and *Kazakhstan Aluminium Smelter JSC*, with an annual capacity of 1.4 Mtpa and 0.25 Mtpa of alumina and aluminium respectively[22], 90 % of which is exported to target markets including Russia, Belarus, Ukraine, Uzbekistan, Kazakhstan and other CIS[23] countries. In 2022, Türkiye, Italy, and Greece were the top three destinations for Kazakhstan's aluminium exports. The Kazakh aluminium industry is, however, not only aimed at producing finished aluminium products, but also at exporting raw materials or intermediates such as bauxite or alumina, with an annual mining production of 4.3 Mtpa bauxite in 2023[24]. The expansion of sales into new markets such as Belarus, Bulgaria, Italy, and Poland bolstered Kazakhstan's export growth. In 2023, the country ranked 12th in the world for bauxite reserves with 365 Mt, and 10th for mine bauxite production with 4.3 Mtpa (Deloitte 2021).

Recycling of aluminium scrap is currently only done by adding some shares to the primary production route, but not through dedicated secondary scrap smelting. As far as the authors are aware, there are no definite plans to exceed capacity, either secondary or primary.

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[18] https://gmk.center/en/news/kazakhstans-qarmet-shuts-down-converter-1-for-overhaul/

[19] https://2024.minexasia.com/kazakhstan-announces-major-industrial-projects-to-boost-metal-production/

[20] https://gmk.center/en/news/erg-will-jointly-develop-hbi-production-in-kazakhstan-with-baowu/

[21] Eurasian Resources Group (ERG) Kazakhstan – Aluminium department

[22] https://www.eurasianresources.lu.

[23] The Commonwealth of Independent States (CIS) is a loose political and economic union of former Soviet republics. The current member states of the CIS are: Armenia, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan and Uzbekistan. Georgia, Turkmenistan and Ukraine are not official members, but have participated in some CIS activities in the past.

[24] https://de.statista.com/statistik/daten/studie/386942/umfrage/minenproduktion-von-bauxit-in-kasachstan/

3.3 Kazakhstan's climate neutrality strategy

Kazakhstan has set itself the goal of achieving a climate-neutral economy by 2060. This goal is enshrined in the "Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan by 2060", which was approved by Decree of the President of the Republic of Kazakhstan No. 121 of 2 February 2023. The strategy includes ambitious targets, such as reducing the energy intensity of GDP by 50 % by 2050 (compared to 2008) and the medium-term target to reduce greenhouse gas emissions by 15 % by 2030 compared to 1990 levels. The latter target can be increased to 25 % under certain conditions, such as international support. This ambitious strategy requires far-reaching changes in all sectors of the economy (Government of the Republic of Kazakhstan 2023).

The strategy is based on the principles of responsible implementation, scientific basis, transparency and participation as well as gradual implementation. It includes sectoral strategies for energy, industry, agriculture and waste management as well as overarching measures that affect all sectors.

Key measures of the strategy include:

- the promotion of renewable energy and moving away from fossil fuels. By 2050, the share of renewable energies in electricity generation should reach 50%.
- reducing energy consumption by increasing energy efficiency in all sectors, particularly in energy-intensive metallurgy. The aim is to significantly reduce energy consumption per unit of GDP (energy intensity).
- development of a hydrogen economy
- carbon capture and storage (CCS)
- reducing waste and promoting recycling in an increasingly circular economy
- measures to increase carbon sequestration in soils and forests
- promote technology transfer in the field of decarbonisation through international cooperation.

The following measures in particular are recommended for the steel and aluminium industry (Global Factor International Consulting 2024):

- Transition to low-emission production processes: The strategy envisages gradually replacing the traditional blast furnace-converter route with direct reduction processes using natural gas and later hydrogen.
- Electric arc furnaces powered by renewable electricity
- The use of steel scrap in electric arc furnaces
- The use of inert anodes instead of carbon anodes for aluminium electrolysis.

3.4 Availability of resources for low-CO_2 metals production

3.4.1 Renewables-based electricity

Electricity plays a central role in the energy transition and the decarbonisation of all sectors of the economy. Modernising the electricity generation sector by phasing out coal and expanding renewable energies is therefore of the utmost importance. The share of variable renewable energies (wind, solar) in the country's energy mix reached five per cent by 2023 (Agora Energiewende 2024). The government plans to increase the share of variable renewable energy in electricity generation to 15 per cent by 2030 and 50 per cent by 2050 (Government of the Republic of Kazakhstan 2023).

The potentials for renewables are considered being substantial (IEA 2022a). For example, IRENA (2024) suggests that about 20% of the land surface of Kazakhstan features good conditions for wind energy with a wind power density at 100m height of 420 W/m² or higher. These areas are distributed across large parts of the country, in particular the south-western area at the Caspian Sea and in the norther region.[25] Also Kazakhstan potential for solar energy is considerable, with the most favourable conditions being in the southern part of the country (IEA 2022a).

Challenges for upscaling renewables include technical aspects, in particular the limited capacity of the grid to integrate fluctuating electricity generation. The integration of new technologies such as smart grids and energy storage is thus essential to ensure the reliability and flexibility of the electricity system as the share of renewable energies increases (IEA 2022a). From an economic perspective, the high upfront investment costs for renewables and existing tariffs that do not fully reflect costs of fossil-based electricity generation constitute barriers for investments in renewables capacity (Agora Energiewende 2024).

3.4.2 Hydrogen

The country's large wind and solar energy potential could be utilised for the cost-effective production of green hydrogen. The vast, sparsely populated areas of Kazakhstan offer sufficient space for large-scale wind and solar parks, which are needed for the production of green hydrogen on an industrial scale. Kazakhstan is also rich in critical raw materials that are essential for the production of electrolysers, wind turbines and solar modules. This reduces dependence on imports and strengthens the domestic value chain. The development of a green hydrogen industry would reduce Kazakhstan's dependence on fossil fuels and create new industries and jobs in the fields of renewable energy, electrolysis, hydrogen transport and storage. The metalworking industry in particular could benefit greatly from the use of green hydrogen for the production of sustainable steel (Tleubergenova et al. 2023; Kazenergy Association 2021).

Technical challenges include, however, the development of an efficient and cost-effective hydrogen infrastructure that includes transport, storage and distribution – although Kazakhstan's well-developed oil and gas infrastructure, including pipelines and transport networks, could be partially adapted for the transport of hydrogen. Economically, the competitiveness of green hydrogen against fossil fuels must be ensured, which can be achieved through government policies (Kazenergy Association 2023; Tleubergenova et al. 2023). Kazakhstan has developed a series of strategies and initiatives with the objective of leveraging the potential of green hydrogen and establishing a sustainable hydrogen economy. International cooperation with countries that already have experience in hydrogen technology can accelerate technology transfer and the development of industry standards and eventually the development of the hydrogen economy in Kazakhstan (Government of the Republic of Kazakhstan 2023; IEA 2020b).

The production of green hydrogen through electrolysis consumes large quantities of water, which could put additional pressure on water resources. Kazakhstan is a dry country with an average observed annual precipitation of about 250 mm (World Bank Group 2021)[26] and fundamentally affected by water scarcity. The

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[25] https://globalwindatlas.info/en/area/Kazakhstan

[26] For comparison: Germany has an average annual precipitation of about 750 mm (World Bank Group 2021)

total volume of surface water resources in Kazakhstan (excluding seawater) totalled 100.9 km³ in 2020, of which 54.5 km³ was produced domestically. The other half (46.4 km³) came from river runoff from the neighbouring countries of China, Uzbekistan, Russia and Kyrgyzstan. The largest consumer of water is agriculture, which accounts for more than 62.5 % (15.4 km³) of total water withdrawal. Water consumption by industry (mainly heat generation, metals and oil and gas) and water consumption by households account for 23.7 % (5.9 km³) and 3.9 % (0.96 km³) respectively. Water consumption in Kazakhstan is expected to increase by 56 % by 2040 (Government of the Republic of Kazakhstan 2024; Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan 2022; Tleubergenova et al. 2023). Kazakhstan's water resources are not evenly distributed across the regions. There are eight water basins in the country with varying water availability: Aral-Syrdarya, Balkhash-Alakol, Ertis, Yesil, Zhaik-Caspian Sea, Nura-Sarysu, Tobyl-Torgay and Shu-Talas. The Ertis, Nura-Sarysu and Balkhash-Alakol basins currently have no problems with water shortages. The other basins have water deficits in groundwater and surface water. The western and southern regions of Kazakhstan are particularly affected by water shortages. The three large lakes in Kazakhstan - the Caspian Sea, the Aral Sea and the Balkhash Sea - are all transboundary watercourses. The Aral Sea is the most severely affected by water stress. To a lesser extent, the Caspian Sea has also been affected by water scarcity recently (Tleubergenova et al. 2023).

It is estimated that the production of 2-10 million tonnes of green hydrogen would require an amount of water equivalent to 0.6-3% of current industrial water consumption in Kazakhstan (0.036-0.18 km³ per year). This would put additional pressure on already scarce water resources and could lead to conflicts with other water users, especially agriculture. Utilising the Caspian Sea and Lake Balkhash as potential water resources for green hydrogen production would require a reduction in water consumption by industries that rely on the watercourses that feed these two lakes (Tleubergenova et al. 2023). The quality of water resources is also an important factor. Pollution of water sources from industrial activities and inadequate wastewater treatment can limit the availability of water for the production of green hydrogen (Global Factor International Consulting 2024).

Besides its potential impacts on water scarcity, large scale hydrogen production may also have environmental impacts that require consideration. For example, the planned construction of large wind energy capacities for hydrogen production at the Caspian Sea raises concerns among civil society organizations about high risks to biodiversity, particularly migratory birds.

3.4.3 Natural gas

Natural gas can play a key role in Kazakhstan as a transitional energy source on the path to climate neutrality. It is seen as a bridging energy to reduce coal dependence while ensuring energy security (Government of the Republic of Kazakhstan 2023; Kazenergy Association, 2021, 2023). Natural gas is currently available primarily in the western and southern part of the country. The expansion of gas infrastructure, particularly in the area of gas pipelines, is necessary to ensure security of supply throughout the country (IEA 2020b).

3.4.4 Biomass

According to IRENA (2024), the net primary production of biomass, measured as tC/ha/yr, is low in Kazakhstan, compared to the global average. Nevertheless, Handrich et al. (2023) see potential for (additional) heat and electricity production from biomass, mainly from agricultural wastes such as animal manure and crop residues that are used for biogas production. Such a decentralized use of agricultural wastes for biogas production is, however, of limited relevance to the steel and aluminium industries, which require large amounts of energy which is constantly provided. Other forms of biomass would be required, such as wood chips and biochar (Global Factor International Consulting 2024). To the authors knowledge there exists no data on the domestic potential of biomass for the Kazakh metals sector.

3.4.5 CO_2 storage (CCS)

The assessment of the CO_2 storage potential of sedimentary basins requires the consideration of various factors, including geological factors (e.g. tectonic stability, depth and thickness of the formation, porosity and permeability), technical factors (e.g. injection infrastructure and monitoring technologies) and economic factors (e.g. costs of CO_2 storage, potential for CO2-EOR, regulatory framework and public acceptance). In Kazakhstan, three main categories of CO_2 storage sites are considered (Abuov et al. 2020):

- Oil reservoirs: Storing CO2 in depleted oil reservoirs is attractive as it can improve oil production through enhanced oil recovery (CO2-EOR). Kazakhstan has significant oil deposits that could be suitable for CO2-EOR.
- Gas reservoirs: Similar to oil reservoirs, depleted gas reservoirs can also be used to store CO2, but have a lower storage capacity.
- Brine aquifers: Deep brine aquifers offer great potential for CO2 storage and account for the majority of the estimated effective CO2 storage capacity in Kazakhstan.

Abuov et al. (2020) assessed six sedimentary basins in Kazakhstan with regards to their suitability for CO_2 storage: the Pre-Caspian Basin, the Mangyshlak Basin, the South Torgay Basin, the Ustyurt Basin, the Chu-Sarysu Basin and the Zaysan Basin. The Pre-Caspian Basin is considered the most promising location for geological CO_2 storage in Kazakhstan. It is characterised by stable tectonics, deep-seated faults in the subsurface and good reservoir-seal pairs. The effective CO_2 storage capacity of the basin is estimated at ~462 Gt CO_2. In addition to the Pre-Caspian Basin, the Mangyshlak, South Torgay and Ustyurt basins are also categorised as suitable for CO_2 storage. They have a well-developed oil and gas infrastructure and offer safe CO_2 storage due to their stable geology. The effective storage capacity of these four basins is estimated at approximately 539 Gt CO_2, which would be sufficient to store Kazakhstan's current annual greenhouse gas emissions for more than 1600 years.

So far, there is however a lack of complete information on CO_2 storage capacity, geological sites and other important data. The "KazCCUS" project was the first CCS-related research project in Kazakhstan investigating the country's geological CO_2 storage potential (Abuov et al. 2020). There is also no clear legal framework for CCS in Kazakhstan.

4 Assessment of decarbonization options for steel and aluminium in the Kazakh context

4.1 Steel

The assessment of decarbonization options for steel in the Kazakh context is based on the descriptions of the technologies (section 1) and the Kazakh context (section 1) and conducted by taking multiple perspectives: availability of resources for steelmaking, a spatial perspective on resource distribution in the country, CO_2 emissions, and production costs. Based on these, conclusions are drawn.

4.1.1 Availability of resources for steel making

The general availability of resources for steel production in Kazakhstan is assessed based on the analysis of the Kazakh context in section 4 and summarized in Figure 4-1.

While Kazakhstan has rich iron ore reserves the iron ore is typically of lower grade and thus requires beneficiation for steel routes that require high-grade iron ore (source: stakeholder interviews). Scrap is available to some extent but based on today's low steel consumption per capita it is not expected that sufficient amounts of scrap will be available in the future to cover large shares of steel production by secondary steel (source: stakeholder interviews). Secondary steel making is therefore excluded from the further analysis.

Figure 4-1: Availability of resources for steel production in Kazakhstan

Resource	**Potential**	**Comment**
Iron ore	🟩	Good availability
Iron ore (high grade)	🟨	Need for enrichment of low quality ores
Scrap	🟨	Low steel consumption per capita
Coal	🟩	Abundant availability
Natural gas	🟨	In some regions only (mostly south / west)
Green electricity	🟩	High potential for wind and solar
Green Hydrogen	🟨	Local water availability might be limited
Biomass	🟥	Low potential
CO2 storage	🟨	Further exploration and geological data required

Source: own figure

Coal is abundant and cheap in Kazakhstan, while natural gas is available in some regions only. This will be discussed further below in the spatial analysis. Kazakhstan has high potentials for wind and solar energy. The current production capacity is, however, low (2900 MW)[27] and implementation of large renewable energy projects would be required to satisfy the electricity needs of future renewables-based steel making. The high renewables potentials provide a strong basis for domestic hydrogen production. But the availability of water for hydrogen production requires further scrutinization because Kazakhstan is a country with water scarcity in many regions (see section 3.4.2). The water demand to produce hydrogen for 5 Mt DRI-H$_2$ is 0.01 km^3 of water (own calculation based on data from section 2), which is 0.15% of Kazakhstan's current industrial water demand of 5.9 km^3, according to Tleubergenova et al. (2023). This rough calculation suggests that water availability for hydrogen production at the magnitude of presumably required hydrogen of a future Kazakh steel industry is probably not critical in absolute terms. But local water availability may require consideration when planning hydrogen projects. Kazakhstan has a low potential for biomass compared to the global average. Furthermore, biomass does not play a major role in the Kazakh decarbonization strategy (Government of the Republic of Kazakhstan 2023). For these reasons, biomass-based steel routes are excluded from the further analysis. Finally, there are promising sites for CO$_2$ storage in Kazakhstan but their exploration is at an early stage and their potential use for the steel industry requires a spatial analysis (see below).

4.1.2 Spatial perspective on resource availability

The spatial distribution of resources in Kazakhstan is largely uneven. As Kazakhstan is a large country – stretching some 3,000 km from west to east and some 1,600 km from north to south – distances between resource sources and uses and the associated transport costs are important. Hence, the spatial distribution of resources requires consideration.

Figure 4-2 shows the locations of the current primary steel site, of iron ore mining regions, natural gas pipelines, potential CO$_2$ storage basins and water basins that have no water deficit.

The map shows that there is a „sweet-spot“ for DRI-NG in the North-West (Rudny), where both iron ore and natural gas is available. This is exactly the location at which ERG currently plans to build-up a DRI production with natural gas, which is expected to be finished by 2028. The current plans focus on export of the DRI (in the form of HBI), but in principle DRI could also be produced for and transported to a domestic steel production site. DRI-NG could also become feasible at the current primary steel plant in Temirtau in the future. Currently, only very limited amounts of natural gas are available in Temirtau for industry from the Saryarka pipeline which delivers natural gas from the south-western region to the north-east and these amounts are not sufficient for DRI production (source: stakeholder interview). An extension of the Saryarka pipeline is planned for 2028–2030[28] which may allow DRI-NG production in Temirtau in the mid- and long-term. Finally, DRI-NG could also be produced in the western

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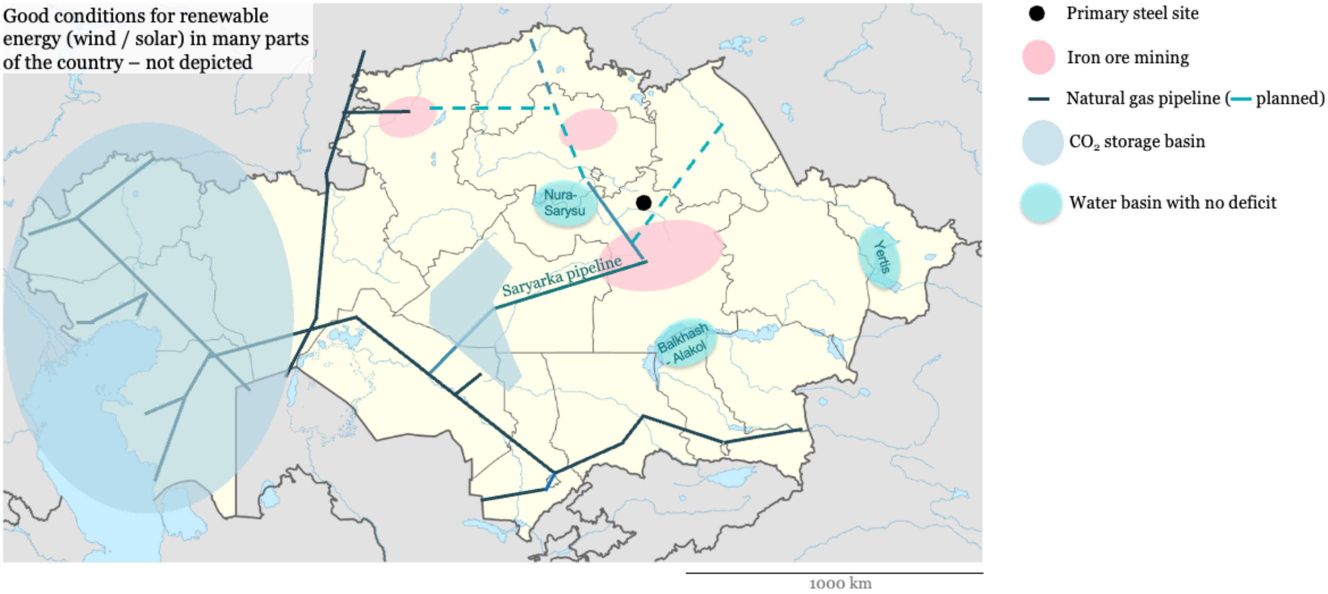
[27] https://qazaqgreen.com/en/map/

[28] https://www.gem.wiki/Saryarka_Gas_Pipeline#:~:text=The%20estimated%20completion%20date%20for,pipeline%20was%20also%20being%20considered.

region at the Caspian Sea. This would require transport of iron ore as well as building-up DRI capacities in that region. An advantage of this region over the other two options could be the potential for combining DRI-NG with CCS with short CO_2 transport distances – if the suitability of storage sites in that region can be confirmed.

Figure 4-2: Spatial distribution of resources for iron and steel production in Kazakhstan.



Source: own figure based on map by NordNordWest, Licence: Creative Commons by-sa-3.0 de. Data on natural gas pipelines taken from IEA (2022a) and https://www.eurasian-research.org/publication/natural-gas-industry-of-kazakhstan-key-features-and-future-prospects/; Data on CO2 storage basins from Abuov et al. (2020); Data on water basins from Tleubergenova et al. (2023)

Given good renewables conditions in many parts of the country including the northern region the production of DRI-H_2 may be possible in spatial proximity to iron ore mining sites, if local water availability allows. The map shows that there is no obvious overlap between water basins with comparably good water availability and iron ore mining activities. But an in-depth spatial analysis of water availability was beyond the scope of the *DeKaMe* project and hence further research will be required to assess the (local) potentials of DRI-H_2 in Kazakhstan from a water availability perspective. If local water scarcity prevents hydrogen production in spatial proximity of iron reduction sites, transportation of hydrogen would become necessary. A large-scale production of DRI-H_2 for an exemplary 5 Mtpa of crude steel would require 11.5 TWh of hydrogen. Transportation of such amounts of hydrogen over longer distances onshore requires pipeline construction and is costly due to transportation losses.

Electrolysis could be done close to iron ore mining or at the current steel production site, if sufficient capacities for (renewables-based) electricity production are built up.

CO_2 storage capacities that could be used for BF-BOF+CCS or DRI-NG+CCS are available in the western part and in the middle of the country, with distance of several hundred up to two thousand kilometres from current iron ore mining and steel production sites. A large-scale application of CCS for DRI or steel production would require the transportation of around

1.7 – 8 Mt CO_2 per year.[29] The transportation of such amounts of CO_2 over long distances would require the build-up of CO_2 pipelines, which would come with high costs and presumably long planning and construction times. However, other CO_2 sources in Kazakhstan may use CCS in the future as well, which may allow pooling of CO_2 transport and the use of pipelines by several emitters. For example, the "carbon neutral" scenario of the Kazakh decarbonization strategy envisions the application of CCS at the scale of about 30 Mt by 2050, across all sectors. Application of CCS in the iron and steel industry must thus be assessed in the context of a broader CCS-strategy in order to assess its feasibility, which was beyond the scope of the *DeKaMe* project. But based on the time required for storage site exploration as well as planning and building pipelines it cannot be expected that CCS becomes available for iron and steel production within the next 10–15 years.[30]

4.1.3 Specific CO_2 emissions

In Figure 4-3 the specific CO_2 emissions of the different steel production routes described in section 2 are compared – both, scope-1 and scope-2 emissions. While scope-1 emissions include direct emissions at the steel plant (including iron reduction) only, scope-2 emissions refer to the indirect CO_2 emissions associated with the generation of electricity and hydrogen. In Figure 4-3, the specific CO_2 intensity of electricity is assumed to be the same as the yearly average reported for Kazakhstan for the year 2019 by the IEA (2022a), i.e., 516 g CO_2-eq/kWh_{el}. The emission intensity of hydrogen is calculated from that of electricity and an efficiency of electrolysers of 70%.

It becomes apparent that DRI-H_2 and Electrolysis are the only technologies that allow (almost) zero CO_2 emissions of steel production, if provided with green electricity and hydrogen (i.e. with scope-2 emissions being zero and thus equalling scope-1 emissions). At the same time, including indirect emissions from electricity / hydrogen production with an emissions intensity at the current Kazakh average level changes the assessment completely. It is therefore crucial to assess emissions of steel production in the context of electricity and hydrogen production and associated GHG emissions. Furthermore, Figure 4-3 shows that steel production routes feature similar specific CO_2 emissions if the basic technological set-up is similar. Therefore, they are grouped for the further analysis into DRI-H_2 (including DRI-H2+EAF and DRI-H_2+ESF-BOF), DRI-NG (including DRI-NG+EAF and DRI-NG+ESF-BOF), DRI-NG+CCS (including DRI-NG+EAF+CCS and DRI-NG+SAF/BOF+CCS) and Electrolysis (including AEL-EAF and MOE).

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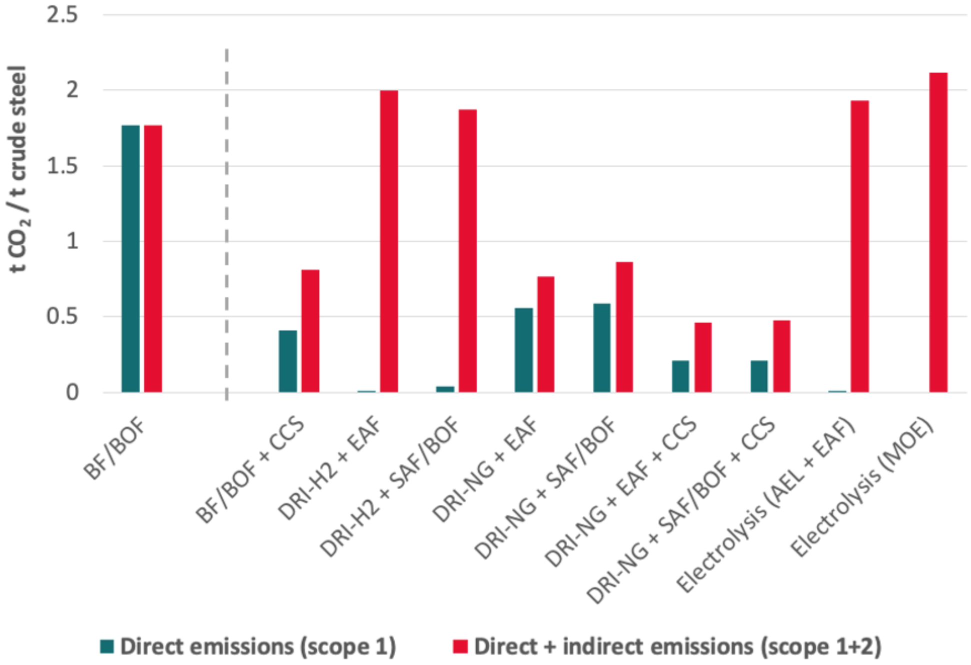
[29] Assuming the production of about 5 Mt of DRI-NG or BF/BOF steel with CCS, respectively.

[30] It should be noted that the Kazakh decarbonization strategy envisions the application of CCS at the scale of >50 Mt by 2040 (and decreasing afterwards). If the build-up of these capacities can be achieved in the envisioned time-frame the availability of CCS for the iron and steel industry may be less restricted than assessed by us, the authors.

Figure 4-3: Specific CO_2 emissions of steel production routes (scope-1 and scope-2)



Source: own figure

Figure 4-4: Scope 1+2 emissions of steel production routes for different electricity emission intensities over time.

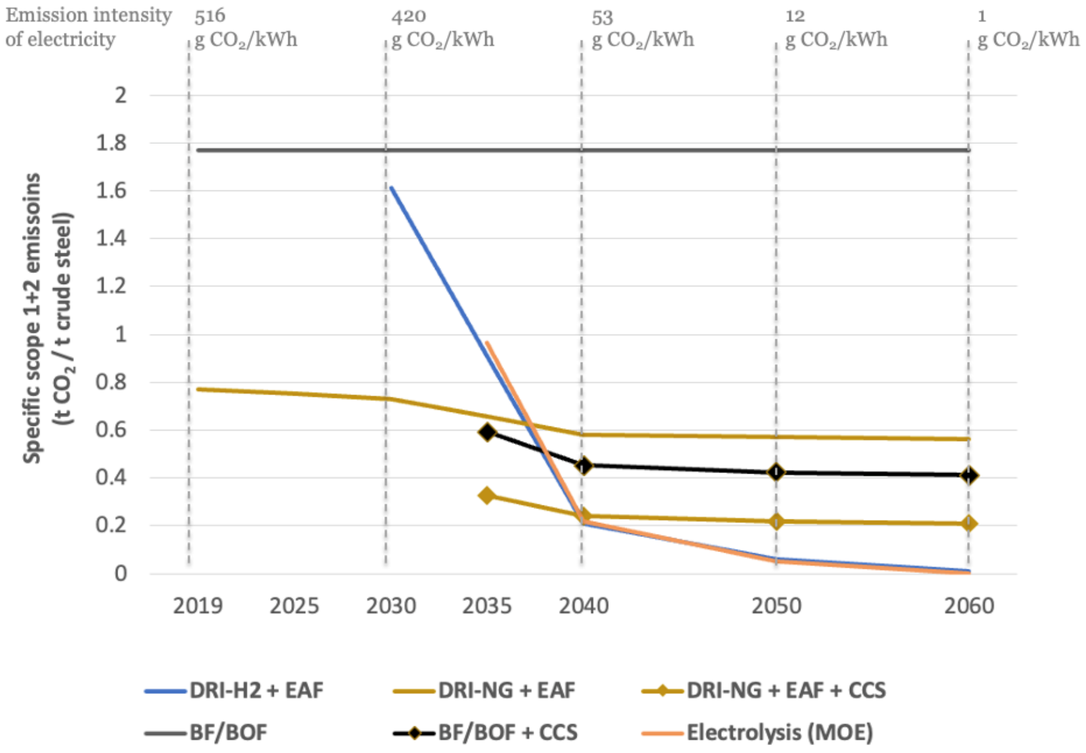


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Figure 4-4 illustrates the change of scope 1+2 emissions with varying emission intensities of electricity and when assuming that the emission intensity of hydrogen changes in line with that of electricity. In Figure 4-4, the emission intensity of electricity is connected to a timeline, based on an approximation of the average emissions intensity of the Kazakh electricity sector according to the carbon neutral scenario of the Kazakh decarbonization strategy (own calculation). Steel production technologies are included in the figure only from their earliest expected (market) availability onwards. The figure shows that all innovative technologies considerably reduce scope 1+2 emissions compared to the conventional BF-BOF-route at or very soon after their market introduction and from 2040 onwards reduce steel related CO_2 emissions to one third or less of the conventional route, if low-carbon electricity for steel can be upscaled at the pace envisioned in the carbon neutral scenario of the Kazakh decarbonization strategy.

4.1.4 Costs

Costs for low-CO_2 primary steel production are significantly higher than those of conventional primary steel production, as illustrated in Figure 4-5. Considering uncertainties related to major cost factors such as electricity, hydrogen and CO_2 transport and storage costs it can be observed that production costs of low-CO_2 routes are in a similar range – except DRI-H_2 steel production, which is more expensive. It becomes apparent that low-CO_2 steel production requires policy support – such as a CO_2 price – to be economically viable, also in the long-term. More ambitious climate targets and a significant CO_2 price that increases over time could change the price relation between options in the future. Table 4-1 lists the core cost assumptions used for the calculations.

Figure 4-5: Primary steel production costs for various routes over time.

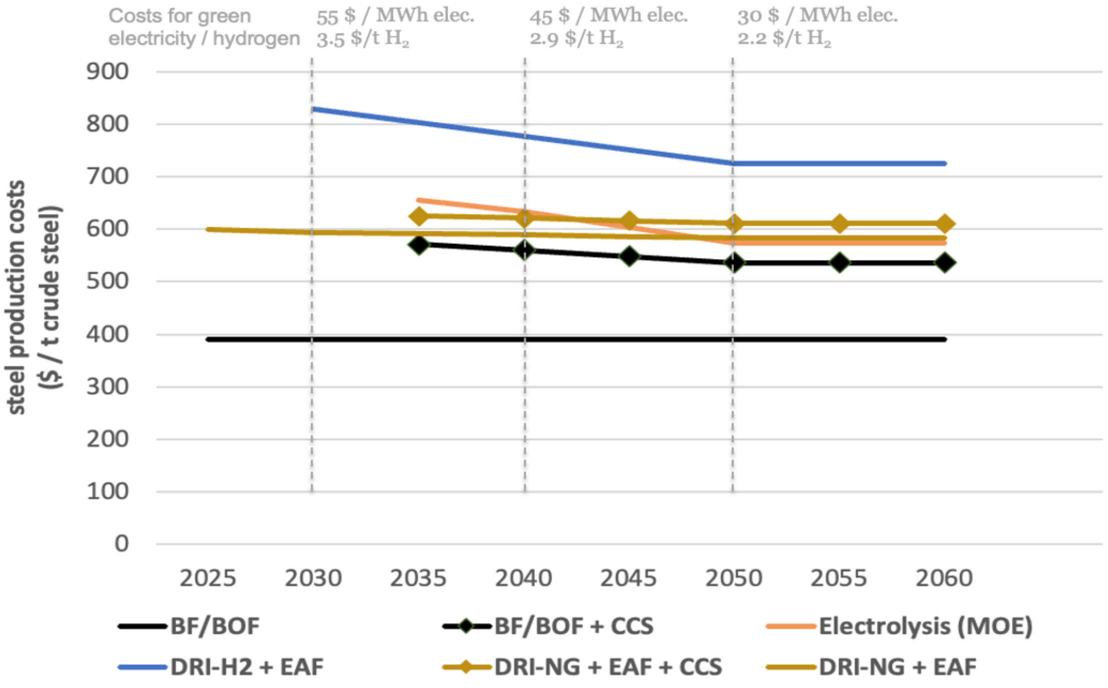

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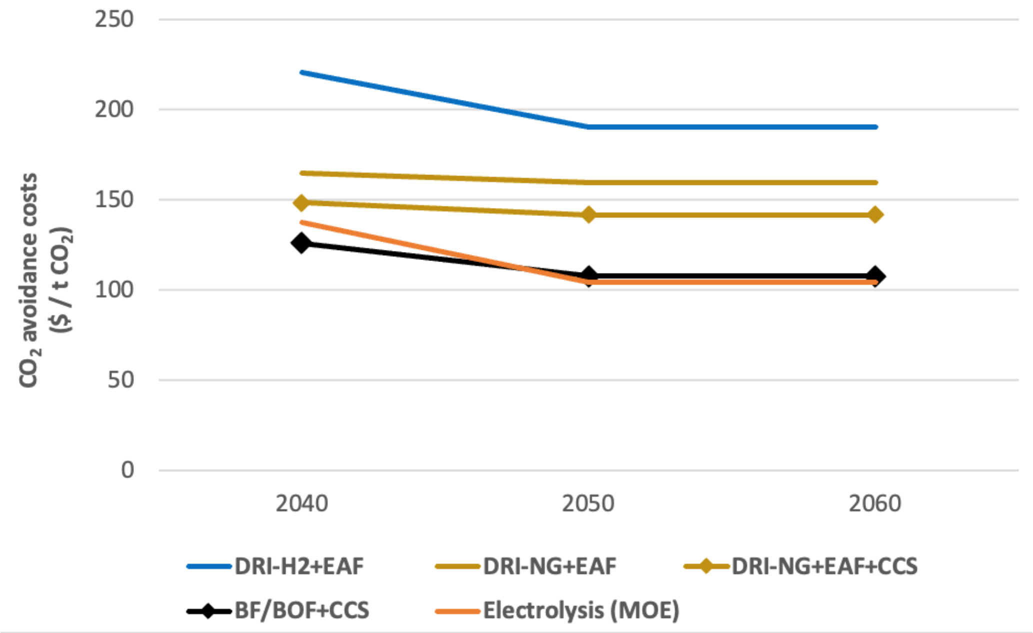
Table 4-1: Core cost parameters used in the calculations

	Unit	2030	2040	2050	2060	Sources
Electricity	\$/MWh	55	45	30	30	Own calculations based on Agora Energiewende[31] and Fraunhofer IEE[32]
Hydrogen	\$/kg	3.5	2.9	2.2	2.2	
CO_2 transport and storage	\$/t CO_2	70	60	50	50	Own assumption
Natural gas	\$/GJ	1.7 (all years)				Own calculation based on Bureau of QazStat (2024)
Coal	\$/GJ	0.75 (all years)				

Figure 4-6: CO_2 avoidance costs of steel production routes over time



Source: own figure

Figure 4-6 shows the CO_2 reduction associated with the different routes in relation to their additional production costs, expressed in terms of the cost of avoiding CO_2 emissions. BF/BOF+CCS and electrolysis[33] feature the lowest CO_2 avoidance costs while DRI-H_2 is the most expensive option.

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[31] https://www.agora-energiewende.org/data-tools/ptx-business-opportunity-analyser-1#top

[32] https://maps.iee.fraunhofer.de/ptx-atlas/#user

[33] It should be noted that electrolysis is at an early stage of development and therefore technological and cost parameters include a high level of uncertainty.

4.1.5 Conclusions for steel

The above analysis does not lead to clear-cut conclusions on a selection of "best" future primary steel production routes for Kazakhstan.

DRI-NG is the technically most advanced and most cost-effective option for significant near-term (before 2035) CO_2 reduction and all major requirements for implementation at the current "sweet spot" for DRI-NG in Rudny are fulfilled. The processing of DRI into steel would require additional investments in an electric arc furnace or – if steel making would take place at the existing primary steel site in Temirtau – an electric smelter to melt the DRI for further processing in the BOF. However, for achieving near-zero steel production in the longer term while further utilizing invested capital, a "second step" is required which could be either a switch from DRI-NG to DRI-H_2 or to DRI-NG in combination with CCS. It is currently unclear which of these options will be available in Rudny (or Temirtau) in the future. Studies on local water availability for hydrogen production as well as exploration of geological sites for CO_2 storage and CO_2 infrastructure planning are required.

BF-BOF+CCS is – according to the above calculations and underlying cost assumptions – a comparably low-cost option that allows significant CO_2 reduction compared to the conventional unabated route. However, it has higher remaining emissions compared to the other low-CO_2 routes (except DRI-NG) and it should be noted that potential costs associated with these emissions have not been included in the production cost calculations. Moreover, the feasibility of BF-BOF+CCS (at the current primary steel site in Temirtau) hinges on the feasibility and implementation of a large-scale CCS-infrastructure in Kazakhstan that would connect iron and steel production sites to storage sites, for which (to the authors' knowledge) no detailed planning exists, yet.

Similarly, DRI-NG+CCS has higher remaining emissions, compared to renewables-based steel making (DRI-H_2, Electrolysis) and its feasibility hinges on the implementation of a large-scale CCS-infrastructure. However, if CCS becomes feasible, DRI-NG+CCS could be a second step building on near-term implementation of DRI-NG – in particular in case that DRI-H_2 turns out to be too costly or unfeasible due to water scarcity.

DRI-H_2 allows near-zero emissions steel production and is more advanced technologically than Electrolysis (which is the other near-zero option). Renewable potentials for producing hydrogen for DRI-H_2 are high in Kazakhstan. But local water scarcity might be an issue for realizing large-scale hydrogen production in spatial proximity of iron ore reduction sites. Therefore, the feasibility of DRI-H_2 might depend on the construction of a hydrogen grid. Moreover, based on the above calculations, DRI-H_2 apparently is the most expensive near-zero option, both with regards to steel production costs as well as CO_2 avoidance costs, even without considering hydrogen transportation costs.

Electrolysis also allows near-zero emissions steel production but has a comparably low TRL and is associated with uncertainties regarding its capabilities and technological characteristics. If the above made assumptions on technological parameters and costs are confirmed in the future, electrolysis would be the option that allows near-zero emissions at lowest CO_2 avoidance costs.

In sum, there are various potential routes towards low-CO_2 primary steel production in Kazakhstan. Which option is best, depends on aspects that require further investigation: hydrogen availability and costs at iron and steel making sites, availability of CO_2 infrastructure and CCS costs, and the further technological development of electrolysis technologies.

All options except DRI-NG require significant amounts of additional (green) electricity, in particular DRI-H_2 and Electrolysis. Upscaling green electricity is therefore of prime importance for mitigating scope-2 emissions associated with low-CO_2 steel production.

Finally, the analysis shows that all low-CO_2 options will stay significantly more expensive than the conventional BF-BOF route, if CO_2 emissions are not charged. Therefore, policy measures are required for introducing and upscaling low-CO_2 steel production in Kazakhstan.

4.2 Aluminium

The assessment of low-CO_2 technologies for aluminium production is based on the descriptions of technologies in section 1 and the Kazakh context in section 1. Each of the technological options is discussed in turn.

4.2.1 Inert anodes

Replacing carbon anodes with other inert materials could in principle avoid process emissions from aluminium smelting, including both: CO_2 emissions and PFC's. Whether and when this option becomes technically available (and at which costs) depends on its technological development, as described in section 2.2.1. The Kazakh context does not play a decisive role for the applicability of this technology to Kazakh aluminium smelting.

4.2.2 CCS

Section 2 describes the technical characteristics of CCS at the aluminium smelter: the capture addresses the process CO_2 included in the off-gases of the smelter, but non-CO_2 GHGs –PFCs – are not captured by the technology. Assuming a 90% CO_2 capture rate for the smelter off-gases and considering the specific emissions of CO_2 and PFC's per ton of aluminium (see section 2.2.2), CCS is able to reduce GHG emissions from aluminium smelting by about 70%, only. The CO_2 concentration in the off-gas stream is very low (1 vol.%), compared to what is typically required for efficient capture (at least 4 vol.%). It can thus be expected that CO_2 capture at aluminium smelters would be very energy intensive. Moreover, it should be noted that CO_2 capture at aluminium smelters has a low TRL and it is unclear when it would be available on the market.

The permanent storage of the CO_2 requires suitable storage sites, which are not yet well explored. According to Abuov et al. (2020), promising storage sites are located in the western part of the country and in the mid region (cf. Figure 4-2). In contrast, the current aluminium smelting site is located in Pavlodar in the north-east of Kazakhstan, which is at least 1000 km away from promising CO2 storage sites. Similar to the situation for steel, continuous transportation of CO2 over such long distances requires the establishment of a CO2 transport infrastructure. Application of CCS must thus be further assessed in the context of a broader CCS-strategy in order to assess its feasibility, which was beyond the scope of the DeKaMe project.

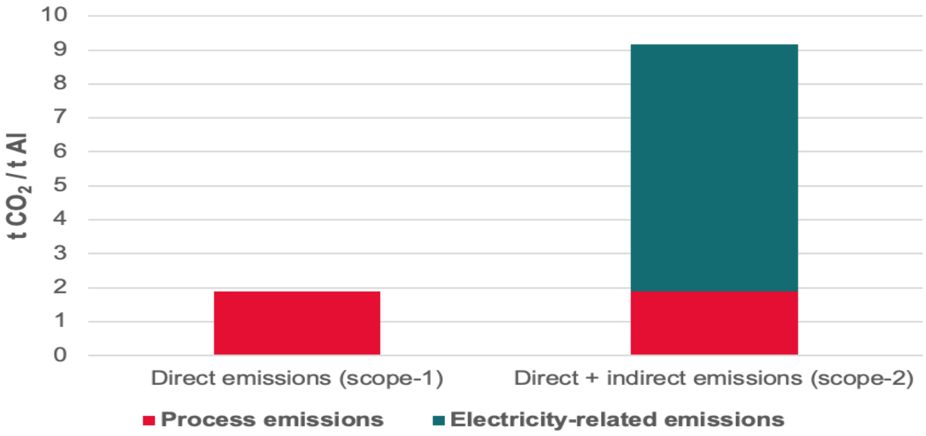
4.2.3 Use of low-CO_2 electricity

As described in section **Error! Reference source not found.**, the aluminium smelting process consumes significant amounts of electricity. Depending on how this electricity is generated, its production implies scope-2 emissions that may well be much higher than the scope-1 emissions from the aluminium production process itself.

Figure 4-7 compares the scope-1 emissions from aluminium smelting to scope-2 emissions from the generation of electricity required for the smelting process assuming an emission factor of 516 g CO_2/kWh_{el} – which reflects the average emission factor of electricity in KZ in 2019, according to IEA (2022a).

The figure shows that indirect, electricity related emissions are about four times higher than direct, process-related emissions. The provision of low-CO_2 electricity is therefore of prime importance to reduce GHG emissions related to aluminium production.

Figure 4-7: Comparison of direct and indirect emissions of the aluminium smelting process



Source: own figure

The provision of the required amount of electricity from renewable sources constitutes a considerable challenge, though. The smelting of 250 kt aluminium – which is the current yearly production in Kazakhstan – requires about 3.5 TWh electricity. Assuming good wind conditions[34] the production of such an amount of electricity by wind energy would require the installation of about 1200 MW capacity – which is almost the wind power capacity currently installed in Kazakhstan as a whole.[35]

For upscaling and using low-CO_2 electricity for aluminium smelting, it needs to be competitive to conventional, coal-based electricity. Figure 4-8 compares estimated costs for renewables-based electricity to different electricity costs in the Kazakh context, which are used as proxies for real-world electricity costs for ERG, the aluminium producing company. The figure shows that renewables-based electricity is on the verge of being competitive to the current electricity purchase costs from the grid. However, compared to producer prices – which with very high likelihood much better reflect electricity costs for large companies with own electricity generation – renewables-based electricity becomes competitive only in the very long term. It should be noted that the estimates for green electricity costs are taken from calculations for costs of hydrogen derivates. But aluminium smelting may require higher full load hours per year, compared to hydrogen

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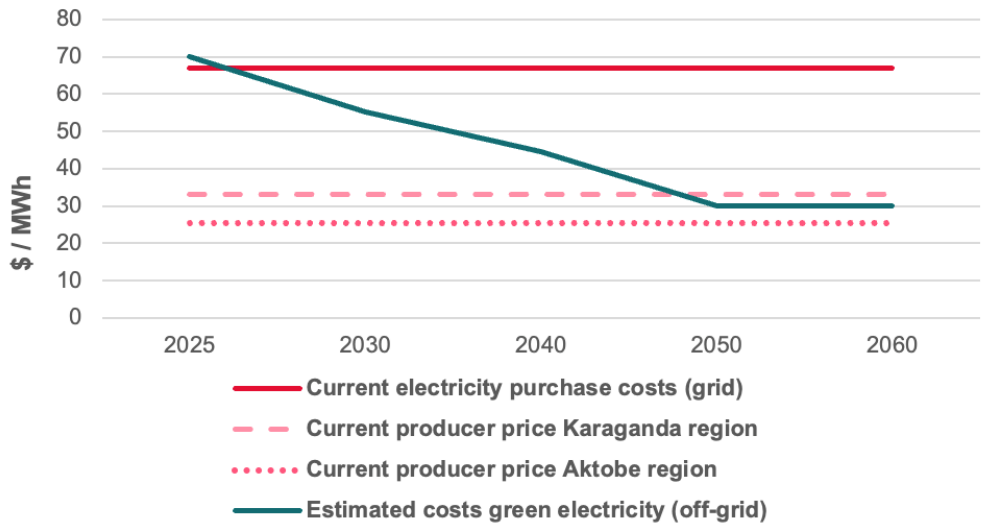
[34] For the rough calculations made here about 3000 full load hours per year were assumed.

[35] Which is 1410 MW (https://qazaqgreen.com/en/map/ ; visited in January 2025)

electrolysis.[36] This may induce higher balancing needs and thus may result in higher costs than estimated.

Figure 4-8: Comparison of electricity costs



Sources: Own figure. Data for current electricity prices / costs taken from QazStat (2024)

4.2.4 Conclusions for aluminium

In order to reduce overall GHG emissions related to aluminium production in Kazakhstan, the substitution of fossil-based electricity with renewables-based electricity is most important, because scope-2 emissions related to electricity provision are about four times higher than direct, process-related emissions. The economic viability of upscaling and using renewables-based electricity for aluminium smelting depends on local circumstances such as renewables costs compared to coal prices, and the willingness to pay for “green aluminium” in target markets and policies.

For reducing or avoiding process-related emissions from aluminium smelting, CCS or the use of inert anodes could be options in the future, but both of these options require additional research and none of them will be available for application at industrial scale in the short term. The inert anode could potentially reduce process-related emissions to zero, while CCS can reduce emissions only by about 70% and its application would be dependent on the erection of a national CO_2 infrastructure.

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[36] The flexibility of aluminium electrolysis can be improved through innovative approaches: https://www.trimet.eu/en/magazin/trimet-equips-aluminium-smelters-for-greater-sustainability

5 Funding instruments and emerging markets for low-carbon metals

The deployment of new technologies for the decarbonisation of the energy-intensive metallurgical sector often entails higher investment and operational costs than those of conventional technologies, as well as financial risks due to uncertainties about price developments and other factors. For low-CO_2 steel in Kazakhstan, for example, estimates on the cost gap vis-a-vis conventional steel range from 35 to 120 % (cf. section 1.1). Additionally, the level of demand for climate-friendly produced metals is often not clear.

Thus, investments in decarbonisation technologies are currently limited in volume in countries around the world, as these technologies are not yet competitive and as companies do not have sufficient trust that they will become viable business cases in the future. Governments aiming to foster the decarbonisation of energy-intensive industries therefore need to provide support. This support can come in different forms and target various relevant conditions.

This section gives an overview of different types of instruments, presents best-practise examples and identifies measures that could be particularly interesting for the government in Kazakhstan to consider. It also gives an overview of international activities on green lead markets.

5.1 Mapping of supply side instruments focusing on financial support

Carbon pricing is presented and shortly discussed as a basis for industrial decarbonisation, but not analysed in detail. The focus is on four categories of funding instruments and key design elements that are currently being deployed and developed in countries with high ambitions to decarbonise energy-intensive industries: investment grants, amortisation accounts for intermediary financing, contracts for difference (CfDs) as well as tax breaks. While investment grants and amortisation accounts provide support for investment costs, CfDs and tax breaks also address the operational cost gap. For each of these instruments, best-practise examples or case studies are presented that highlight key design elements of the specific funding instrument.

5.1.1 Carbon pricing as a basis for industrial decarbonisation

Carbon pricing is a market-based instrument which aims at curbing greenhouse gas (GHG) emissions by assigning a price on CO_2. Its objective is to discourage the use of carbon dioxide-emitting fossil fuels by passing the cost of emitting on to the emitters. Thus, it creates a financial incentive for polluters to decrease their level of emissions.

Carbon pricing instruments can be implemented in different forms (CPLC 2024). The EU, e.g., established its Emission Trading System (EU ETS) as a cap-and-trade system. It sets a limit ("cap") on total direct GHG emissions from certain sectors and includes a market where the rights to emit (in the form of carbon certificates) can be traded. The cap-and-trade system thus ensures that a previously set emission limit is not exceeded, while polluters can meet the reduction targets flexibly and at the lowest cost. The CO_2 price fluctuates depending on market demand for certificates. In order to mitigate the risk of carbon leakage and concede energy-intensive companies more time for their transformation, the EU ETS grants some sectors certain amounts of allowances for free (EU COM 2025a). However, the number of free allocations is to be reduced gradually from 2026 to 2034, while the new Carbon Border Adjustment Mechanism (CBAM) will be phased-in as the EU's new instrument against carbon leakage (EU COM 2025b).

Carbon pricing plays an important role as a basis for industrial decarbonisation. If a carbon pricing scheme is in place and certificate prices reach a relevant level, CO_2-intensive production becomes more expensive for companies. As a result, the cost gap between CO_2-intensive production and the currently more costly low-CO_2 production decreases. The financial incentive for an investment in climate-friendly technologies grows. Hence, carbon pricing constitutes a measure which can be applied by politics as a means towards obtaining rentability of climate-friendly production. Another, potentially complementary measure to further reduce the economic viability gap for low-emission technology options are financial support instruments. Having both in place, a functioning carbon pricing system can relieve the public budget by reducing the need for additional financial support for the industry transformation.

While carbon pricing increases the cost for companies with CO_2-intensive production processes, companies might also benefit from the considerable public funds that are generated by it. The revenues from the sale of certificates can be distributed for the deployment of net-zero and innovative technologies through grants and auctions. In the EU, the revenues from its Emission Trading System (ETS) are significant. The EU Innovation Fund will be able to provide about €40 billion in funding for the commercial demonstration of innovative low-carbon technologies from 2020 to 2030 (assuming a carbon price of €75/tCO_2) (EU COM 2025c).

5.1.2 Investment grants: Important Projects of Common European Interest (IPCEIs)

Background

An investment grant is a certain amount of money provided by the government to a company to allow it to invest in a project considered important by the funder. Unlike loans, investment grants are usually non-repayable subsidies. In the following, the EU investment grants for "Important Projects of Common European Interest" (IPCEIs) are presented as an example for an investment grant.

The EU and its Member States set ambitious targets for its green and digital transitions and aim at improving their competitiveness and strategic autonomy (EU COM 2025d). To realise these targets, large investments in innovative breakthrough technologies and important infrastructure are necessary. For cases in which companies cannot afford funding such ambitious projects alone, the European Commission can allow Member States to give State aid to support so-called "Important

Projects of Common European Interest" (IPCEIs). While State aid is generally forbidden in the EU to prevent market distortion between Member States, it can be allowed if the aid's positive effects outweigh its distortive effects (which should be minimized). The state aid should only cover the funding gap and ensure sufficient profitability. After the end of the funding period, the Member States have to check whether they 'overfunded' the project and, if so, reclaim the complete funding or part of it (BMWK 2020a). Generally, IPCEI funding focuses on investment cost (CAPEX), exceptionally also allowing OPEX subsidisation (e.g. for hydrogen to be used in steel companies' DRI plants) (BMWK 2020b).

Member States may jointly decide to initiate an IPCEI in a specific sector or technology (but established products and existing technologies are explicitly excluded from funding). An IPCEI includes integrated large-scale cross-border projects from at least 4 Member States which are associated with large technological or financial risks and benefit the entire EU. From 2018 to today, 10 integrated IPCEIs in 5 value chains have been approved by the European Commission in the areas of batteries (2 calls), cloud and edge computing (1), health (1), hydrogen (4), and microelectronics (2) (EU COM 2025d). Depending on the IPCEI, there were huge variations in the number of individual projects, the Member States involved, the approved state aid and the expected private investments. In the framework of the hydrogen IPCEIs, for example 4 projects from German steel plants were granted state aid for investments in hydrogen-based direct reduction of iron: Salzgitter AG, thyssenkrupp Steel Europe, Stahl-Holding-Saar and ArcelorMittal (plants in Bremen and Eisenhüttenstadt). In general, the IPCEI funding is limited (the most competitive companies should receive the subsidies) and decided on a case-by-case basis (GCEE 2023). This funding approach implies greater planning security and the possibility of control for the state (compared e.g. to the U.S.' IRA[37]). However, due to the complex application procedures, it is unclear how efficiently funds are allocated.

Initial situation

- Companies in different EU Member States would like to invest in innovative technologies or important infrastructure but do not have sufficient funds to do so.
- There is a lack of EU-internal value chains in specific sectors or for particular technologies.

Risks to be addressed by the policy instrument

- Companies and financiers refrain from investing in ambitious technologies or infrastructure due to high financial and/or technological risks.
- As a result, the market ramp-up of the technologies or its use (due to missing infrastructure) slows down and ambitious transition targets might not be achieved.
- A lack of cross-border cooperation between companies and Member States hinders the development and expansion of value chains within the EU, resulting in a lower level of strategic autonomy.

Desired effects of the policy instrument

- Enabling companies to realise ambitious projects which help to achieve climate goals, increase competitiveness and strategic autonomy.

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[37] Inflation Reduction Act, see section 5.1.5

- Exchange of know-how, joint developments and identification of new business opportunities by networking of companies of the same value chain across EU Member States.
- Additional funding opportunities for supported projects as a result of increased visibility.

Key design elements of the policy instrument

- EU-wide coordinated process:
    - At least 4 Member States jointly decide to initiate an IPCEI in a specific sector or technology and then conceptualise and design its scope and goals.
    - Member States organise open calls to collect project proposals matching the IPCEI design. Subsequently, they choose projects based on their contribution to the objective of the IPCEI and their compliance with IPCEI criteria.
    - The European Commission assesses the projects based on the IPCEI criteria (see below).
- (Selection of) criteria the IPCEI projects must comply with:
    - Significant contribution to the objectives of the IPCEI
    - Design to overcome important market or systemic failures or societal challenges that could not otherwise be addressed
    - Demonstration of research, development, innovation and/or first industrial deployment OR construction of key open infrastructure
    - Effective cross-border collaborations with other IPCEI participants
    - Positive spill-overs, by widely sharing the know-how generated by the project or allowing open and non-discriminatory access to the infrastructure
    - Co-financing contribution from the companies
    - No significant harm to the environment

5.1.3 Amortisation account for intermediary financing: WANDA mechanism for hydrogen core grid

Background

The amortisation account is a new instrument developed by the German government in consultation with the gas transmission system operators. It aims at providing intermediary financing for the development of the German hydrogen core grid. The financing concept is based on two key design elements: a constant ramp-up grid charge (the intertemporal cost allocation mechanism) and an amortisation account (the state-secured interim financing) (BNetzA 2024a).

The constant ramp-up fee will be applied at all entry and exit points of the hydrogen core grid from the beginning in 2025, if possible staying constant and predictable over the entire period until the investment's amortisation (BNetzA 2024a). At the beginning, the ramp-up network charge will be lower than the transmission system operators' actual costs as there are only few initial users. However, later on the price level will generate revenues above the operators' cost, allowing for the grid costs to be recouped at a later point in time when more hydrogen consumers are connected to the grid. As a result, the investment by the transmission system operators is expected to be refinanced by 2055 (BNetzA 2024a). Meanwhile, the transmission system operators' financing gap (due to initial grid charges below actual cost levels) will be filled in an interim period by a state-secured funding mechanism, called an amortisation account.

The transmission system operators appoint a separate entity to open and manage an amortisation account (BMJ & BfJ 2024). On behalf of the federal government as the lender, the account-holding office concludes loans for the intermediary financing of grid development. At times when cost exceed revenues from the ramp-up network charge, the grid operators receive payments from the amortisation account. Later on, when revenues exceed cost, the transmission system operators pay their surpluses back to the amortisation account (BMJ & BfJ 2024). Thereby, the loan is repaid step by step and the amortisation account shall be balanced by the year 2055, as mentioned above. If the amortisation account is not balanced by 2055 due to unexpected developments, the subsidiary financial safeguard will come into effect and the federal government will equalise the majority of the remaining deficit. The transmission system operators will have to contribute a deductible of up to 24 per cent of the deficit (BMWK 2024a). By providing this financial safeguard, the government aims at reducing the investment risk for transmission system operators.

The development of this financing instrument became necessary as in Germany, the use of green hydrogen is a key strategy for achieving climate neutrality by 2045. In the industrial sector especially the chemical but also the steel industry require climate-neutral hydrogen in order to transform their production processes. In order to allow for the transport of large amounts of hydrogen, a new energy infrastructure called the 'hydrogen core network' will be created from 2025 to 2032 (EU COM 2024). It will be oversized at the beginning, as it will be sized to accommodate the expected future customer base. Of the 9,040 pipelines kilometres 44% will be newly built while 56% consist of converted natural gas pipelines (BNetzA 2024b). The core grid will be a Germany-wide transport network that connects the currently known major consumption and production regions with each other, such as large industrial centres, storage facilities, power plants and import corridors. Subsequently, hydrogen distribution grids will be built to supply further consumers. By use of the intertemporal cost allocation mechanism, the costs incurring in the present can also be passed on to future customers, who are key drivers of these costs as well.

The grid development will be financed only by private investments (besides the IPCEI-supported pipeline projects). The financing concept (defined in the "Provisions for calculating the network tariffs chargeable for access to the hydrogen core network and for establishing a payback mechanism effective for a certain period", abbreviated "WANDA" (BNetzA 2024c)) only contains a subsidiary financial safeguard for the federal government against unforeseeable developments.

Initial situation

- Low demand for hydrogen transport services as the market for hydrogen only starts to develop (only first movers) and the utilisation of the hydrogen core network will only gradually increase over time
- High costs for network development right from the start

Risks to be addressed by the policy instrument

- High network charges for few initial customers let them refrain from demanding hydrogen transport services.
- High investment risk for network operators prevents grid expansion.

Desired effect of the policy instrument

- Ensure that the investments for the development of the German hydrogen core grid can be recouped by the investors → creation of a business case for grid developers
- Without this being accompanied by excessively high and therefore no longer marketable network charges for hydrogen customers

Key design elements

- Constant ramp-up grid charge (intertemporal cost allocation mechanism): One predetermined ramp-up fee will be applied from the beginning in 2025 until the investment's amortisation (expected by 2055).
- Amortisation account (state-secured interim financing): The transmission system operators' financing gap (due to initial grid charges below actual cost levels) will be filled in an interim period by an amortisation account. Later on, when revenues exceed cost, the transmission system operators pay their surpluses back to the amortisation account.

5.1.4 Contracts for Difference (CfDs) and instruments using a CfD-like logic: H2Global and Klimaschutzverträge

Background

Generally, two-way Contracts for Difference (CfDs) are financial contracts between buyers and sellers in which payments are determined for cases in which actual (future) costs are uncertain and, at maturity, there is a difference in the actual asset price and a strike price previously agreed on by the parties. If the asset price is below the strike price, the buyer pays the price difference to the seller and vice versa. CfDs are used for different purposes in financial and energy markets. As a governmental support instrument in energy markets, CfDs provide price support as well as stability and predictability of future revenue streams. Thereby, they incentivise investments in sustainable energy technologies which might otherwise enter the market significantly later or even not at all.

Governments increasingly choose CfDs as a financial support instrument for incentivising clean energy projects. Being firstly introduced as part of the UK's 2013 Electricity Market Reform, they became known as a success factor for the accelerated development of offshore wind energy in the UK (Ason & Dal Poz 2024). In the UK, CfDs are contracts between electricity generators and the government's Low Carbon Contracts Company (LCCC). If the electricity market price is below the contract's strike price, the LCCC pays the price difference to the generator. However, if the market price is above the strike price, the generator pays the LCCC.

In many other European countries, CfDs now also constitute an important part of electricity market reforms which aim at a successful accommodation of increasing levels of renewable energy generation (Ason & Dal Poz 2024). Compared to other funding instruments, CfDs have the advantage of better using the public budget as there is no risk of budget overruns. Furthermore, stable revenue profiles reduce the risk premium demanded by lenders. Additionally, CfDs are lower in their operational complexity (compared e.g. to feed-in-tariffs or power purchase agreements) and inherently imply consumer fairness (as strike prices are set at the beginning and in periods of high prices generators pay back price differences to the government) (Ason & Dal Poz 2024).

Recently, CfDs have also been identified as a suitable instrument to foster clean energy projects beyond power generation. CfDs or instruments using CfD-like logic are now being developed or implemented to create business cases for low-carbon hydrogen and carbon capture and storage (CCS) in the UK, the EU and other jurisdictions (Ason & Dal Poz 2024).

Historically being applied to foster clean energy production, EU Member States now also consider CfDs a suitable instrument to support low-carbon hydrogen consumption. In Germany, for example, the H2Global scheme started in 2022. Not exactly being a CfD, it uses a CfD-like logic to bridge the gap between supply and demand prices for "clean" hydrogen (Hintco 2024). In a first step an intermediary company called Hintco buys clean hydrogen products (which are usually still more expensive than carbon-intensive hydrogen products) from the producer asking for the lowest price. In a second step, the intermediary sells the product (also by means of an auction) at a lower price to end consumers. The price difference is covered by governmental funding. Hence, H2Global simulates a functioning market, thereby accelerating the creation of a real hydrogen market.

Another funding scheme recently initiated by the German government, called "Climate Protection Contracts" ("Klimaschutzverträge" in German), is based on another CfD-like instrument called Carbon Contracts for Difference (CCfDs) (BMWK 2024b). CCfDs adhere to the same underlying logic as CfDs and similarly work as a price hedge. However, while CfDs aim at providing stable revenues for clean energy technologies, CCfDs cover the additional costs of low-carbon technologies compared to conventional industrial production technologies (Ason & Dal Poz 2024). Thus, production CfDs support supply while CCfDs rather target demand for innovative clean technologies. In the German "Klimaschutzverträge" approach, the government auctions payments for 15 years to industrial companies. The auctions are won by those companies which are able to reduce the most carbon at the lowest cost, for example by switching to hydrogen, CCS or other low-emission production technologies. The winning bidder receives a financial compensation for the additional CAPEX and OPEX cost arising from the use of the low-carbon technology, in comparison to the carbon-intensive technology (Ason & Dal Poz 2024). If at some point in time the cost for low-emission production falls below those of the carbon-intensive technology, the situation is reversed and companies have to pay back the difference (BMWK 2024b).

Initial situation

- Due to high cost and price risks, many carbon-intensive companies are shying away from investing in low-carbon technologies.
- The German policy mix so far did neither include funding for hydrogen import and consumption (such as H2Global) nor a broad-impact funding for medium-sized and large industrial companies operating large-scale plants (such as the Klimaschutzverträge).

Risks to be addressed by the policy instrument

- If carbon-intensive companies do not start investing in low-carbon technologies, the industrial sector might not achieve the target of climate neutrality by 2045.
- If necessary, reinvestments are made in conventional carbon-intensive technologies, there is a lock-in effect, as investment cycles in these industries are long.

Desired effect of the policy instrument

- Introduction of price certainty to suppliers and/or consumers of low-carbon energy
- Support of the market ramp-up of low-carbon energy carriers and technologies

Key design elements

- Auctioning of contracts with funding being awarded to companies indicating the best cost-benefit ratio for the deployment of low-carbon energy carriers and technologies
- Payment of differences between the market price and a previously agreed strike price

5.1.5 Tax breaks: The Inflation Reduction Act[38]

Background

Tax breaks are a financial support instrument by the government, which reduces a person's or company's total tax liability. As a result, taxpayers or businesses have more money left to invest in other things, which might stimulate the economy.

Signed in August 2022 by US President Biden, the Inflation Reduction Act's (IRA) objective is to combat inflation, reduce greenhouse gas emissions and establish domestic value chains for future technologies in the USA. It consists of a package of laws that predominantly aim at supporting investments in the build-up of a clean energy economy, but also health care.

The IRA contains incentives for switching to low-emission production processes, mostly through tax credits for investment in and production with predominantly low-emission technologies. Thereby, the overall rate of support depends on the implementation of wage and qualification programmes, the use of domestic products and support for energy and low-income communities or specific regions, among other things (BCG 2022). Altogether, the IRA's tax breaks afterwards reduce a company's cost for the investment in and deployment of specific technologies.

According to BCG (2022), the IRA might reduce the levelized cost of generating renewable energy by 41% for solar, 57% for onshore wind and 35% for offshore wind. The cost reductions for companies generating low-emission products can be passed on along the value chain and thus also have an effect on economic activity in upstream and downstream sectors. Different studies expect that the IRA's subsidies for low-emission and sustainable electricity generation will lower the electricity price in the U.S. by about 1 ct/kWh (e.g., GCEE 2023). Regarding the production of green hydrogen, tax credits of US$ 0.6 to US$ 3/kg can be obtained, depending on the amount of CO_2 emissions per kg H_2 produced (BCG 2022). This approach implies technology openness on hydrogen use, aiming at the greatest possible supply in a short time.

The unbureaucratic approach of widely granting tax credits brings along the advantage of simplicity and planning security. At the same time, it also bears the risk of deadweight losses caused by companies which do not depend on subsidies to introduce low-carbon production processes (GCEE 2023). As there is no fixed funding limit, this kind of subsidy scheme might also turn out expensive for the government.

As assessed by the German Steel Association, the IRA's most important contents regarding steel production are the promotion of renewable energy and production of climate-friendly hydrogen as well as the preferential treatment of domestic industry through local content regulations (part of the tax credit for energy projects is only granted if the share of US steel reaches a certain domestic content threshold) (WVS 2022).

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[38] The instrument's description bases on the situation before the start of Donald Trump's second presidential term and thus does not include changes possibly made after 20 January 2025.

Initial situation

- President Biden's government wanted to foster the development of domestic clean energy production (as well as reduce its budget deficit and decrease the prices of prescription drugs).
- There was no existing business case for the use of many clean energy technologies, thus a lack of an economic incentive to deploy them.

Risks to be addressed by the policy instrument

- Companies do not invest in the build-up of a clean energy economy due to a lack of planning and investment security.
- There is no development of a clean energy market and no significant emission reductions resulting from industry transformation.

Desired effect of the policy instrument

- Steering effect in the direction of low-emission technologies, resulting in a competitive advantage for US companies:
  - Increased supply of low-cost renewable electricity, thus enabling e.g. the US steel industry to offer large amounts of low-carbon steel at competitive prices.
  - Accelerated hydrogen market ramp-up and hence creation of conditions for lead markets for hydrogen applications in the individual sectors.
- Economic, industrial and geopolitical goals, among others: increase in economic autonomy, creation of domestic manufacturing jobs and becoming a frontrunner in clean technologies.
- Accelerated achievement of the U.S.'s climate goals

Key design elements

- Pragmatic and simplified support for greenfield projects while leaving the market to promote technological solutions (e.g. by linking the amount of subsidies to CO2 emissions).
- Planning security for companies as a focus of the IRA's funding approach: They can easily calculate business cases for potential investments in IRA-supported products. Additionally, the period of time for which subsidies will be received is determined.
- The subsidy amount rises proportionally with the investment or production volume. Hence, if production is expanded, further subsidies are granted at the same rate.
- Neither the total sum of subsidies nor the amount for individual companies are limited. Hence, the IRA incentivises the expansion of production capacities (CAPEX subsidies) and production volume (OPEX subsidies).

Table 5-1 provides an overview of the key facts of the four financial support instruments described above.

Table 5-1: Key facts of the four financial support instruments

Funding programme	**Important Projects of Common European Interest (IPCEIs)**	**Financing mechanism for hydrogen core grid (WANDA)**	**H2Global and Klimaschutzverträge**	**Tax breaks in The Inflation Reduction Act**
Region	EU	Germany	Germany	USA
Implementing institution(s)	EU COM and Member States	BNetzA (Federal Network Agency)	Federal Ministry for Economic Affairs and Climate Action (both cases)	Various federal agencies, e.g. the Department of the Treasury, Department of Energy
Timeline	Since 2018	Since 2024	Since 2022 (H2Global) and 2024 (Klimaschutzverträge)	Since 2022
Source of finance	National/regional budgets of EU Member States	National budget	National budget	National budget
Type of funding	Repayable grants, loans, guarantees or non-repayable grants (to be decided by the Member State)	Loans that are processed via a government-backed amortisation account	Grants for price differences	Combination of grants, loans, rebates, incentives, and other investments, but mostly tax incentives
Budget	Over €103 billion so far (state aid + expected private investments)	€3 billion	€900 million H2 global pilot tender and € 4 billion for the first round of Klimaschutzverträge	No upper limit, official estimate: $369 billion for energy security and climate change projects for ten years
Key design elements	EU-wide coordinated process, funding criteria	Constant ramp-up grid charge, amortisation account (state-secured interim financing)	Auctioning of funding contracts, funding through payment of price differences	Tax incentives (nearly 75% of climate change funding budget)
Targeted cost	CAPEX (exceptionally also OPEX)	CAPEX	CAPEX and OPEX funding possible	CAPEX and OPEX
Desired effect	Realisation of ambitious industry transition and infrastructure projects, markets and supply chain development	Limitation of hydrogen grid network charges for first movers, creation of a business case for network operators	Price and investment security for energy-intensive companies, development of markets for low-carbon technologies and energy	Combating inflation, reduction of greenhouse gas emissions, establishment of domestic value chains for future technologies
Targeted sector/ process	Sectors relevant for the green and digital transitions	Hydrogen grid developers and users	Industrial companies with carbon-intensive production processes	Clean energy processes in different economic sectors
Applicability to other sectors	Applicable to a variety of technologies and sectors, where innovative technologies or important infrastructure are	Suitable for different kinds of grid development, if the need for investment initially precedes the growth of transport demand	Historically used to booster renewable energy supply, now also developed as multiple-technology schemes for different industry sectors	Potential for a broadly applicable instrument which can be designed without too much bureaucratic efforts for the applicants (but potentially cost-

	required to achieve transition targets			intensive for the government)
Particularly interesting for the Kazakh government due to…	Dedicated funding for low-carbon projects; incentive for investments in renewable energy	Applicability also for electricity grid development; provision of long-term financing for infrastructure development	Reduction of investment risk increases chance for bank loans; efficient use of public budget; option for renewable energy development; support of market development	Low complexity for applicants

5.2 Demand side instruments: German and EU efforts on green lead markets for energy-intensive industry products

5.2.1 Rationale for green lead markets

Green lead markets can be conceptualised as markets where low-emission or climate-neutral products or materials can be sold at a price that at least partly covers the additional costs that may be associated with their production ("green premium"). Green lead markets emerge if there is a demand for these products. The demand can originate in a willingness-to-pay by certain consumers – for instance if automobile producers seek to buy climate-friendly steel to be able to offer climate-friendly cars to their customers. However, policy-making may support the emergence and growth of green lead markets through measures that enable a matching of supply and demand or that strengthen demand.

Green lead markets are high on the agenda of current EU climate and industry policy-making. End of February 2025 the European Commission will put forward a strategy document for an EU Clean Industrial Deal that will put emphasis on the support for green lead markets (von der Leyen 2024). The German Ministry for Economic Affairs and Climate Protection in 2024 published the Concept "Lead markets for climate-friendly basic materials" (BMWK 2024c), which focuses on the three largest sectors of energy-intensive basic materials: steel, cement and base chemicals. The rationale behind the increasing political support for green lead markets is that they can be an important element in the policy mix for industry decarbonisation, as they reduce the need for subsidies and synergistically interact with carbon pricing.

High levels of investment are required to convert the production of basic materials such to climate-friendly technologies based on green electricity, green hydrogen, biomass or carbon capture and storage. These new technologies are in many cases associated with higher operating costs or higher operating cost risks than fossil-based production processes. In addition to the cost risks, there are further technological, regulatory and social risks, high time pressure and the need for different players to coordinate their activities, for example to establish a hydrogen supply or for more circular supply and value chains.

In the EU, the CO_2 price caused by the European Emissions Trading System makes a big contribution of closing the cost gap between conventional and low-CO_2 production and in some cases brings new technologies already close to competitiveness. For other solutions such as green steelmaking, the CO_2 price is not sufficiently high yet, and its future development is subject to uncertainty. Governments in the EU accordingly employ financial support instruments to nevertheless enable investments in the new technologies, which in the case of Carbon Contracts for Difference are specifically coupled to CO_2 price developments (see section 5.1.4). However, public funding is limited, other public goals compete for the resources, and subsidies are supposed to be only temporary.

So, climate-friendly products eventually need to be able to thrive on markets by themselves. Green lead markets are based on strengthening and securing demand for climate-friendly products. They also improve the starting conditions for investments, since companies and investors can be more confident that there will be reliable demand for their products. If green lead markets are successful, this reduces the need to subsidise the production of climate-friendly basic materials on the supply side. In view of the climate targets, the long-term aim must be to ensure that all products on the markets are produced in a climate-friendly way. To achieve this, various instruments must work together to gradually push products that are not climate-friendly out of the markets and enable producers to gradually convert their production accordingly.

5.2.2 The role of definitions for climate-friendly products or materials

For green lead markets to work, market actors first need to be able to recognize and distinguish climate-friendly products. Only then can buyers with a willingness to pay the green premium decide to purchase the climate-friendly product, and only then can governments privilege green products through specific policy instruments. Since basic materials from climate-friendly production do not look different from conventionally produced materials, some kind of labelling or certification system is necessary. The information conveyed by these systems needs to be reliable and transparent and to allow for the comparison of different products.

Individual companies for instance in the steel sector have been developing labels and product names to distinguish products with a superior climate performance.[39] This indicates that companies are working on reducing greenhouse gas emissions and on marketing the resulting products. However, their labels and product names are designed to reward the specific measures taken by the individual company and may reflect different requirements, and they are not necessarily based on the same measurement standards and methodologies. Therefore, common definitions with some legitimacy are necessary to ensure transparency and comparability (and also to safeguard against greenwashing). Here, state actors have an important role to play, either by themselves offering definitions and labels or by coordinating efforts between market actors.

Achieving agreement among stakeholders on common definitions can, however, be difficult, as the technical criteria of the definition determine the chances of different producers to reap the green premium. Among these potentially controversial criteria are:

- The scope: Which emission sources are taken into account? To what extent are upstream and downstream emissions considered?
- Threshold values: Which emission reduction requirements should need to be fulfilled by products that are to be sold as "green" or "low-emission"?

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[39] E.g. SSAB: „fossil free steel", GMH group: "Green Steel", thyssenkrupp: "bluemint Steel", Tata steel: "Zeremis Carbon Lite", Arcelor Mittal: "XCarb ®".

- Different production processes: Should threshold values vary to take account of differences between production methods, such as primary and secondary steelmaking?
- Pathways: How should intermediate stages in transformation processes be reflected in definitions?

As an example, the following section introduces the definition for climate-friendly (“near zero”) and low-emission steel that was recently put forward by the German steel association (WVS), and compares it to the definitions proposed by the International Energy Agency (IEA) and the Chinese iron and steel association (CISA).

5.2.3 Green steel definitions

In 2024, the German steel association (Wirtschaftsvereinigung Stahl, WVS), published a proposal for a Low Emission Steel Standard (WVS 2024a). LESS is based on definitions of different levels of performance that reflect consecutive steps towards climate-neutral steel production and allow to compare different steel products according to their climate performance. The definition was discussed and further developed in a stakeholder process carried out by the German Ministry of Economic Affairs in 2023. The definitions that build the basis of LESS can also be found in the Ministry’s concept document (BMWK 2024c) and thus have political backing. They are based on previous work by the IEA (2022b), adopting the key principles of the IEA definition but developing it further. WVS is currently establishing a voluntary label for steel products based on the LESS classification concept that will be open to all European and non-European steel producers.

In terms of system boundaries, the LESS classification takes into account the key drivers of emissions in the value chain. It includes emissions generated during steel production at the site up to the production of hot-rolled steel. In addition, emissions resulting from the procurement and use of energy sources and reducing agents (scope-2) and most emissions from the production of upstream products (scope-3 upstream) are also included. Scope-3 emissions from the provision of energy sources and reducing agents (e.g. coal, coke, natural gas, electricity, hydrogen), materials that flow directly into steel production (e.g. scrap, ore, alloying agents, slag formers, refractory materials, technical gases and other consumables) and their transport are therefore taken into account (WVS 2024b).[40]

By including hot rolling and comprehensive scope-3 emissions in the accounting framework, LESS differs from the IEA proposal and the Chinese proposal (see below). The inclusion of hot rolling makes it possible to incentivise emission reductions in this processing step (e.g. use of hydrogen instead of natural gas for hot rolling), which opens up additional scope for action, particularly for secondary steel production. The comprehensive inclusion of scope-3 emissions, including those of alloys, is due to the fact that these emissions represent a large proportion of the remaining residual emissions in decarbonised production routes. Steel producers can therefore only be classified as ‘near zero’ if they also work towards reducing emissions in their supply chain. Overall, at least 90 per cent of the total emissions from steel production, including scope-2 and scope-3 upstream, are recorded.

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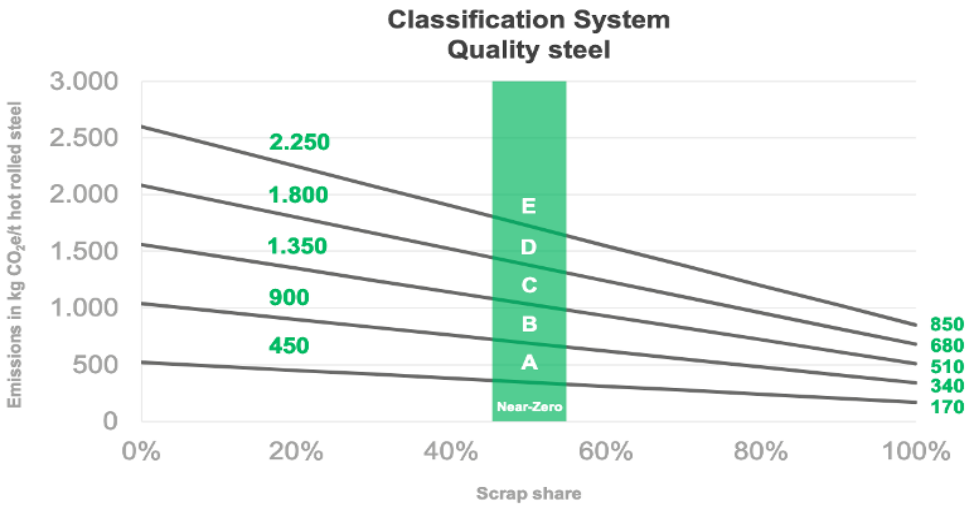
[40] Downstream scope-3 emissions (use and disposal) are not taken into account, i.e. the system follows a cradle-to-gate approach. For steel, downstream emissions do not belong to the key emission drivers.

Figure 5-1: Low Emission Steel Standard (LESS) classification system for quality steel



Source: WVS 2024a

Figure 5-1 shows the threshold values underlying the classification system. The system employs a so-called “sliding scale”, which means that the thresholds in each category are higher for steel production with lower shares of scrap input. The sliding scale takes into account that conventional primary production a priori generates significantly higher emissions than secondary production, meaning that greater efforts are required in primary production than in secondary production to achieve a low level of emissions. The differentiation of the threshold values depending on the scrap share thus reflects the effort to set equal incentives for the decarbonisation of both routes compared to the status quo. A fixed threshold value, on the other hand, would lead to a stronger incentive to increase secondary steel production.

LESS classifies steel along six different levels. Quality steel would be classified as “near zero emission steel” if emissions associated with its production are below 450 kg CO_2e/t hot rolled steel in the case of 20% scrap input and 170 kg CO_2e/t in the case of 100% scrap share.[41] For primary production the near-zero level can only be achieved with 1) new technologies (such as Direct Reduction or Electric Arc Furnace), 2) the use of fully climate-neutral energy (hydrogen and electricity) and 3) significant emission reductions in the upstream scope-3 emissions. Classification levels A to D represent steel produced with lower emissions than in conventional production that does not yet reach the level of near zero. For instance, according to WVS, level C can only be achieved by employing technologies *compatible* with a “near-zero” ambition, but allows for the at least partial use of fossil energy (e.g. natural gas instead of green hydrogen in DRI).

The China Iron and Steel Association (CISA) also proposed a Low Carbon Emission Steel Standard in 2024.[42] The standard was developed based on a scenario modelling approach and in collaboration of steel companies led by the China Baowu Group and

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[41] There are separate thresholds for structuring and reinforcing steel because of their lower alloy content.

[42] http://english.chinaisa.org.cn/do/cn.org.chinaisa.view.Column.d?column=9&article=34458.

key stakeholders. Like LESS it takes previous work by IEA and other international actors into account. System boundaries are narrower than in the case of LESS and more closely aligned with those proposed by the IEA definition, i.e. fewer upstream emission sources are included than in the case of LESS. Thresholds are defined for crude steel, but adjustments can be made for different hot-rolled products. Due to the differences in system boundaries, threshold values of the CISA standard and LESS are not directly comparable, with LESS thresholds adjusted upwards compared to IEA and CISA to account for the broader scope (IEA 2024). At the same time, the general approach is similar and it appears possible to create interoperability of the two standards.

Several initiatives at international level, most notably the Climate Club[43] and the Industrial Deep Decarbonization Initiative (IDDI),[44] work on making standards globally consistent or interoperable, supporting mutual recognition and harmonizing measurement methodologies.

5.2.4 Policy instruments for green lead markets

Green lead markets can be actively shaped and supported by policy-makers through instruments that enable a matching of demand and supply (e.g. voluntary labelling schemes), strengthen or create demand (e.g. green public procurement), or product regulation that introduces requirements products or their production processes need to fulfil in order to be sold on the markets (e.g. EU Ecodesign for sustainable products regulation).

While the costs of producing basic materials in a climate-friendly way may be substantially higher than those of conventional production, the extra costs of end products using those materials may be very small. For instance, the costs of producing climate-friendly steel from DRI-EAF with green hydrogen is assumed to be between 20 and 100% higher than those of conventional steel (Tönjes et al. 2022; CISL & Agora Energiewende 2021), end products using green steel such as cars, buildings or wind turbines are expected to be between 1 (cars) and 5 (wind turbines) percent more expensive than the same products made with conventional steel. While basic materials often are responsible for large shares of a products' overall carbon footprint, they usually play a minor role for their final price compared to other input factors or labour costs. There are indications that a certain willingness-to-pay a green premium may actually exist among consumers of end products globally (Voigt et al. 2023).

So, the prerequisite for green lead markets to emerge is the labelling of products, as it enables a potential willingness-to-pay to become effective, and as it allows for political interventions targeted at strengthening demand. The voluntary labelling schemes proposed by the Chinese and German steel associations presented above are an example.

If public procurement globally were to purchase climate neutral products only, costs would rise by 3 to 6% according to the World Economic Forum (WEF & BCG 2022). Public procurement of green basic materials could create an important demand signal, since it tends to constitute a significant share of GDP (15% in the EU) and of steel and other basic materials' demand (10% of steel demand in Germany) due to the public sector's role in construction and infrastructure provision.

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[43] https://climate-club.org/.

[44] https://www.unido.org/IDDI.

Regulations for public procurement could contribute to creating lead markets for instance by giving preference to climate-friendly basic materials in the procurement process, introducing minimum standards, or introducing purchase quotas for these materials (e.g. for steel of a certain LESS category) in public procurement. Purchase quotas or minimum requirements for products eligible for public procurement could be made more stringent over time, depending on which materials are available on the market at a given time.

Procurement by private companies can also be a powerful contribution to green lead markets, in particular if companies jointly commit to procuring green materials or products and introduce mechanisms that ensure following-up on commitments and pledges. In the First Movers' Coalition (FMC),[45] member companies set themselves targets that certain shares of their annual purchases e.g. of aluminium or steel meet or exceed certain criteria defined by the FMC.

Through product regulation policy-makers can introduce requirements, for instance a maximum carbon footprint of products, that apply to all products in the market. While such minimum requirements need to be defined in a way that reflects the currently available technologies and a realistic assessment of how fast progress can be made, they are a powerful tool as they have an effect beyond public and voluntary private procurement and can shift the whole market towards lower carbon footprints. In the EU, the Ecodesign for sustainable products regulation (ESPR) allows to set such requirements for the EU single market. Individual regulations under the ESPR for specific product groups and materials including for iron and steel are expected to be put forward from 2026 onwards. The requirements may for instance refer to minimum values for recycled content or maximum values for the CO_2 footprint. These regulations will apply across the EU, but also to products imported from outside the EU.

5.3 Summary and conclusions on policy support

Industry transformation, and specifically the decarbonisation of the metal industry is supported by current policy-making in Germany and the EU, given that they are key for achieving the climate protection targets. However, the choice and design of policies is complex and often controversial.

Innovative support and de-risking instruments are being developed to address coordination, economic and risk problems. They often aim at closing the cost gap between conventional and climate-friendly technologies only insofar as it is not yet covered by the CO_2 price. While funding instruments at EU level would be beneficial in the context of the single market, it is notoriously difficult to pool Member States' resources at EU level or to issue common debt. A large share of industry transformation funding still takes place at national level, but also at national level budgets for subsidies are limited and different public goals compete for resources. This is one of the reasons why green lead markets are currently high on the political agenda at national, EU and international level. Given parallel transformation dynamics in many countries, among other in China, it seems likely that international markets for green metals and other materials will emerge and provide new opportunities for companies investing in climate-friendly production.

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[45] https://initiatives.weforum.org/first-movers-coalition/home.

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