CLIMATE CHANGE
52/2025

Annex B: Decomposition of CO2 emissions from iron and steelmaking in the EU

Identifying drivers of emissions trends in the EU ETS

Annex to the final report of project no. FKZ 3719 42 505 0

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German Environment Agency

CLIMATE CHANGE 52/2025

Ressortforschungsplan of the Federal Ministry for the
Enviroment, Nature Conservation and Nuclear Safety

Project No. (FKZ) 3719 42 505 0

FB001711/ENG

Final report

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On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
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06844 Dessau-Roßlau
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Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de

Report performed by:
Oeko-Institute e.V.
Borkumstr. 2
13189 Berlin
Germany

Report completed in:
November 2024

Edited by:
Section V 3.3 Section Economic Aspects of Emissions Trading, Auctioning, Evaluation
Frank Gagelmann, Alexandra Zirkel

DOI:
https://doi.org/10.60810/openumwelt-7670

ISSN 1862-4359

Dessau-Roßlau, September 2025

The responsibility for the content of this publication lies with the author(s).

Abstract: Annex B:
Decomposition of CO2 emissions from iron and steelmaking in the EU

Iron and steel industry plays an important role for value creation and employment in the EU-27 It is also the industrial sector with the highest absolute CO_2 emissions. Since the introduction of the European Emissions Trading System (EU ETS) in 2005, total sector emissions covered by the scheme have declined from 235 Mt CO_2 to 178 Mt CO_2, in 2022. With two rounds of scope extensions for the EU ETS, emissions from installations now covered by the scheme have most probably declined even stronger. Note that these figures also do not include indirect emissions from electricity consumption, which are particularly important on the EAF-route, and DRI-EAF-route. In this paper we are able to shed light on the drivers of the declining trend, including both direct and indirect emissions, and with a special focus on the role of the EU ETS.

The decline of emissions from iron and steelmaking covered by the EU ETS in the EU 27+UK was primarily driven by a reduction of production on the emissions intensive BF-BOF-route. There was no major shift in production routes, but rather production was decreased in times of economic downturn, and instead of full recovery due to renewed economic development, increasing demand was also met with a boost in imports. No shift from the BF-BOF-route to the electricity based EAF-route could be observed, which would have reduced direct emissions to less than 20%. This could be due to limited scrap resources in the EU, the need for new large-scale investments in EAF installations and large-scale electricity connectors, and the limited substitutability of EAF-based crude steel and crude steel for primary production routes (BF-BOF route, DRI-EAF route). On the country level, Italy and UK have seen the largest decline in emissions. While the Spanish iron and steelmaking industry was heavily hit by the financial and later by the Euro crisis, the German steel industry was much less affected. Neither a significant change in the energy mix on a particular route nor a change in technology influencing efficiency was found in the data. Hence, at least the combination of both had no substantial effect on emissions decline. Emission reductions in power generation are clearly mirrored in the data on indirect emissions of the iron and steel production.

Kurzbeschreibung: Dekompositionsanalyse der CO_2-Emissionen der Eisen- und Stahlherstellung

Die Eisen- und Stahlindustrie spielt eine wichtige Rolle für die Wertschöpfung und Beschäftigung in der EU-27. Sie ist auch der Industriesektor mit den höchsten absoluten CO_2-Emissionen. Seit der Einführung des Europäischen Emissionshandels (EU-ETS) im Jahr 2005 sind die Gesamtemissionen des Sektors, die unter das System fallen, von 235 Mio. t CO_2 auf 178 Mio. t CO_2 im Jahr 2022 zurückgegangen. Da der Geltungsbereich des EU-ETS in zwei Runden erweitert wurde, sind die Emissionen der jetzt unter das System fallenden Anlagen höchstwahrscheinlich noch stärker zurückgegangen. In diesen Zahlen sind darüber hinaus die indirekten Emissionen aus dem Stromverbrauch nicht enthalten, der insbesondere auf der EAF-Route und der DRI-EAF-Route anfällt. In diesem Papier beleuchten wir die Ursachen für den rückläufigen Trend, wobei wir uns besonders auf die Rolle des EU-Emissionshandelssystems konzentrieren und dabei sowohl direkte als auch indirekte Emissionen berücksichtigen.

Der Rückgang der Emissionen aus der unter das EU-ETS fallenden Eisen- und Stahlerzeugung in der EU 27+UK war in erster Linie auf eine Verringerung der Produktion auf der emissionsintensiven BF-BOF-Route zurückzuführen. Es gab keine größere Verlagerung der Produktionsrouten, sondern die Produktion wurde in Zeiten des wirtschaftlichen Abschwungs zurückgefahren, und statt einer vollständigen Reaktivierung der Kapazitäten aufgrund einer erneuten wirtschaftlichen Entwicklung wurde die steigende Nachfrage auch durch einen Anstieg der Importe gedeckt. Es kam nicht zu einer Verlagerung von der BF-BOF-Route auf die strombasierte EAF-Route geführt, die die direkten Emissionen auf weniger als 20 % reduziert

würde. Dies könnte auf die begrenzten Schrottressourcen in der EU, die dann notwendige Großinvestitionen in neue EAF-Anlagen und große Stromanschlüsse sowie die begrenzte Substituierbarkeit von EAF-basiertem Rohstahl und Rohstahl aus den primären Produktionsrouten (BF-BOF-Route, DRI-EAF-Route) zurückzuführen sein. Auf Länderebene haben Italien und das Vereinigte Königreich den stärksten Emissionsrückgang zu verzeichnen. Während die spanische Eisen- und Stahlindustrie von der Finanz- und später von der Eurokrise schwer getroffen wurde, war die deutsche Stahlindustrie weit weniger betroffen. Emissionsrückgänge bei der Stromerzeugung spiegeln sich deutlich in den Daten zu den indirekten Emissionen der Eisen- und Stahlproduktion wider.

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ASU	Apparent steel use
BAT	Best available technology
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CBAM	Carbon Boarder Adjustment Mechanism
CCfDs	Carbon Contracts for Differences
CDF	Comprehensive Decomposition Framework
CO	Carbon monoxide
CO_2	Carbon dioxide
COG	coke oven gas
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EEA	European Economic Area
Em	Emissions
EU ETS	EU Emissions Trading System
EUTL	EU Transaction Log
GDP	Gross domestic product
GHG	Greenhouse gas
GVA	Gross value added
HBI	hot briquetted iron
Ind Em	Indirect emissions
LHV	lower heating value
LMDI	Logarithmic mean Divisia index
NDC	Nationally Determined Contributions
PJ	Petajoule
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change

Summary

Iron and steel industry plays an important role for value creation and employment in the EU 27, It is also the industrial sector with the highest absolute CO_2 emissions. Since the introduction of the European Emissions Trading System (EU ETS) [1] in 2005, total sector emissions covered by the scheme have declined from 235 Mt CO_2 to 178 Mt CO_2, in 2022. With two rounds of scope extensions of the EU ETS, emissions from installations now covered by the scheme have most probably declined even stronger. These figures also do not include indirect emissions from electricity consumption, which are particularly important on the electric arc furnace (EAF)-route. The effect of the decarbonization of the electricity supply decreased emissions by another 10 Mt CO_2. In this paper we are able to shed light on the importance of different drivers of the declining trend, including both direct and indirect emissions, and with a special focus on the role of the EU ETS.

The study uses the Logarithmic Mean Divisia Index (LMDI) decomposition method to analyze these drivers, focusing on economic demand, production shifts, production route changes, emission intensity variations, and indirect emissions.

In theory, the EU ETS might impact iron and steel emissions through three main mechanisms:

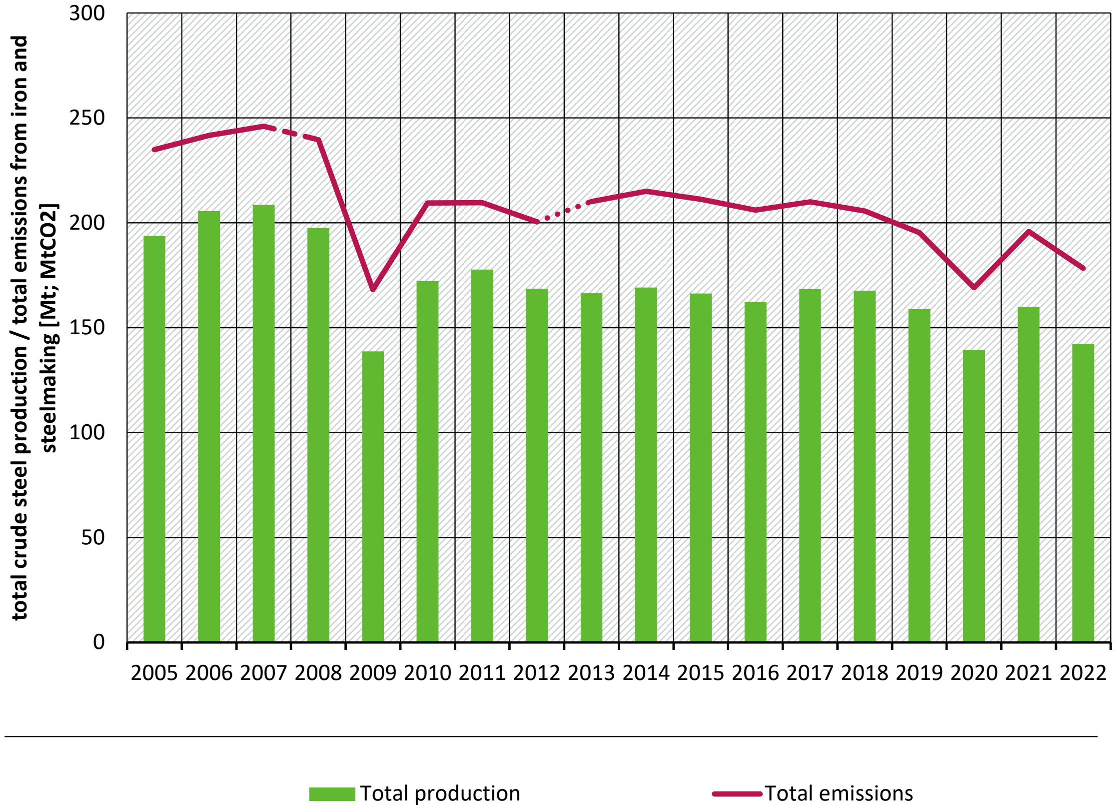
1. Direct Emission Intensity: The carbon price should incentivize less CO_2-intensive fuels;
2. Production Routes: Less carbon-intensive routes (EAF, DRI-EAF) might gain a competitive advantage.
3. Domestic Steel Production: Carbon prices might reduce the competitiveness of domestic steel production compared to imports, despite measures to protect against carbon leakage.

These effects might be limited because of the rules of free allocation together with the level of current and expectations on future carbon prices during the examined time period. Importantly, other drivers such as fuel prices, import duties, global overcapacities overlap with the effects of the EU ETS and have not been assessed in this study. Initial considerations are drawn here but these are not fully analyzed and must remain the subject of further research.

In addition, the EU ETS contributed to the decreasing CO_2 intensity of the electricity grid. Less carbon-intensive electricity supports the overall decarbonization of iron and steelmaking. However, this is external to the sector and not further analyzed in this study.

[1] Whenever the term EU ETS is used, it refers to the EU ETS 1 covering operators of large energy installations and energy-intensive industrial plants as well as aircraft and ship operators.

Figure 1: Development of total emissions from iron and steel production and total crude steel production for the EU 27+UK, 2005-2022.



Note: Due to changes in geographical coverage and sectoral scope, there are inconsistencies in the timeline with the beginning of the second (2008) and third trading period (2013).
Source: own calculations based on Worldsteel (2023) and EEA (2023a).

The decline of emissions from iron and steelmaking covered by the EU ETS in the EU 27+UK was primarily driven by a reduction of production on the emissions intensive BF-BOF-route. Emissions from the BF-BOF route account for over 95% of total emissions, the trends and drivers for BF-BOF emissions mirror those of total emissions. There was no major shift in production routes, but rather production was decreased in times of economic downturn, and instead of full recovery due to renewed economic development, increasing demand was also met with a boost in imports. No noticeable shift from the BF-BOF-route to the electricity based EAF-route could be observed, which would have reduced direct emissions to less than 20%. This could be due to limited scrap resources in the EU, the need for new large-scale investments in EAF installations and large-scale electricity connectors, and the limited substitutability of EAF-based crude steel and crude steel for primary production routes (BF-BOF route, DRI-EAF route).

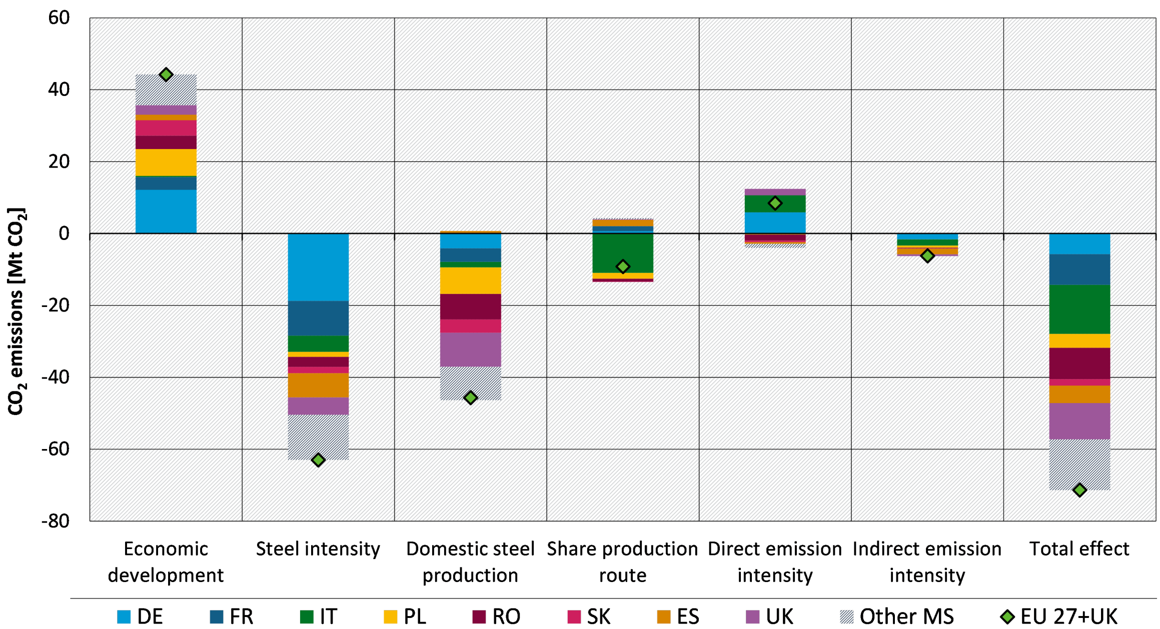
From 2005 to 2022, direct and indirect CO_2 emissions from iron and steelmaking in the EU and UK decreased by at least 71.4 Mt CO2, a reduction of 29%. This decline is likely underestimated due to the expansion of the EU ETS scope in 2008 and 2013, which included additional emission sources not covered in 2005. These scope extensions complicate direct comparisons across years, potentially underestimating reductions and overestimating increases.

All analyzed Member States contributed to the emission's decline. The primary driver of increased emissions was economic development, despite a reduction in absolute steel consumption. The largest driver of emissions reduction was the decreased steel intensity (steel usage per unit of GDP). Domestic steel production also decreased significantly, turning the EU into a net importer of steel by 2015, with domestic production 15% below consumption in 2022. The impact of reduced steel intensity was most significant in Germany, France, and Spain, while reduced domestic production was most pronounced in the UK, Poland, and Romania.

Minimal changes occurred in the share of different steel production routes, except in Italy, where the BF-BOF route's share declined significantly. Direct emission intensity increased over time, particularly in Italy and Germany, due to factors like fuel switching from gas to coal, lower utilization rates, and ageing steel production plants. Indirect emission intensity decreased due to a cleaner electricity grid, with increased renewables and reduced coal-fired power generation. However, indirect emissions have a smaller impact compared to direct emissions from the BF-BOF route.

On the country level, Italy and UK have seen the largest decline in emissions. While the Spanish iron and steelmaking industry was heavily hit by the financial and later by the Euro crisis, the German steel industry was much less affected. Neither a significant change in the energy mix on a particular route nor a change in technology influencing efficiency was found in the data. Hence, at least the combination of both had no substantial effect on emissions decline. Emission reductions in power generation are clearly mirrored in the data on indirect emissions of the iron and steel production.

Figure 2: Decomposition of the change of EU 27+UK CO_2 emissions from iron and steelmaking between 2005 and 2022 by country and effect



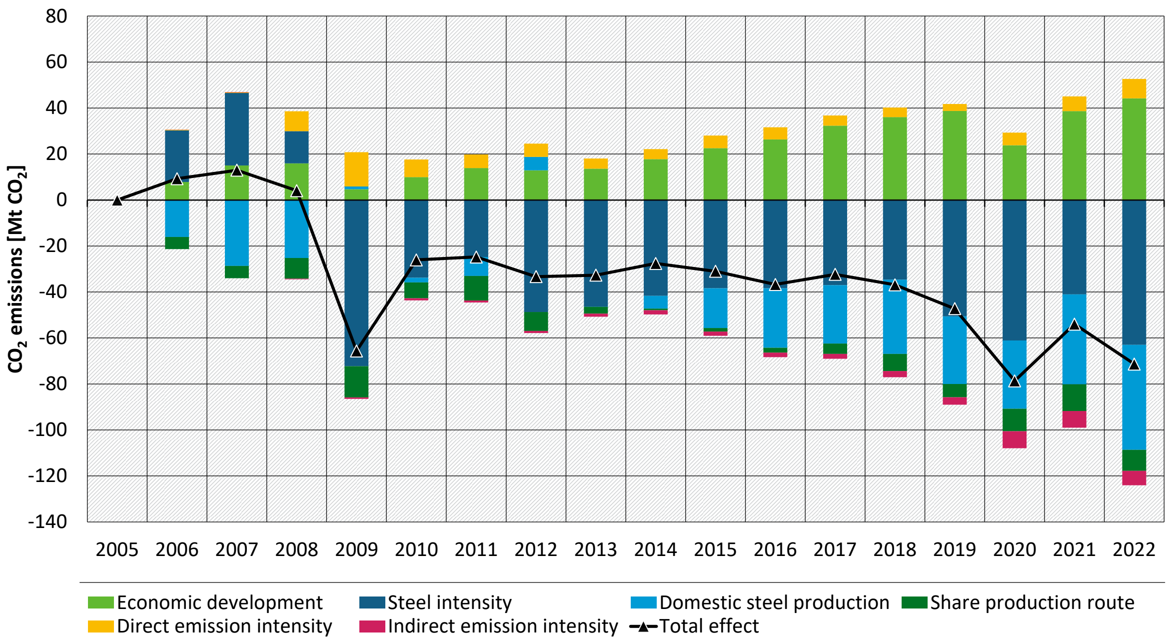
Source: Own calculations using the data sources in Table 4, Öko-Institut

The timeline of emissions in Figure 3 can be divided into four periods:

1. 2005 – 2008: Stable emissions, with higher steel intensity and economic development nearly offset by higher imports.
2. 2009: A sharp reduction in steel demand and emissions due to the global financial crisis.
3. 2010 – 2017: Stable emissions with recovering steel intensity, but below pre-crisis levels. Increasing steel demand was met by higher imports from 2015 onwards.

4. 2018 onwards: Declining emissions, with the COVID-19 pandemic causing a temporary dip in 2020. The main driver of emissions reduction was decreased steel intensity.

Figure 3: Decomposition of the development of CO2 emissions from iron and steelmaking since 2005 in the EU 27+UK



Source: Own calculations, Öko-Institut

The eight countries with the largest impact on the total emission development in decreasing order are discussed below.

Italy has significantly contributed to the EU's CO_2 emission reduction in the iron and steel sector, accounting for nearly 20% of the total reduction. Unlike the broader EU trend, Italy's GDP has remained stable since 2005, which means it has not contributed to increased emissions. However, emissions per unit of steel from the BF-BOF route have increased due to lower efficiency at Italy's only integrated steelworks. There has been a notable shift in the share of the Electric Arc Furnace (EAF) route, with stable EAF production and a 55% decrease in the electricity grid emission factor, which has helped reduce EAF emissions.

From 2014 to 2022, **UK** steel production dropped from 12 Mt/year to 6 Mt/year. The 2009 economic crisis and the 2015 insolvency of a major steelworks significantly impacted production. Steel consumption never returned to pre-crisis levels. The EAF route, making up 20% of UK production (compared to the EU average of 40%), has remained constant, with emission reductions mainly due to a cleaner electricity grid.

Romania's CO_2 emissions from iron and steelmaking have been primarily influenced by a decline in domestic production, especially between 2005 and 2007 prior to the application of the EU ETS in Romania. The 2009 financial crisis and recent price shocks further impacted production. Unlike the EU trend, Romania's BF-BOF emission intensity has gradually decreased since 2012, potentially due to the ETS. However, the grid emission factor has not significantly contributed to emission reductions.

France's CO_2 emissions closely followed the EU-wide trends. Direct emission intensity improved compared to 2005, except in 2022 due to high gas prices following the Russian invasion of Ukraine. The share of EAF in total production declined slightly, which is unusual compared to other countries. Indirect emissions were negligible due to the already mostly decarbonized French electricity grid in 2005.

As the EU's largest economy and steel producer, **Germany's** emission drivers align closely with EU trends. However, Germany's emissions from iron and steelmaking have remained almost stable. The decline in domestic steel production is less pronounced than in other EU countries, and the share of EAF and DRI-EAF has decreased. Unlike the EU, Germany's steel intensity peaked in 2011 and only declined significantly from 2018 onwards. The decarbonization of the electricity grid is also evident in the data.

The **Spanish** economy, particularly steel demand, was severely impacted by the 2008 global financial crisis and the 2011/2012 Euro crisis, leading to a permanent decline in steel intensity. The Spanish steel industry partially compensated by increasing exports, though export shares fell again during the COVID-19 pandemic and after the Russian invasion of Ukraine. Spain has a high share of EAF production (almost 70%), and the decarbonization of the electricity system is evident in the overall emission trends.

Since the introduction of the ETS, **Poland's** emissions from iron and steelmaking have remained relatively stable. Strong economic growth was offset by a lower share of domestic steel production, with increased steel demand met by higher imports. Steel intensity has remained constant. There has been a slight improvement in direct emission intensity over the last five years, possibly due to the closure of an integrated steelworks in 2019. Despite nearly 60% of steel production via the EAF route, indirect emission intensity has not improved significantly.

Emissions in **Slovakia** remained stable until recent years. Strong economic growth was balanced by higher imports, with a notable improvement in direct emission intensity until 2019, peaking in 2018 but declining in 2020. Steel intensity has fluctuated, dropping during the 2008 crisis, recovering, and then declining again during the COVID-19 pandemic and the 2022 Russian invasion of Ukraine. The production routes have not changed significantly, with only 10% of steel production from the EAF route.

Zusammenfassung

Die Eisen- und Stahlindustrie spielt eine wichtige Rolle für die Wertschöpfung und die Beschäftigung in der EU-27. Sie ist auch der Industriesektor mit den höchsten absoluten CO_2-Emissionen. Seit der Einführung des EU-Emissionshandelssystems (EU-ETS[2]) im Jahr 2005 sind die Gesamtemissionen des Sektors, die unter das System fallen, von 235 Mt CO_2 auf 178 Mt CO_2 im Jahr 2022 zurückgegangen. Nach zwei Runden der Erweiterung des Geltungsbereichs des EU-ETS sind die Emissionen aus Anlagen, die jetzt unter das System fallen, höchstwahrscheinlich noch stärker zurückgegangen. In diesen Zahlen sind die indirekten Emissionen aus dem Stromverbrauch nicht enthalten, die insbesondere bei Elektrolichtbogenöfen (EAF) besonders wichtig sind. Durch die Dekarbonisierung der Stromversorgung sind die Emissionen um weitere 10 Mt CO_2 gesunken. In diesem Papier beleuchten wir die Bedeutung der verschiedenen Treiber für den rückläufigen Trend, einschließlich der direkten und indirekten Emissionen mit besonderem Augenmerk auf die Rolle des EU-ETS.

In der Studie wird die LMDI-Dekompositionsanalyse (Logarithmic Mean Divisia Index) verwendet, um diese Faktoren zu untersuchen, wobei der Schwerpunkt auf der wirtschaftlichen Nachfrage, Produktionsverlagerungen, Änderungen der Produktionsrouten, Änderungen der Emissionsintensität und indirekten Emissionen liegt.

Theoretisch könnte das EU-ETS die Eisen- und Stahlemissionen durch drei Hauptmechanismen beeinflussen:

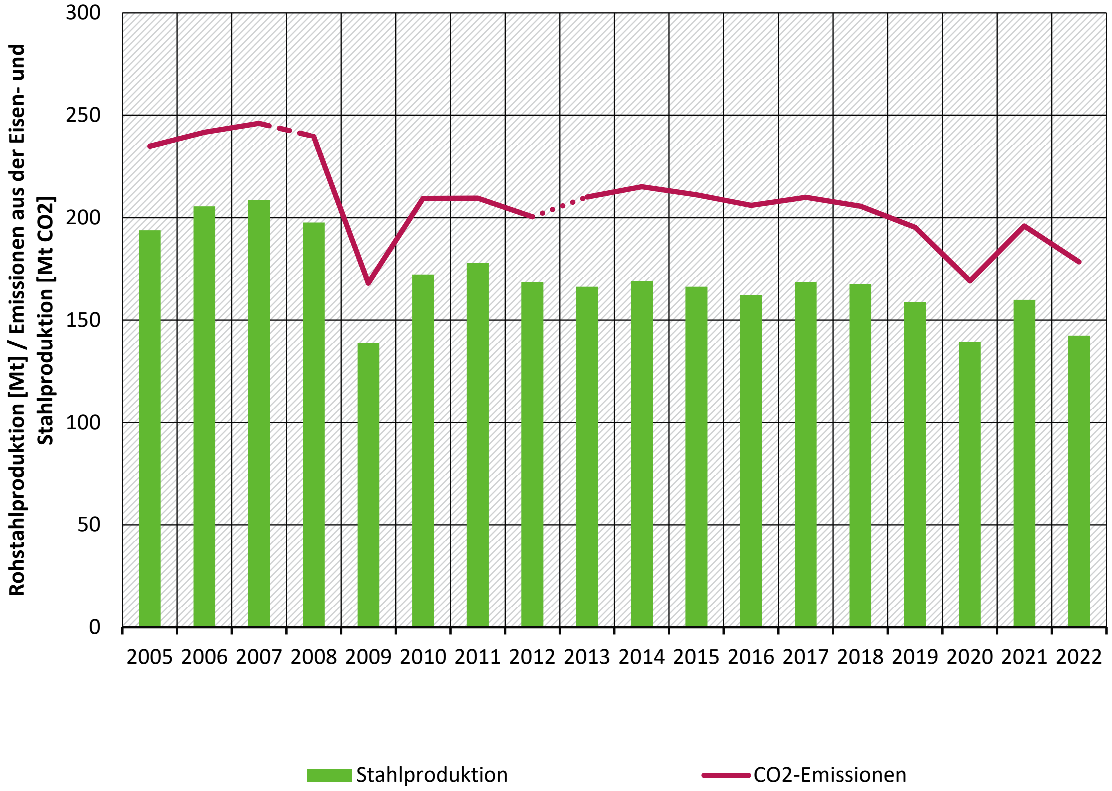
1. Direkte Emissionsintensität: Der Kohlenstoffpreis sollte Anreize für weniger CO_2-intensive Brennstoffe schaffen.
2. Produktionsrouten: Weniger kohlenstoffintensive Verfahren (Elektrolichtbogenöfen, DRI-EAF) könnten einen Wettbewerbsvorteil erhalten.
3. Inländische Stahlproduktion: Die Kohlenstoffpreise könnten die Wettbewerbsfähigkeit der heimischen Stahlproduktion gegenüber Importen verringern, auch wenn Maßnahmen zum Schutz vor der Verlagerung von Emissionen (Carbon Leakage) ergriffen werden.

Diese Auswirkungen könnten aufgrund der Regeln für die freie Zuteilung zusammen mit der Höhe der derzeitigen und der erwarteten künftigen Kohlenstoffpreise im untersuchten Zeitraum begrenzt sein. Außerdem sind andere Faktoren wie Brennstoffpreise, Einfuhrzölle und globale Überkapazitäten, die sich mit den Auswirkungen des EU-ETS überschneiden, in dieser Studie nicht bewertet. Erste Überlegungen dazu werden angestellt, können jedoch nicht abschließend analysiert werden und müssen deshalb Gegenstand weiterer Untersuchungen bleiben.

Darüber hinaus trug das EU-ETS zur Verringerung der CO_2-Intensität des Stromsektors bei. Strom mit geringeren CO_2-Emissionen unterstützt die allgemeine Dekarbonisierung der Eisen- und Stahlerzeugung. Dieser Faktor ist jedoch sektorextern und wird in dieser Studie nicht weiter analysiert.

[2] Wenn der Begriff EU-ETS verwendet wird, bezieht er sich auf das EU-ETS 1, das die Betreiber von großen Energieanlagen und energieintensiven Industrieanlagen sowie die Betreiber von Flugzeugen und Schiffen umfasst.

Abbildung 1: Entwicklung der Gesamtemissionen aus der Eisen- und Stahlproduktion und der gesamten Rohstahlproduktion für die EU 27+UK, 2005-2022



Anmerkung: Aufgrund von Änderungen der geografischen Abdeckung und des sektoralen Geltungsbereichs gibt es Inkonsistenzen in der Zeitleiste mit dem Beginn des zweiten (2008) und dritten Handelszeitraums (2013).
Quelle: eigene Berechnungen auf der Grundlage von Worldsteel (2023) und EWR (2023a)

Der Rückgang der unter das EU-ETS fallenden Emissionen aus der Eisen- und Stahlerzeugung in der EU-27+Vereinigtes Königreich war in erster Linie auf eine Verringerung der Produktion auf der emissionsintensiven Hochofen-Route zurückzuführen. Die Emissionen der Hochofen-Route machen über 95 % der Gesamtemissionen des Sektors aus, und die Trends und Treiber der Hochofen-Emissionen spiegeln die der Gesamtemissionen wider. Es gab keine größere Verlagerung der Produktionsrouten, vielmehr wurde die Produktion in Zeiten des wirtschaftlichen Abschwungs zurückgefahren, und statt einer vollständigen Erholung nach einem wirtschaftlichen Aufschwung wurde die steigende Nachfrage auch mit einem Anstieg der Importe beantwortet. Es konnte keine spürbare Verlagerung von der Hochofen-Route zu strombasierten Elektrolichtbogenöfen beobachtet werden, die die direkten Emissionen auf weniger als 20 % reduziert hätte. Dies könnte auf die begrenzten Schrottressourcen in der EU, die Notwendigkeit neuer Großinvestitionen in Elektrolichtbogenöfen und elektrische Anschlussleistung sowie die begrenzte Substituierbarkeit von Stahl auf EAF-Basis und Rohstahl für primäre Produktionsrouten (Hochofen-Route, DRI-EAF-Route) zurückzuführen sein.

Von 2005 bis 2022 sind die direkten und indirekten CO_2-Emissionen aus der Eisen- und Stahlerzeugung in der EU und im Vereinigten Königreich um mindestens 71,4 Mt CO_2 zurückgegangen, was einem Rückgang von 29 % entspricht. Dieser Rückgang ist wahrscheinlich unterschätzt, da der Geltungsbereich des EU-ETS in den Jahren 2008 und 2013 erweitert wurde, wodurch zusätzliche Emissionsquellen einbezogen wurden, die 2005 nicht erfasst waren. Diese

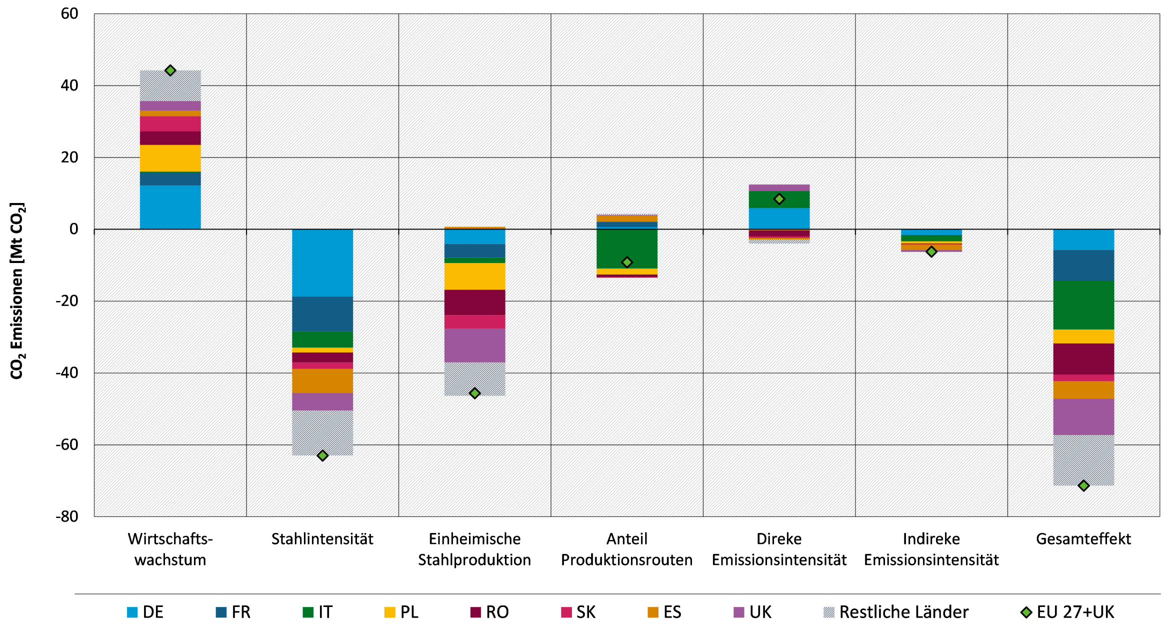
Erweiterungen des Geltungsbereichs erschweren direkte Vergleiche zwischen den Jahren und können dazu führen, dass Rückgänge unterschätzt und Anstiege überschätzt werden.

Alle analysierten Mitgliedstaaten trugen zum Rückgang der Emissionen bei. Die Hauptursache für den Anstieg der Emissionen war die wirtschaftliche Entwicklung, trotz eines Rückgangs des absoluten Stahlverbrauchs. Der größte Treiber für den Emissionsrückgang war die geringere Stahlintensität (Stahlverbrauch pro BIP-Einheit). Auch die inländische Stahlproduktion ging deutlich zurück, so dass die EU ab 2015 zu einem Nettoimporteur von Stahl wurde und die inländische Produktion im Jahr 2022 15 % unter dem Verbrauch lag. Die Auswirkungen der verringerten Stahlintensität waren in Deutschland, Frankreich und Spanien am stärksten, während der Rückgang der inländischen Produktion im Vereinigten Königreich, Polen und Rumänien am ausgeprägtesten war.

Bei den Anteilen der verschiedenen Stahlproduktionsrouten gab es nur minimale Veränderungen, außer in Italien, wo der Anteil der Hochofen-Route deutlich zurückging. Die direkte Emissionsintensität nahm im Laufe der Zeit zu, insbesondere in Italien und Deutschland, was auf Faktoren wie die Umstellung von Gas auf Kohle, eine geringere Auslastung und alternde Stahlproduktionsanlagen zurückzuführen ist. Die indirekte Emissionsintensität ging aufgrund eines emissionsärmeren Stromnetzes mit mehr erneuerbaren Energien und weniger Kohleverstromung zurück. Die indirekten Emissionen haben jedoch geringere Auswirkungen als die direkten Emissionen aus der Hochofen-Route.

Auf Länderebene konnten Italien und das Vereinigte Königreich den stärksten absoluten Rückgang der Emissionen verzeichnen. Während die spanische Eisen- und Stahlindustrie von der Finanz- und später von der Eurokrise schwer getroffen wurde, war die deutsche Stahlindustrie weit weniger betroffen. Weder eine signifikante Änderung des Energiemixes auf einer bestimmten Route noch eine Änderung der Technologie, die sich auf die Effizienz auswirkt, wurde in den Daten festgestellt. Zumindest die Kombination aus beidem hatte also keinen wesentlichen Einfluss auf den Emissionsrückgang. Die Emissionsminderungen bei der Stromerzeugung spiegeln sich deutlich in den Daten zu den indirekten Emissionen der Eisen- und Stahlerzeugung wider.

Abbildung 2 Dekomposition der Veränderung der CO_2-Emissionen aus der Eisen- und Stahlerzeugung in der EU 27+UK zwischen 2005 und 2022 nach Ländern und Auswirkungen

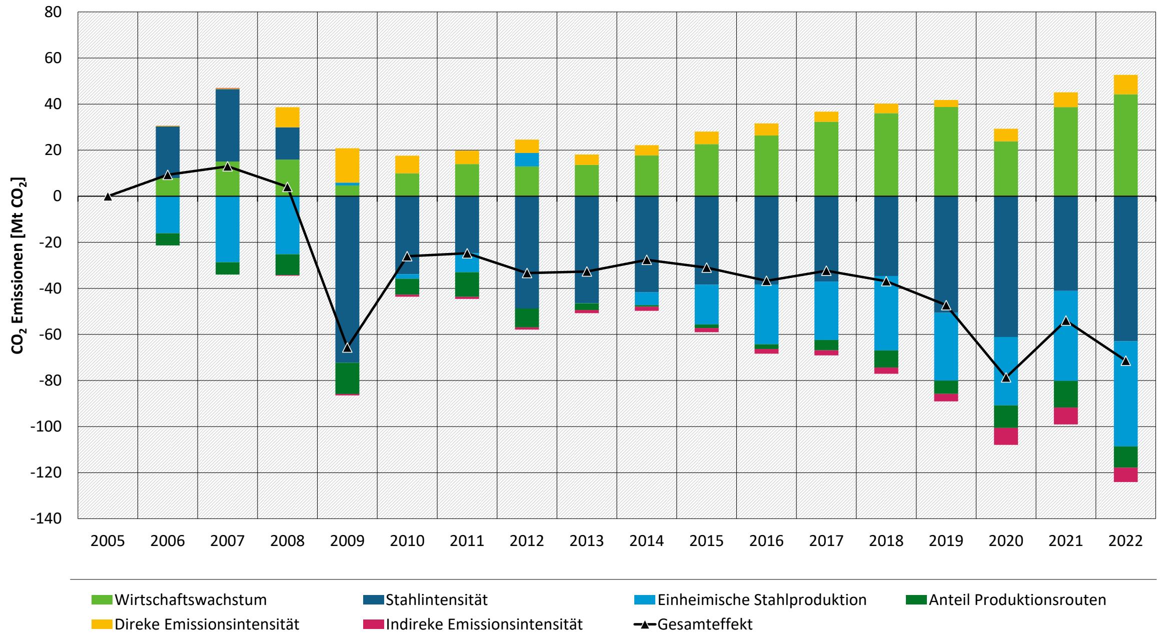


Quelle: Eigene Berechnungen unter Verwendung der Datenquellen in Table 4, Öko-Institut

Die Zeitachse der Emissionen in Abbildung 3 kann in vier Zeiträume unterteilt werden:

1. 2005-2008: Stabile Emissionen, wobei die höhere Stahlintensität und die wirtschaftliche Entwicklung durch höhere Importe fast ausgeglichen werden.
2. 2009: Starker Rückgang der Stahlnachfrage und der Emissionen aufgrund der weltweiten Finanzkrise.
3. 2010-2017: Stabile Emissionen mit steigender Stahlintensität, aber unter dem Vorkrisenniveau. Die steigende Stahlnachfrage wurde ab 2015 durch höhere Importe gedeckt.
4. Ab 2018: Rückläufige Emissionen, wobei die COVID-19-Pandemie im Jahr 2020 einen vorübergehenden Einbruch verursachte. Der Hauptgrund für den Emissionsrückgang war die geringere Stahlintensität.

Abbildung 3 Dekomposition der Entwicklung der CO_2-Emissionen aus der Eisen- und Stahlerzeugung seit 2005 in der EU 27+UK



Quelle: Eigene Berechnungen, Öko-Institut

Die acht Länder mit den größten Auswirkungen auf die Entwicklung der Gesamtemissionen werden im Folgenden in absteigender Reihenfolge erörtert.

Italien hat mit einem Anteil von fast 20 % zu der Gesamtreduktion der CO_2-Emissionen des Eisen- und Stahlsektors in der EU erheblich beigetragen. Im Gegensatz zum allgemeinen EU-Trend ist das italienische BIP seit 2005 stabil geblieben, was bedeutet, dass es nicht zu einem Anstieg der Emissionen beigetragen hat. Allerdings sind die Emissionen pro Stahleinheit aus der Hochofen-Route aufgrund der geringeren Effizienz in Italiens einzigem integrierten Stahlwerk gestiegen. Der Anteil der Elektrolichtbogenöfen-Route (EAF) ist gestiegen, wobei die EAF-Produktion stabil geblieben ist. Der Emissionsfaktor des Stromnetzes ist um 55 % gesunken, was zu einer Verringerung der EAF-Emissionen beigetragen hat.

Von 2014 bis 2022 sank die Stahlproduktion im **Vereinigten Königreich** von 12 Mio. t/Jahr auf 6 Mio. t/Jahr. Die Wirtschaftskrise von 2009 und die Insolvenz eines großen Stahlwerks im Jahr 2015 haben die Produktion erheblich beeinträchtigt. Der Stahlverbrauch erreichte nie wieder das Vorkrisenniveau. Die EAF-Route, die 20 % der britischen Produktion ausmacht (im Vergleich zum EU-Durchschnitt von 40 %), ist konstant geblieben, wobei der Emissionsrückgang hauptsächlich auf ein emissionsärmeres Stromnetz zurückzuführen ist.

Rumäniens CO_2-Emissionen aus der Eisen- und Stahlerzeugung wurden in erster Linie durch einen Rückgang der inländischen Produktion beeinflusst, insbesondere zwischen 2005 und 2007, bevor das EU-ETS in Rumänien eingeführt wurde. Die Finanzkrise 2009 und die jüngsten Preisschocks haben die Produktion weiter beeinträchtigt. Im Gegensatz zum EU-Trend ist die Emissionsintensität aus der Hochofenroute in Rumänien seit 2012 schrittweise zurückgegangen, was möglicherweise auf das EU-ETS zurückzuführen ist. Der Emissionsfaktor des Stromnetzes hat jedoch nicht wesentlich zur Emissionsreduzierung beigetragen.

Die CO_2-Emissionen **Frankreichs** folgten weitgehend den EU-weiten Trends. Die direkte Emissionsintensität hat sich im Vergleich zu 2005 verbessert, außer im Jahr 2022 aufgrund der hohen Gaspreise nach der russischen Invasion in der Ukraine. Der Anteil von Stahl aus der

Elektrolichtbogenöfen-Route an der Gesamtproduktion ging leicht zurück, was im Vergleich zu anderen Ländern ungewöhnlich ist. Indirekte Emissionen waren aufgrund des bereits 2005 weitgehend dekarbonisierten französischen Stromnetzes vernachlässigbar.

Als größte Volkswirtschaft und größter Stahlproduzent der EU sind die Emissionstreiber in **Deutschland** eng mit den EU-Trends verknüpft. Allerdings sind die deutschen Emissionen aus der Eisen- und Stahlerzeugung nahezu stabil geblieben. Der Rückgang der heimischen Stahlproduktion ist weniger ausgeprägt als in anderen EU-Ländern, der Anteil von EAF-Stahl und DRI-Stahl ist leicht zurückgegangen. Anders als in der EU erreichte die Stahlintensität in Deutschland im Jahr 2011 ihren Höhepunkt und ging erst ab 2018 deutlich zurück. Die Dekarbonisierung des Stromnetzes wird in den Daten ebenfalls deutlich.

Die **spanische** Wirtschaft und insbesondere die Stahlnachfrage wurden durch die globale Finanzkrise 2008 und die Eurokrise 2011/2012 stark beeinträchtigt, was zu einem dauerhaften Rückgang der Stahlintensität führte. Die spanische Stahlindustrie kompensierte dies teilweise durch steigende Ausfuhren, obwohl die Exportanteile während der COVID-19-Pandemie und nach der Invasion Russlands in der Ukraine wieder zurückgingen. Spanien hat einen hohen Anteil der EAF-Produktion (fast 70 %), und die Dekarbonisierung des Stromnetzes zeigt sich in den allgemeinen Emissionstrends.

Seit der Einführung des EU-ETS sind die Emissionen **Polens** aus der Eisen- und Stahlerzeugung relativ stabil geblieben. In der Folge des starken Wirtschaftswachstums ging der Anteil der heimischen Stahlproduktion zurück, und die gestiegene Stahlnachfrage wurde durch höhere Importe gedeckt. Die Stahlintensität ist konstant geblieben. Die direkte Emissionsintensität hat sich in den letzten fünf Jahren leicht verbessert, was möglicherweise auf die Schließung eines integrierten Stahlwerks im Jahr 2019 zurückzuführen ist. Obwohl fast 60 % der Stahlproduktion über die Elektrolichtbogenöfen-Route erfolgen, hat sich die indirekte Emissionsintensität nicht wesentlich verbessert.

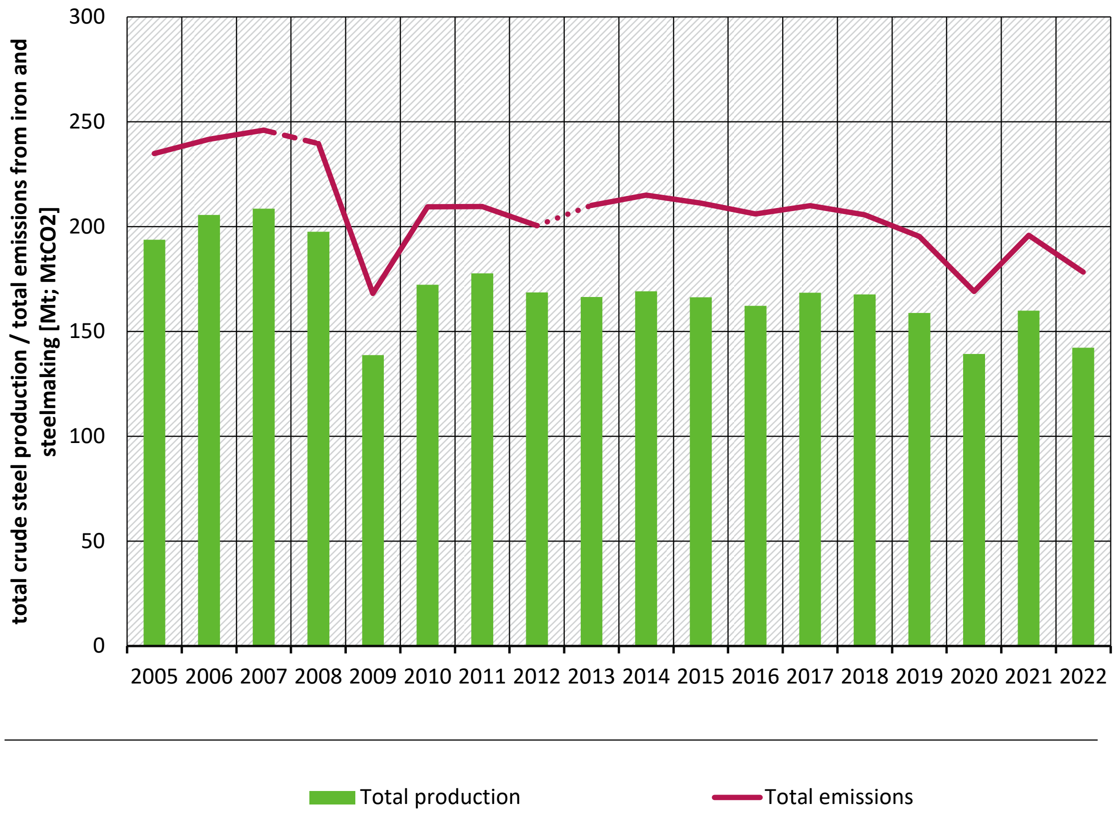
Die Emissionen in der **Slowakei** blieben in den letzten Jahren stabil. Das starke Wirtschaftswachstum wurde durch höhere Importe ausgeglichen, wobei sich die direkte Emissionsintensität bis 2019 deutlich verbesserte, 2018 einen Höchststand erreichte und 2020 zurückging. Die Stahlintensität schwankte, ging während der Krise 2008 zurück, erholte sich dann und ging während der COVID-19-Pandemie und der russischen Invasion in der Ukraine 2022 wieder zurück. Die Produktionsrouten haben sich nicht wesentlich verändert, nur 10 % der Stahlproduktion erfolgen auf der EAF-Route.

1 Introduction and literature review

With a turnover of about 130 billion EUR, gross value added of 107 billion EUR (direct and indirect, i.e., from derived products), 300,000 direct and 1,550,000 indirect jobs in 2022, the iron and steel industry plays an important role for value creation and employment in the EU-27, and it entails substantial intra-EU as well as extra-EU trade (EUROFER 2023). It is also the industrial sector with the highest absolute Carbon dioxide (CO_2) emissions. Its share of emissions in the EU Emissions Trading System (EU ETS) for EU 27+UK was 14% in 2022 (EEA 2023a) and the share of total EU 27+UK emissions is 5%.

Emissions from iron and steelmaking are reported under activity codes 22-25 in the EU ETS. Additionally, emissions from waste gas combustion in power plants is reported under activity code 20. Since the introduction of the EU ETS in 2005, total emissions have declined from 235 Mt CO_2 to 178 Mt CO_2 in 2022 (see Figure 4). In this paper we want to shed light on the drivers behind this development, with a special focus on the role of the EU ETS.

Figure 4: Development total emissions from iron and steel production and total crude steel production for the EU 27+UK, 2005-2022.



Note: Due to changes in geographical coverage and sectoral scope, there are inconsistencies in the timeline with the beginning of the second (2008) and third trading period (2013).
Source: own calculations based on Worldsteel (2023) and EEA (2023a).

A series of different factors potentially have contributed to this change:

- Extensions of sectoral scope and changes in geographical coverage of the EU ETS: the EU ETS underwent several rounds of geographical extensions, to include new EU Member States and EEA countries; also the scope of the processes and installations covered in the EU ETS was extended, e.g. the inclusion of steel processing (activity 25) in 2013. These extensions are associated with an increase in total emissions from iron and steelmaking.

- Total production or shifts in trade patterns: emissions are strongly linked to production levels, hence an emission reduction could imply a decline in domestic production. However, the emission reduction can have different reasons: a decline in demand, a relative increase in imports or a shift between production routes.
- Shares of the different production routes: There are two primary (iron ore-based) production routes: The BF-BOF-route (Blast Furnace-Basic Oxygen Furnace) and the DRI-EAF-route (Direct Reduced Iron-Electric Arc Furnace). Furthermore, a third route is the secondary EAF-route (recycling steel from steel scrap). The three routes come with significantly different emissions intensities. Hence, a decline in emissions could also be driven by a shift from one route to another. Annex I provides a detailed description of the three production routes, involved technologies, energy requirements and associated specific emissions.
- Process efficiency and fuel choice (as far as this is partially flexible within a production route) on the different production routes: Besides a pure shift in routes, reduction in direct and indirect emissions could also be due to efficiency improvements on either of the routes.

In order to systematically assess and quantify the contribution of different drivers to the change in total emissions from iron and steelmaking we rely on a well-established decomposition method: logarithmic mean Divisia index (LMDI). LMDI is an index decomposition method based on the development of the analyzed variable (i.e. CO_2 emissions in this case) and drivers influencing this development (e.g. economic development). For a more detailed explanation see Emele et al. (2022).

The next section provides an introduction into the method and gives a short overview of other papers that have used similar approaches. Based on the literature review, we introduce our approach in section 1.2. Section 2 then provides a detailed description of how drivers are constructed and provides details on data sources. Section 3 provides results on the EU 27+UK level, and details for selected countries. Section 4 concludes.

1.1 Other decomposition analyses of iron and steel

The decomposition method has been used in several other research papers to quantify the effects of significant drivers on the evolution of a variable (such as annual emissions) over time. It is crucial to emphasize that the method's effectiveness heavily relies on selecting the appropriate drivers. However, the method does not allow to determine whether any drivers have been omitted or if a driver's influence on the analyzed variable is spurious[3] (thus, it cannot establish causal relationships). Expert knowledge is required to identify drivers which are causally linked to the emission development. Additionally, the method does not offer explanations for the drivers' own development.

Table 1 details various decomposition analysis for energy intensive industries in general, and the iron and steel industry, in particular. Most studies use emission intensity of production, changes in the energy mix and economic activity as variables to explain changes in emissions. However, none of the studies include trade patterns as potential drivers. Moreover, the studies

[3] For example, you could use the number of storks per habitant to describe the development of birth rates in a country. The LMDI might show a strong dependence of birth rates on stork intensity despite a lack of any causality.

stay agnostic on the underlying technological options, while there are the three fundamentally different production routes, associated with different technologies and associated energy mixes.

The two last studies mentioned in Table 1 take a more technical view and include technology and route-specific analysis. They describe drivers of CO_2 emissions by route and technology, and also list other important influence factors, such as embodied emissions in traded inputs such as iron ore, coke or DRI, but also the role of final products and age of installations. Hasanbeigi (2022) also mention that different shares of typical feedstocks (e.g., strap steel as additional input on the BF-BOF-route, or DRI input on the ordinary EAF-route).

Table 1: Drivers of emissions from iron and steelmaking identified in the literature

Source	industry focus, method, and type of analysis	Drivers	Type of emissions accounted for and further notes
Song et al. (2018)	Decomposition of energy-related CO_2 emissions in China's iron and steel industry Comprehensive Decomposition Framework (CDF) Panel over Chinese regions and over time	• Energy mix • Energy efficiency • Economic activity • Potential energy intensity • Energy savings technology • Desirable output technology efficiency • Desirable output technology	• Accounts for direct energy-related emissions, process-related emissions from feedstock and indirect emissions • CDF allows to track technology change and provides consistent results on industrial structure and energy efficiency • Change in technology is assessed by calculating the "distance" to best performing installations and resulting theoretical emission and productivity levels
Wang et al. (2020)	Decomposing the decoupling of CO_2 emissions and economic growth in China's iron and steel industry Tapio elasticity Time series	• Energy mix • Electricity intensity of gross output value • Industrial gross output value • Industrial added value	• Accounts for direct energy-related emissions, process-related emissions from feedstock and indirect emissions • Analysis focusses on decoupling of emissions and economic activity • Reduction in production is only considered indirectly, as output value can be driven by quantity or by prices
Du et al. (2018)	A decomposition analysis of energy-related CO_2 emissions in Chinese six high-energy intensive industries LMDI	• Energy mix • Emissions intensity of energy • Gross Value Added (GVA) share of respective industry per total GVA Energy consumption per unit of industrial value added	• Process-related CO_2-emissions are not assessed, however they are an important factor on the primary routes due to the need for a reduction agent in order to oxidate the iron ore.

Source	industry focus, method, and type of analysis	Drivers	Type of emissions accounted for and further notes
Zhang et al. (2019)	Decomposition analysis of China's CO_2 emissions (2000–2016) and scenario analysis of its carbon intensity targets in 2020 and 2030 LMDI	• Energy mix • Emissions intensity of energy • Share in GVA per Gross domestic product (GDP) • Economic activity • Population	• Process-related CO_2-emissions are not assessed, however they are an important factor on the primary routes due to the need for a reduction agent in order to oxidate the iron ore.
Wörtler et al. (2013)	Steel's Contribution to a Low-Carbon Europe 2050 CO_2 footprint analysis	• Emissions intensity per production route • Share of production route • Total steel production	• Accounts for direct energy-related emissions, process-related emissions from feedstock and indirect emissions • Takes into account the specificities of the different production routes • Economic factors and trade patterns are not considered
Hasanbeigi (2022)	Steel Climate Impact International Benchmarking of Energy and CO_2 Intensities	• Energy mix • Emission intensity of energy • Energy efficiency • EAF steel in total steel production • Type of feedstocks in BF-BOF and EAF • Age of steel manufacturing facilities in each country • Capacity utilization • Environmental regulations • Cost of energy and raw materials • Boundary definition for the steel industry	• Accounts for direct energy-related emissions, process-related emissions from feedstock and indirect emissions • Highlights role that trade patterns play in determining specific emission intensity • Comprehensive comparison of emissions intensity of iron and steelmaking in different countries and assessment of underlying drivers • No assessment over time • Economic factors are not accounted for

Source: own table.

1.2 Our approach

Our approach will allow to assess the following drivers of emissions from iron and crude steel production covered under the EU ETS:

- Economic drivers of demand for final steel products.
- Shifts between import and domestic production.
- Shifts between different production routes.
- Changes in emission intensity of crude steel production by production route.

- Direct emissions:
  This is a mixed effect combing changes in energy efficiency and changes in the fuel mix. Insights on the industry and country level will be used to give a qualitative assessment of the split between these two drivers.

- Indirect emissions:

  - changes in the grid emission factor and

  - changes in the emission factor of hydrogen supply

2 Decomposition approach and data sources

This section describes the governing function and its elements as well as the data sources and inputs used for the analysis.

2.1 Governing function

Emissions from iron and steel production depend both on the production process but also on the production quantities. Total production is driven by economic growth and total demand for steel. For each country or region, this overarching governing function is used in the LMDI approach:

$$
\begin{aligned}
Em_{tot} &= Economic\ development \cdot Steel\ intensity \cdot Share\ of\ domestic\ production \\
&\quad \cdot Emission\ intensity \\
&= GDP \cdot \frac{Consumption}{GDP} \cdot \frac{Production_{tot}}{Consumption} \cdot \frac{Em_{tot}}{Production_{tot}} \\
&= GDP \cdot \frac{Consumption}{GDP} \cdot \frac{Production_{tot}}{Consumption} \cdot \sum_i \left[\frac{Production_i}{Production_{tot}} \cdot \frac{D_{Em_i} + Ind_{Em_i}}{Production_i} \right]
\end{aligned}
$$

With

- GDP: economic development which also drives steel demand
- Consumption: the apparent consumption of steel in a country[4]
- $Production_{tot}$: the total quantity of crude steel produced across all routes in a country
- $Production_i$: quantity of crude steel produced by a specific process (see below)
- Em_{tot}: total emissions from iron and crude steel production across all routes in a country
- D_Em_i/Ind_EM_i: direct/indirect emissions associated with route i

2.2 Direct and indirect emissions

In our approach, we try to integrate as many of the technology- and industry-specific details mentioned by Hasanbeigi (2022), as possible. At the same time, we add economic drivers which are also used in several other decomposition studies. As described by Hasanbeigi (2022), detailed information on the composition of the energy mix is required in order to calculate emissions from the steelmaking industry. While such data is available from the International Energy Agency (IEA) as energy balances for individual countries or regions, this data lacks information on how the fuel use is split between the different production routes BF-BOF, (secondary) EAF and the combined DRI-EAF route. The EU ETS, on the other hand, provides site-specific data and emissions can be attributed to the different routes. In our approach, we manually categorised each installation according to the production route to enable an assessment by route. We opt to use the EU ETS as the basis for the information on CO_2 emissions, thereby allowing a direct link between the drivers and change in emissions reported under the EU ETS.

[4] "Apparent consumption is also referred to as 'steel demand'. It is total deliveries of all steel products and qualities by EU producers plus imports less 'receipts' into the EU (that is, imports by EU producers themselves of material that is further processed), minus exports to third countries." (EUROFER 2020) (https://www.eurofer.eu/statistics/about-eurofer-statistics/eurofer-statistics-definitions/)

We base the assessment of emissions on crude steel as the final product. Data on crude steel production is widely available for different production routes. The production steps until crude steel is produced are the most emission-intensive ones, which can for example be seen when comparing total emissions from EU ETS activity code 22-24 (all related to producing pig iron and/or crude steel) to code 25 (related to further processing of crude steel or pig iron into intermediate products such as coils, wire rods etc.)in Table 2.

Table 2: Overview of emissions from the iron and steel sector included in the EUTL for EU 27+UK

Activity Code	Name	Emissions [Mt CO_2]								
		2005	2009	2010	2015	2018	2019	2020	2021	2022
20	Waste gas combustion installations	59.3	42.2	59.9	56.0	58.7	53.9	44.4	55.1	51.2
22	Production of coke	13.3	11.0	13.3	11.6	11.1	10.0	9.6	5.6	5.4
23	Metal ore roasting and sintering	5.9	2.0	2.8	2.8	2.8	2.7	2.3	2.4	2.0
24	Production of pig iron or steel	134.5	104.5	128.5	130.4	121.8	118.4	104.9	113.1	102.6
25	Production or processing of ferrous metals	10.0	8.4	5.0	10.4	11.1	10.2	8.0	7.9	7.0
Estimated correction for: extension in coverage and Brexit since 2005[1]		11.7	0.0	0.0	0.0	0.0	0.0	0.0	11.9	10.1
Total EU 27+UK iron & steel covered by the EU ETS		234.9	168.1	209.5	211.2	205.6	195.3	169.1	195.9	178.3

Notes: [1]Between 2005 and 2022, the scope of the EU ETS was extended with respect to geographical coverage and sectoral scope. Regarding the geographical coverage, in 2007 Romania and Bulgaria, and in 2013 Croatia joined the EU. In 2020, UK exited the EU and is not covered by the EU ETS from 2021 onwards. To allow a fair comparison on the EU level, we include estimates for the development of the emissions prior to joining the EU (see section 2.3 for details). The sectoral scope, i.e., the coverage of the iron and steel industry in the EU ETS was extended in 2008 and in 2013. For a detailed analysis of the effects of scope extension on total emissions covered by the EU ETS see Graichen et al. (2019). There is no data available on the role of scope extension on emissions covered from the steelmaking sector, only. However, both extensions did also affect iron and steelmaking: among others, the following extensions where made: for integrated steelworks rolling mills, re-heaters, annealing furnaces and pickling are covered by the EU ETS in all Member States since 2008; CO_2 emissions from the production or processing of ferrous metals including ferroalloys, CO_2 emissions from the production and processing of non-ferrous metals, and CO_2 emissions from production of hydrogen (affecting emissions on the DRI-EAF-route) are covered by the EU ETS since 2013.

Source: own calculation based on EUTL.

However, it is not sufficient to focus only on emissions from the activity codes 22 to 24. A significant part of emissions which can be directly attributed to iron and steel making on the BF-BOF route originates from electricity production based on waste gases. Following the source principle, these emissions are accounted for in the combustion sector under code 20. However, a major share of this generation is used to supply electric energy demand from iron and steel making on the BF-BOF route, and only the remainder is supplied to the grid, displacing other generators connected to the grid. To make a fair comparison, these indirect emissions originating from electric energy demand and supply for iron and steel making processes also have to be taken into account for all steel making routes. Hence, total emissions Em_{tot} can be calculated as the sum of direct (D_) and indirect (Ind_) emissions from the different routes:

$$Em_{tot} = D\_Em_{BOF} + D\_Em_{EAF} + D\_Em_{DRI-EAF} + Ind\_Em_{BOF} + Ind\_Em_{EAF} + Ind\_Em_{DRI-EAF}$$

Including **indirect emissions** comes with a caveat: There is no data publicly available on the development of electric energy demand by production route nor by installation. Hence, these can only be calculated assuming fixed electric energy intensities for each production route based on the literature and thereby neglecting potential efficiency improvements. The variation in indirect emissions is then solely governed by the variation in grid emission factor.

Table 3 details total emissions by route for direct and indirect emissions. Values include the corrections for geographical coverage and scope extension of the EU ETS described below Table 2. However, a full scope correction was not possible. Both scope extensions did affect emissions from the steelmaking sector. Due to the lack of full scope correction in the data used for the analysis, the results will tend to underestimate reductions between years before and after a scope extension occurred. Results will also tend to overestimate emission increases between years before and after a scope extension.

Note that a one-to-one comparison between values in Table 2 and Table 3 is not possible. Direct emissions reported in Table 3 cover emissions under code 20, 22, 23, 24, and 25 from integrated steelmaking sites on the BF-BOF-route, as well as emissions from integrated sites[5] on the EAF or DRI-EAF-route under code 24 and 25. However, those installations under codes 24 and 25 not part of an integrated site, are not included in the values reported in Table 3.

Table 3: Summary of direct and indirect emissions by steel production route included in the analysis

		2005	2009	2010	2015	2018	2019	2020	2021	2022
BF-BOF	Direct	215.7	152.9	190.9	188.4	182.1	173.4	150.3	171.9	156.5
	Indirect	6.0	3.7	4.7	4.3	3.8	3.4	2.6	3.1	2.9
EAF	Direct	6.0	4.9	5.7	5.2	5.6	5.2	4.7	5.5	4.8
	Indirect	17.4	13.3	15.2	12.6	12.3	10.5	8.8	10.6	9.7
DRI-EAF	Direct	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.3
	Indirect	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
∑	Direct	222.2	158.3	197.1	194.2	188.2	179.1	155.5	177.9	161.6
	Indirect	23.5	17.2	20.0	17.0	16.2	14.0	11.5	13.8	12.7
	∑	245.7	175.4	217.1	211.2	204.4	193.1	167.1	191.7	174.4

Source: own calculation based on site-specific data compiled in Mendelevitch et al. (2024) using EUTL, and route-specific parameters detailed in sections 2.2.1-2.2.3, and A.1-A.3.

[5] Activity code 25 includes further processing steps such as hot and cold rolling. For integrated sites emissions are only reported in aggregate, including also existing activity code 25 emissions although activity 25 is not part of the BF-BOF route.

2.2.1 BF-BOF-route

- Direct emissions (D_Em_{BOF}): Sum of reported emissions of installations attributed to the BF-BOF-route under activity codes 20, 22-25 at integrated sites, and 20, 22-24 at disintegrated sites.
- Indirect emissions (Ind_Em_{BOF}): Waste gases are used to produce electricity both for own consumption at the site as well as supply to the electricity grid. About 0.33 MWh electric energy is produced per ton of crude steel (see Annex A.1); out of this about 0.20 MWh/t crude steel are used for the process itself and about 0.13 MWh/t crude steel are provided to the grid. We assume that these 0.13 MWh/t crude steel reduces the demand for grid supply from other generators, and hence apply a credit (in other words, an accounted emission reduction due to a replacement of electricity generation by other plants): $Ind_{Em_{BOF}} = ElecNetGen_{BOF} \cdot EF_{grid}$, with
  - $ElecNetGen_{BOF}$: Net electric energy generation from waste gases per tonne of crude steel, assumed constant (-0.13 MWh / t crude steel)
  - EF_{grid}: the emission factor of the electricity grid by country and year

2.2.2 EAF route based on scrap

- Direct emissions (D_Em_{EAF}): Direct emissions are due to fossil fuels used in the process as an additional heat source (natural gas, coal and coke), as well as electrode and foam coal consumption. Direct emissions are about 0.09-0.17 t CO_2 per ton of crude steel (see Annex I). Based on the assignment of installations to production routes, data is available from the EU ETS.
- Indirect emissions (Ind_Em_{EAF}): The EAF process requires about 0.59 MWh/t crude steel (see Annex I). Emissions from the generation of the required electric energy are captured in the term Ind_Em_{EAF}. Again, electricity consumption is not available over time or across countries. Together with the share of EAF, the different electricity grid emission factors impact emissions for this term: $Ind_{Em_{EAF}} = ElecEn_{EAF} \cdot EF_{grid}$, with:
  - $ElecEn_{EAF}$: Electric energy demand, assumed constant (0.59 MWh per ton of crude steel)
  - EF_{grid}: the specific emission factor of the electricity grid by country and year

2.2.3 DRI-EAF route

- Direct emissions (D_Em_{DRI}): Emissions on the DRI-EAF route depend on the source of the hydrogen used. If hydrogen is produced from natural gas, the associated CO_2 emissions are the direct emissions of the production process. Based on the literature around 2.7 MWh natural gas are needed per tonne of DRI crude steel (see Annex I). Additionally, direct emissions for the EAF also need to be taken into account (see Annex I).
- Indirect emissions ($Ind\_Em_{DRI-EAF}$): Indirect emissions are treated identical to the EAF-route; electricity consumption is higher than on the EAF route, because additional electricity is needed to power the DRI process (see Annex I): $Ind_{Em_{DRI-EAF}} = ElecEn_{DRI-EAF} \cdot EF_{grid}$, with:
  - $ElecEn_{DRI-EAF}$: Electric energy demand, assumed constant (0.66 MWh/t Steel)
  - EF_{grid}: the emission factor of the electricity grid by country and year

2.3 Data sources

Table 4: Definition of sets and parameters and data sources

Sets and Parameters	Definition	Data sources
t	Time	
r	Region	
i	Production route	
GDP_{tr}	economic development which also drives steel demand	Eurostat (2023)
$Consumption_{tr}$	the apparent consumption of steel in a country:	Worldsteel Association (2024): World Steel Statistical Yearbook 2023: Apparent steel use (ASU); ASU is obtained by adding up deliveries (defined as what comes out of the steel producer's facility gate) and net direct imports
$tot\_Production_{tr}$	the total quantity of crude steel produced across all routes in a country	Worldsteel Association (2024): World Steel Statistical Yearbook 2023: Total production of crude steel
$Production_{tri}$	Production by year, region, and production route	Worldsteel Association (2024): World Steel Statistical Yearbook 2023: Production of crude steel in basic oxygen furnaces, Production of crude steel in electric furnaces, Production of crude steel in other processes
D_EM_{BOF}	Direct emission on the BF-BOF-route	Own compilation based on EU (2023) and UK Government (2024)for UK installations for 2021 and 2022. Emissions for Romania and Bulgaria were gap-filled based on average emissions intensity for 2007-2011 and respective production rates.
$ElecNetGen_{BOF}$	Net electric energy generation for waste gases per tonne of crude steel; assumed constant: -0.13 MWh per ton of crude steel	See Annex I
EF_{grid}	the emission factor of the electricity grid by country and year	EEA (2023b): Greenhouse gas (GHG) emission intensity of electricity generation
D_Em_{EAF}	Direct emission on the EAF-route	Own compilation based on EU (2023) and UK Government (2024)for UK installations for 2021 and 2022. Emissions for Bulgaria and Croatia were gap-filled based on average emissions intensity for 2007-2011 (Bulgaria), and 2013-2015 (Croatia) and respective production rates
$ElecEn_{EAF}$	Electric energy demand, assumed constant: -0.59 MWh per ton of crude steel	See Annex I

Sets and Parameters	Definition	Data sources
$D\_Em_{DRI-EAF}$	Direct emissions on the DRI route; they depend on the source of the hydrogen used.	Own compilation based on EU Transaction Log (EUTL) Emissions for Germany were gap-filled based on emissions intensity for 2013-2019 and respective production rates
$ElecEn_{DRI-EAF}$	Electric energy demand for DRI, assumed constant: 0.08 MWh per ton of crude steel	See Annex I

Source: own compilation.

3 Decomposition of CO_2 emissions from iron and steelmaking

3.1 Results for the EU-27 including UK

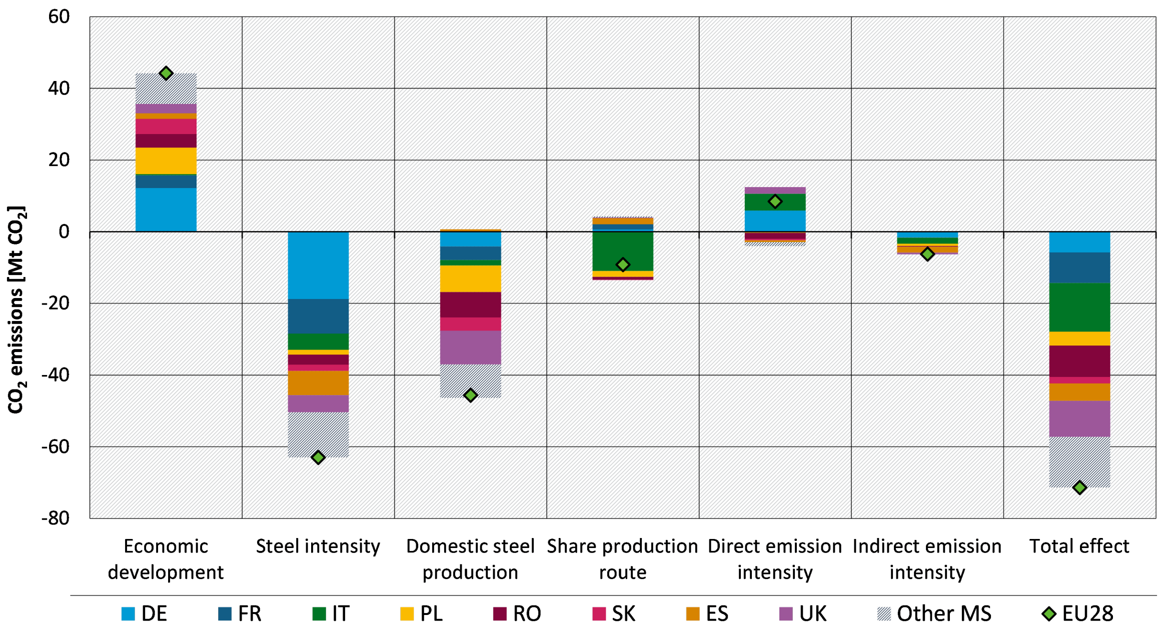
3.1.1 Total emissions

Based on our calculations, direct and indirect emissions from iron and steelmaking in the EU and UK have declined by at least 71.4 Mt CO_2, a reduction of 29 %, between the beginning of the EU ETS in the year 2005 and 2022. While we use the verified emissions in the EU ETS as one of our main sources, not all emissions covered by the EU ETS since 2013 were already covered in 2005. Hence, emissions have very likely declined even stronger. In fact, there were two rounds of scope extensions (in 2008, and in 2013), where additional emission sources were included to be covered by the scheme. As it was not possible to fully correct emission data for these scope extensions, results will tend to underestimate reductions between years before and after a scope extension occurred. Results will also tend to overestimate emission increases between years before and after a scope extension. Also, results will overestimate the effect of drivers increasing emissions, and underestimate the effect of drivers reducing emissions Nonetheless, results are robust on the direction of effects of drivers and give an upper/lower bound on the effect of the respective drivers.

All analysed Member States contributed to the decline in emissions (Figure 5). The main driver which had an increasing effect on emissions was the economic development. Despite this, absolute steel consumption declined between 2005 and 2022. As a result, the steel intensity (i.e. usage of steel per unit of GDP) was the largest driver that brought down emissions. In addition to the reduced steel consumption, domestic steel production decreased even stronger: In 2005, EU wide steel production was 6% higher than apparent consumption. In contrast, since the year 2015 domestic production was lower than consumption, i.e., the EU turned into a net importer. In 2022, domestic production was 15% below consumption. While the impact of a reduced steel intensity on the emission development is the highest in Germany, France and Spain, the reduced domestic production is most pronounced in the UK, Poland and Romania.

In most countries there have only been minimal changes in the share of the different steel production routes. Italy is the exception: over the time period analysed, the share of BF-BOF-route has declined strongly. The direct emission intensity has increased over time especially in Italy and Germany. This could be due to (a combination of) a fuel switch from gas to coal (e.g., in Austria, c.f. Rummer et al. (2017)), lower utilisation rates and the increasing age of steel production plants in the EU (see Mendelevitch et al. (2024) for a detailed country-level analysis). The indirect emission intensity, i.e., emissions associated with electricity consumption, has decreased since 2005. This is linked to the emission grid factor for electricity, which has declined due to an increase in renewables and the gradual phase-out of coal-fired power generation. In absolute terms, indirect emissions have only a small contribution to the overall effect; with emissions from iron and steelmaking dominated by direct emissions from the BF -BOF-route, changes in electricity consumption and/or emission factors have a much smaller impact.

Figure 5: Decomposition of the change of EU 27+UK CO_2 emissions from iron and steelmaking between 2005 and 2022 by country and effect

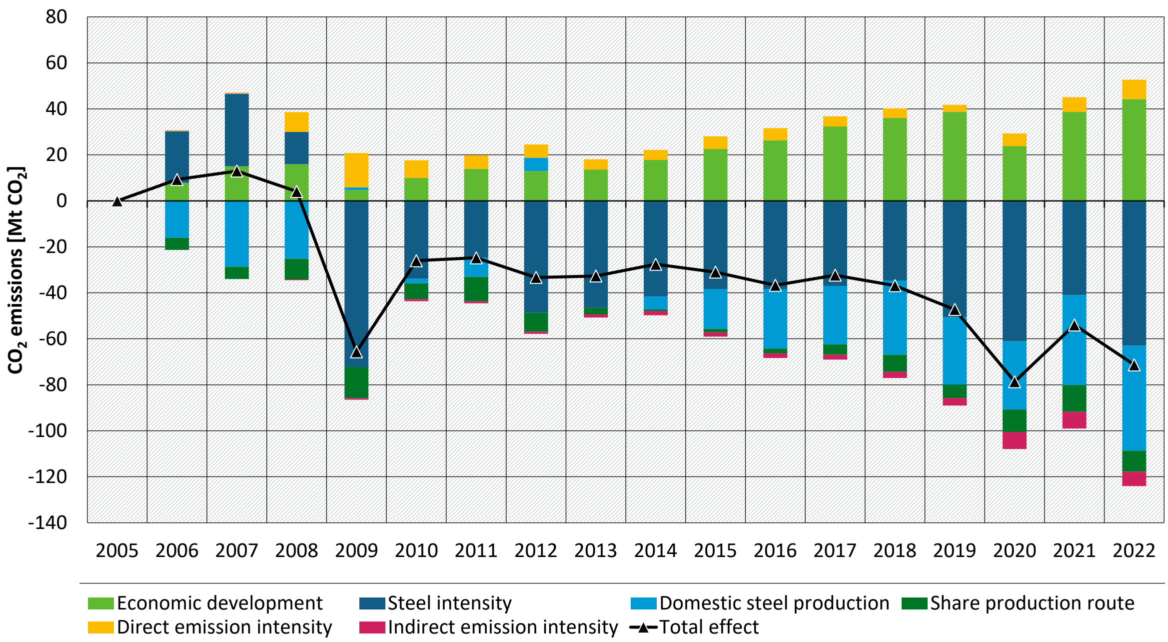


Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 6 shows how the individual drivers develop over time. The timeline can be divided into four periods:

- 2005 – 2008: Relatively stable emissions; the impacts of a higher steel intensity and economic development, i.e., higher steel demand, is nearly offset by higher imports.
- 2009: The global financial crisis led to a strong reduction in steel demand and emissions.
- 2010 – 2017: A second period of stable emissions. Steel intensity recovers but stays well below the levels prior to the financial crisis. From 2015 onwards, increasing steel demand due to economic development is served by higher imports, whereas between 2010 and 2014 the share of domestic production remained relatively constant.
- From 2018 onwards: Emissions from iron and steelmaking in the EU start declining again. The impact of the COVID19 pandemic are visible in 2020 but do not seem to have had a direct long-lasting effect. The main driver bringing emissions down was the decreased steel intensity.

Figure 6: Decomposition of the development of CO_2 emissions from iron and steelmaking since 2005 in the EU 27+UK



Source: Own calculations, Öko-Institut

The annual changes in Figure 7 show a similar story: the "steel intensity" (i.e., demand for steel in relation to the overall economic activity) decreased sharply in 2008/2009, in 2012 and again since 2019.

Steel intensity is the largest driver and an indicator for the transformation of the European economy with an increasing share of less resource-intensive service sectors in total GDP and a decreasing role of steel-intensive industrial production and manufacturing.

Potential impacts of the ETS on EU-wide iron and steel emissions and production should be reflected mainly in three drivers:

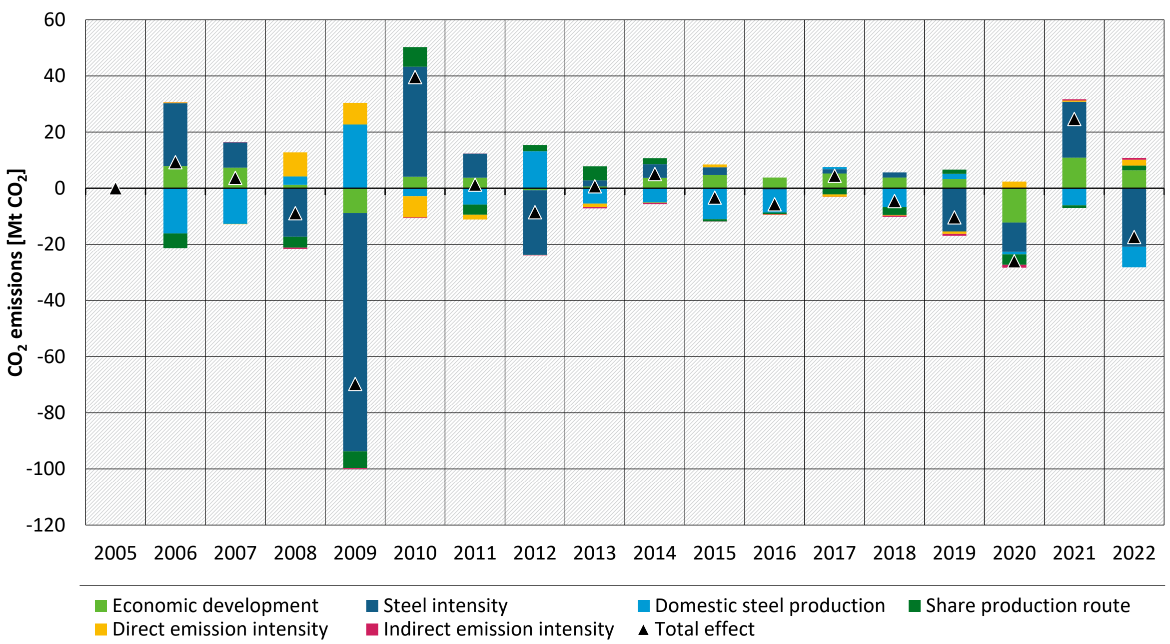
- Direct emission intensity: The carbon price should incentivise the use of less CO_2 intensive fuels.
- Share of production routes: The less carbon intensive production routes (EAF, DRI-EAF) should gain a competitive advantage compared to BF-BOF. This effect, however, is limited due to the current rules for free allocation that grant higher free allocations for the installations using the BF-BOF process. This is driven by concerns regarding carbon leakage risks and a potential constraint on steel scrap available to EAF processes. EU policy has continuously granted free allocations differentiated by the different production routes, thus almost eliminating the price incentives stated above.
- Domestic steel production: Carbon prices might make steel production less competitive compared to imports from third countries despite the rules to protect against carbon leakage.

These effects might be limited because of the rules of free allocation together with the level of current and expectations on future carbon prices during the examined time period. In addition, there are other important drivers such as energy price development, global economic development and global steel production capacity which impact the emission development of the European iron and steel sector. Initial considerations are drawn but these are not fully analysed and must remain the subject of further research.

In addition, the EU ETS contributed to the decreasing CO_2 intensity of the electricity grid. Less carbon-intensive electricity supports the overall decarbonization of iron and steelmaking. These changes are external to the iron and steel sector and not part of this analysis.

None of the three drivers for direct emissions stated above seem to be closely correlated with carbon price developments. Direct emission intensity has increased since the introduction of the ETS, mainly around the 2009 financial crisis. The share of BF-BOF shows two phases: A decline and then return to 2005 levels until the year 2014 and a gradual decline thereafter. The development until 2014 cannot be explained by the CO_2 price development during that time period. Domestic steel production through the BF-BOF route fell by 20 Mt steel/year between 2014 and 2022; about half of that decline came from the UK and Germany. The share of domestic steel production has had a large overall effect, but the decrease happened mainly in 2006/07 and again between 2013 and 2016. CO_2 prices were very low during these periods. Only the latest decline in 2021/22 might be linked to carbon prices.

Figure 7: Decomposition of the annual change of CO_2 emissions from iron and steelmaking in the EU 27+UK

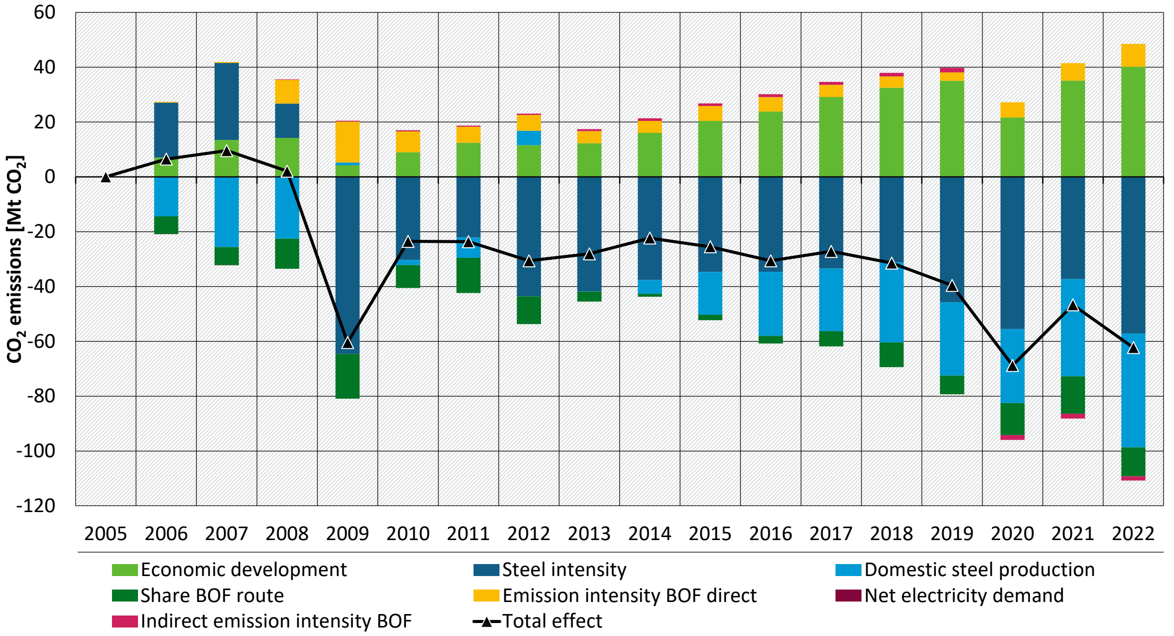


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.1.2 Emissions from the BF-BOF-route

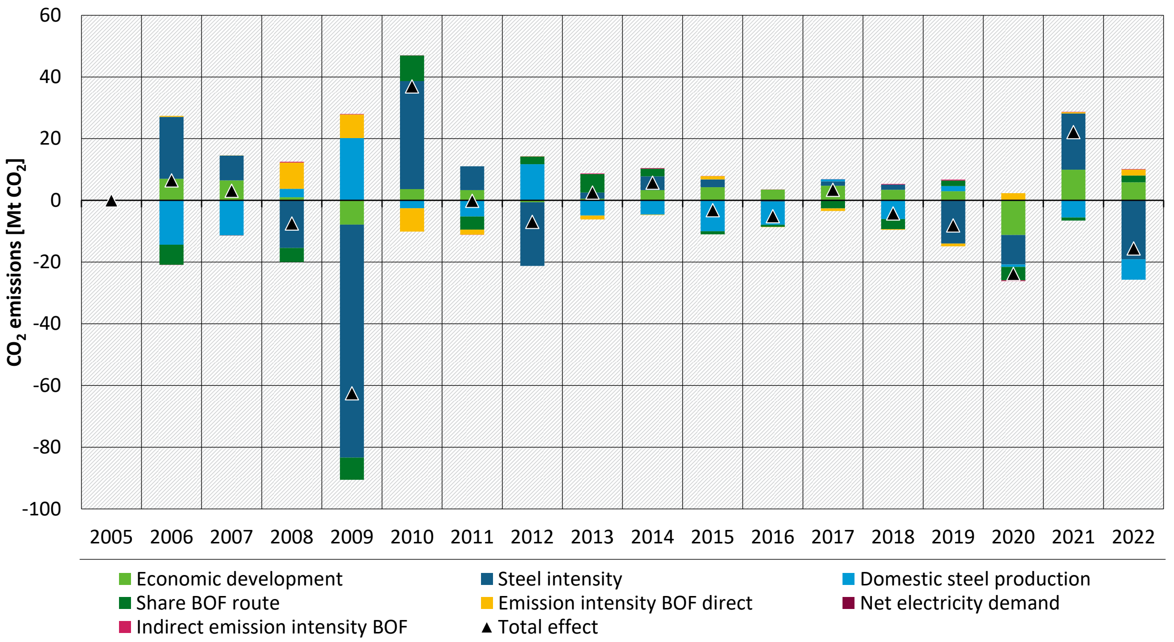
Emissions from the BF-BOF-route are responsible for over 95 % of total emissions from iron and steelmaking in the EU 27+UK. Accordingly, Figure 8 and Figure 9 are very similar to the decomposition of total emissions.

Figure 8: **BF-BOF-route: Decomposition of the development of CO_2 emissions from iron and steelmaking since 2005 in the EU 27+UK**



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 9: **BF-BOF-route: Decomposition of the annual change of CO_2 emissions from iron and steelmaking in the EU 27+UK**



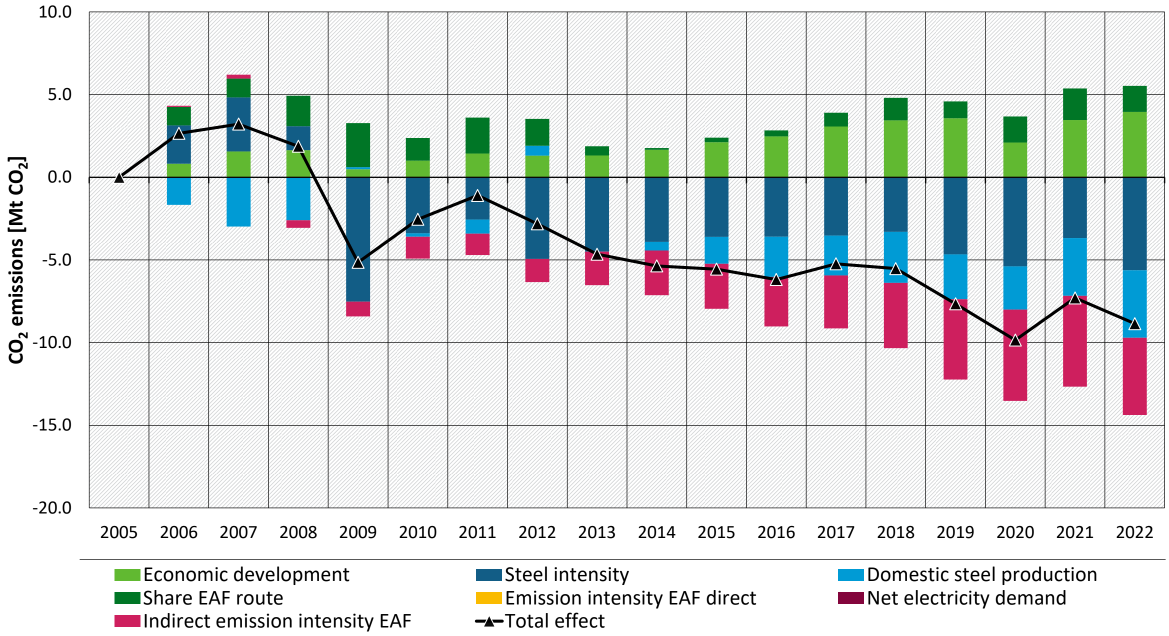
Source: Own calculations using the data sources in Table 4, Öko-Institut

3.1.3 Emissions from the EAF route

The decomposition of the emissions from the EAF route clearly show the impact of the gradual decarbonisation of the European electricity supply (Figure 10 and Figure 11). Indirect emission intensity declined in almost all years since 2005. Notable exceptions are the years 2021 and 2022. In 2022, the Russian invasion of Ukraine started which led to a stark increase of gas prices. As a consequence, electricity generation from coal increased despite high CO_2 prices at the same time. However, this latter effect is considerably smaller than the decline of the indirect emission intensity in the years previous to 2021 and 2022 (see Figure 8), so that the overall effect described above remains valid.

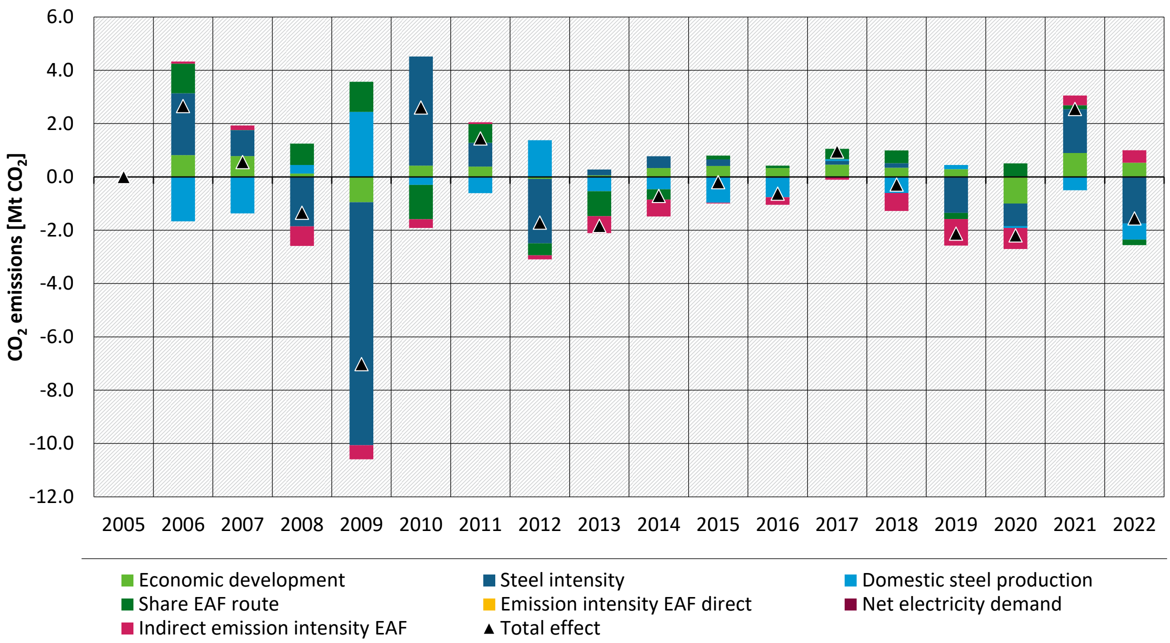
The share of the EAF route is an increasing driver; the decline of iron and steel production in the BF-BOF route was faster than in the EAF route. This mirrors the impact of the share in the BF-BOF route with the opposite sign.

Figure 10: EAF-route: Decomposition of the development of CO_2 emissions from iron and steelmaking since 2005 in the EU 27+UK



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 11: EAF-route: Decomposition of the annual change of CO_2 emissions from iron and steelmaking in the EU 27+UK

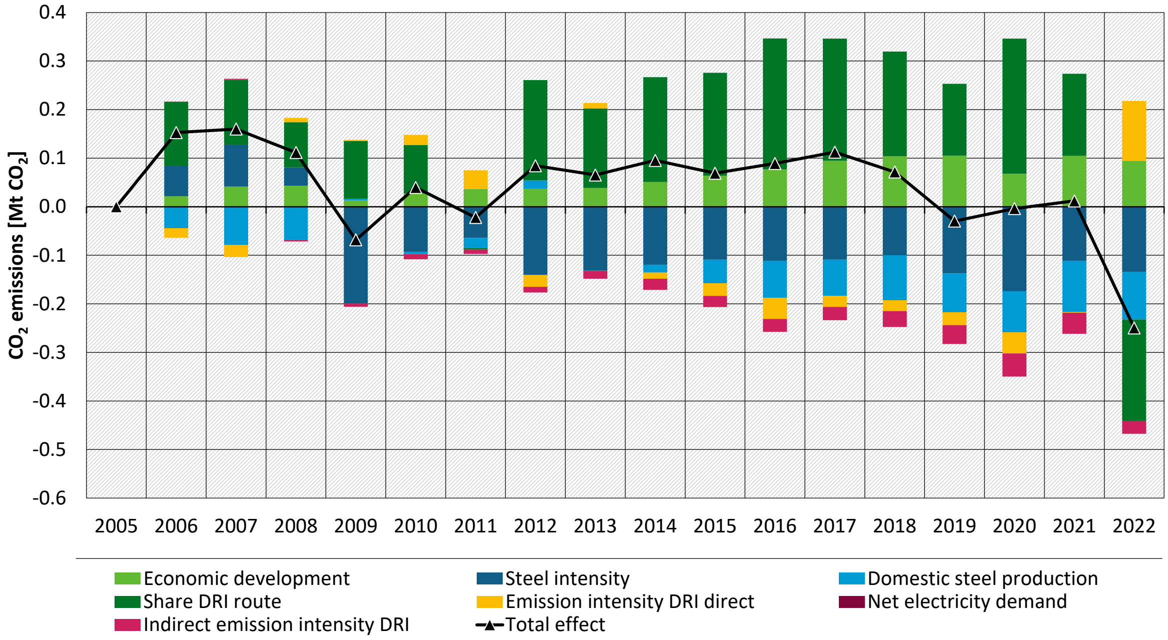


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.1.4 Emissions from the DRI-EAF route

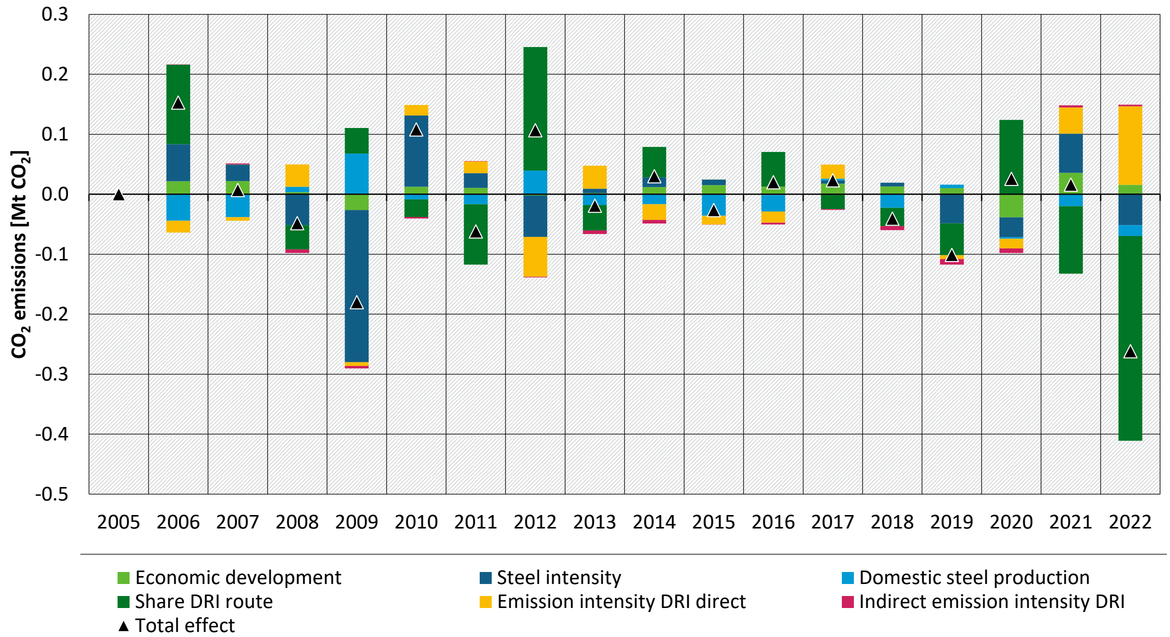
In absolute terms, the DRI-EAF routes is only of minor importance in the EU with only 0.4 % of the steel produced since 2005. Until 2022, about 80 % of DRI-EAF steel was produced in Germany, the remaining share in Sweden. In 2022, production in Germany was reduced by 70%, increasing the share of Sweden in total DRI production to 40 %. Together with the low emissions intensity of the DRI route, the impact on total emissions from the sector is negligible. Due to the identical macro-economic drivers (economic development, steel intensity, share of domestic production) the overall cumulated and annual development (Figure 12 and Figure 13) is very similar to the decomposition of total emissions. The decline in the electricity grid emission factor is clearly visible. Noticeable is the sharp increase of the emission intensity in 2022: this is linked to the very high prices for natural gas after the Russian invasion of Ukraine. DRI production dropped by almost 60% compared to the previous year which seems to have led to a lower capacity utilisation and therefore lower efficiency, on the one hand, and an increase in the relative role of the Swedish DRI production unit, which is based on gasified coal rather that gas as a reduction agent, and hence comes with a much higher emission factor.

Figure 12: DRI-EAF-route: Decomposition of the development of CO_2 emissions from iron and steelmaking since 2005 in the EU 27+UK



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 13: DRI-EAF-route: Decomposition of the annual change of CO_2 emissions from iron and steelmaking in the EU 27+UK



Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2 Results for selected countries

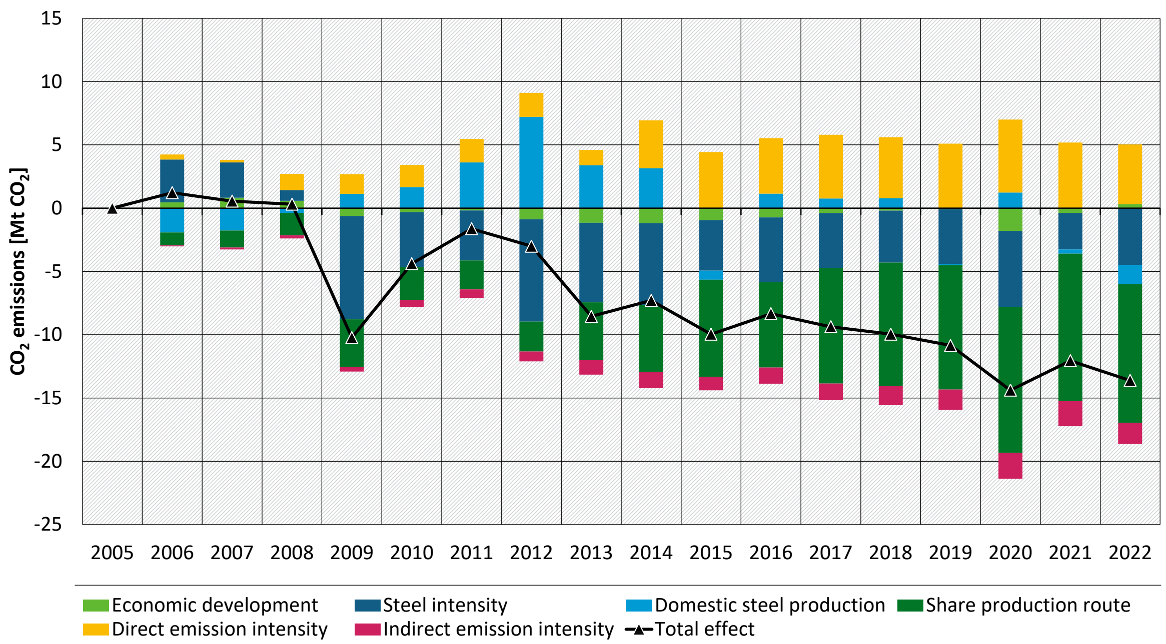
Due to the scope and breakdown of the data sources used, a national assessment is only possible for some countries. In the following we show the results of those countries which have the strongest impact on overall CO_2 emissions from iron and steelmaking in the EU and those that drive the changes in the individual effects. Countries are sorted in decreasing order compared to their impact on total emissions.

3.2.1 Italy

With a share of almost 20 % to the total EU-wide emission reduction, Italy is the country with the largest single contribution to the overall trend. Yet, compared to the EU development there are some stark differences (Figure 14):

- The economic development, the largest driver increasing emissions EU-wide, does not play a role in Italy. In real values, the Italian GDP has remained at 2005 levels.
- The direct emission intensity, i.e. emissions per unit of produced steel from the BF-BOF-route, has had an increasing effect on emissions. This is at least partially due to the only integrated steelworks in Italy. Due to extreme levels of air pollution it was seized by the government and subsequently bought by another company. Current production levels in that plant are about half of 2005; the lower capacity utilisation results in lower efficiencies and therefore higher direct emissions per unit of steel produced (c.f. country level analysis in Mendelevitch et al. (2024).
- The decomposition shows a clear shift towards the EAF-route. In absolute terms, EAF-production remained stable since 2005 while the BF-BOF-route declined. The electricity grid emission factor decreased by 55 % during that period, emissions from the EAF route decreased in parallel.
- The steel intensity and domestic steel production follow the general EU-wide trend but are much less pronounced.

Figure 14: Decomposition of the development of CO_2 emissions from iron and steelmaking since 2005 in Italy

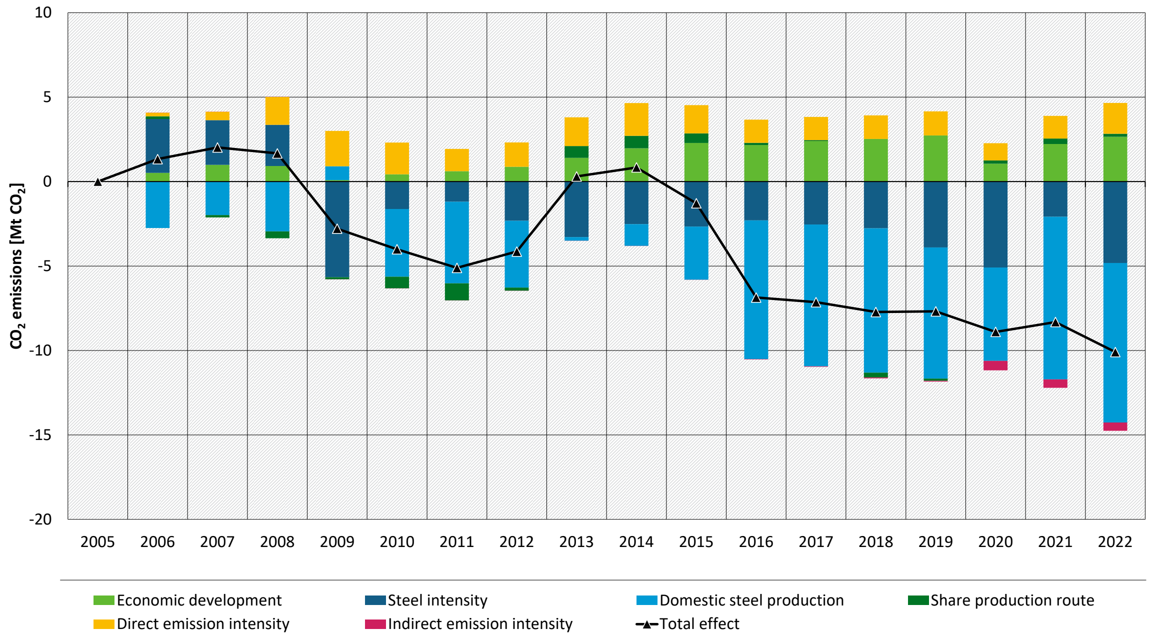


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.2 United Kingdom

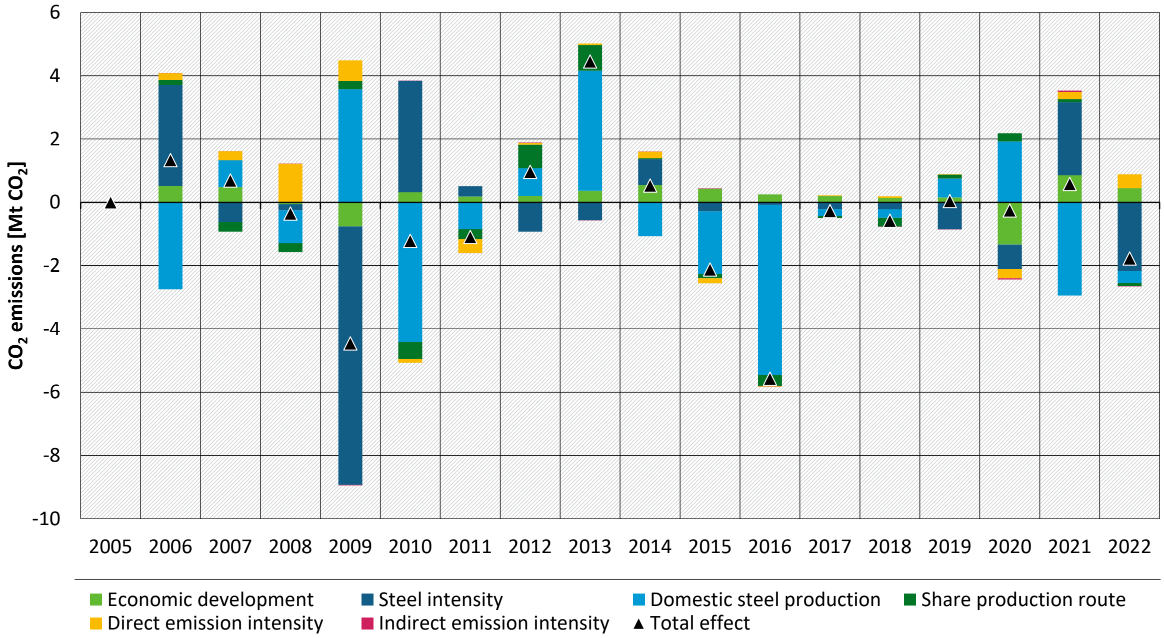
Figure 15 clearly shows the decline of domestic steel production in the UK. Between 2014 and 2022, absolute production went down from 12 Mt steel/year to 6 Mt steel/year. The annual change in Figure 16 shows the impact of the economic crisis around 2009. In absolute terms, production remained at 2009 levels until 2012; the domestic share increased somewhat due to an even stronger decline in steel intensity. Steel consumption never returned to pre-crisis levels. The insolvency of an integrated steelworks which was responsible for 30% of the BF-BOF-route emissions in 2015 has had a clear impact on production levels (c.f. country level analysis in Mendelevitch et al. (2024). With about 20% of total steel production the (secondary) EAF route is relatively small in the UK; the EU 27+UK average is about 40 %. This share has remained constant since the beginning of the ETS and the EAF contribution to emission reductions is only due to a decline in the grid emission factor.

Figure 15: Decomposition of the development of CO_2 emissions from iron and steelmaking in the UK



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 16: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in the UK



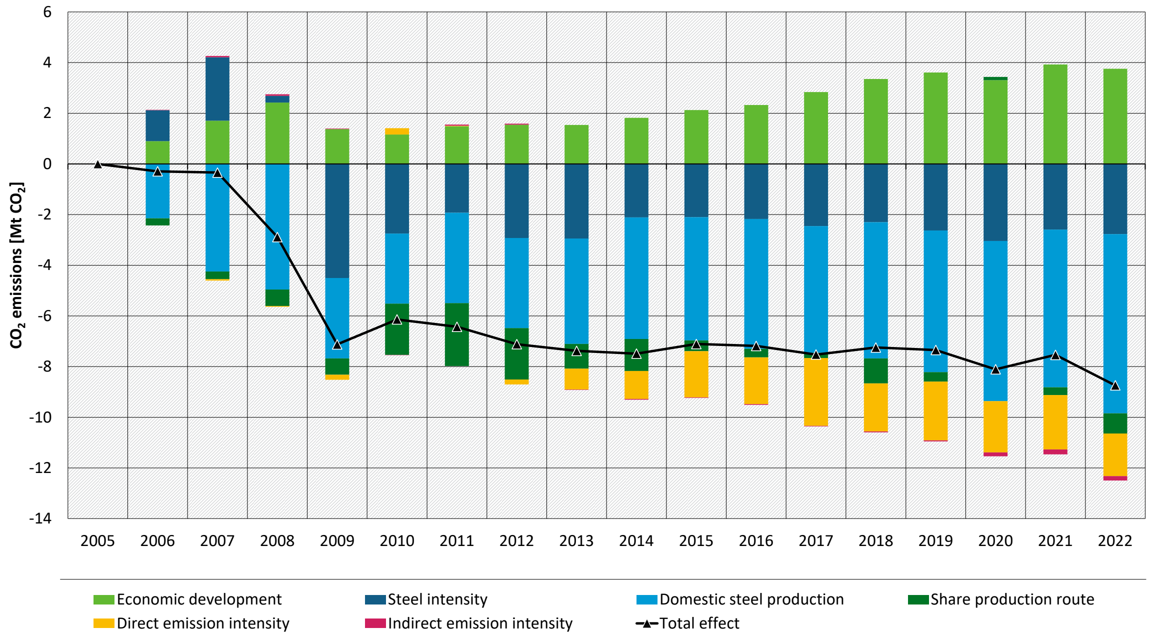
Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.3 Romania

The development of CO_2 emissions from iron and steelmaking in Romania is dominated by the declining share of domestic production. The largest part of this decline happened between 2005 and 2007. Romania only entered the EU in 2007 and in that year CO_2 prices reached almost zero. This decline in domestic reduction is not related to the ETS. The 2009 financial crisis and again the price shocks after the Russian invasion impacted the share of domestic production.

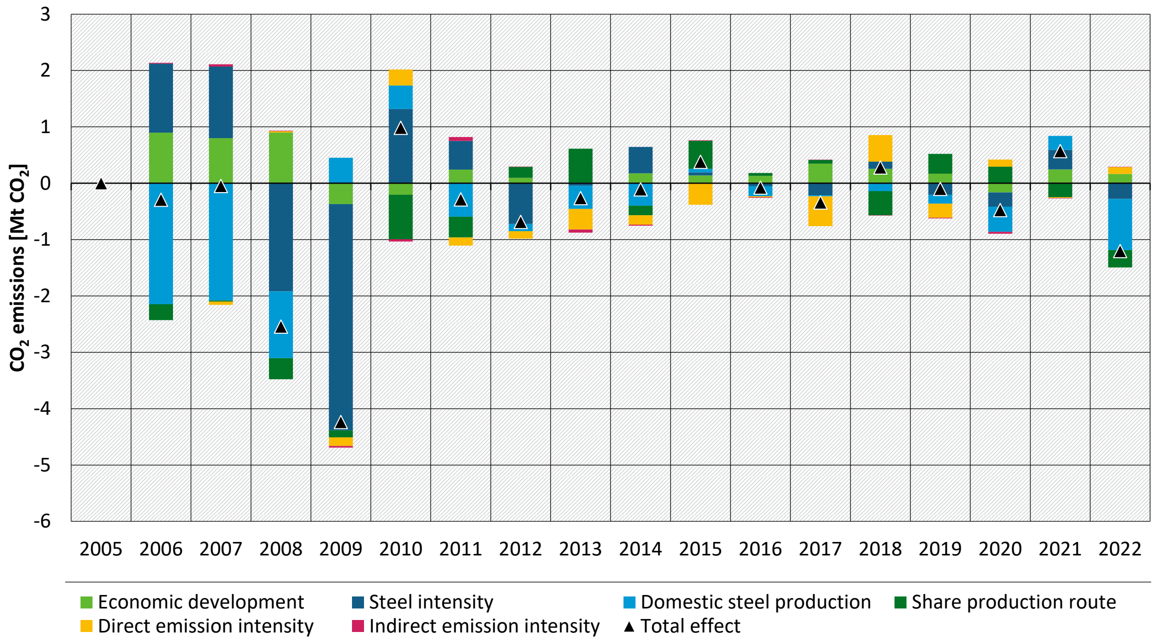
A noticeable difference to the EU-wide trend is the emission intensity from the BF-BOF-route. The emission intensity has reduced emissions gradually since 2012. The EU ETS might have contributed to this development. On the other hand, the grid emission factor has not contributed much to an emission decrease.

Figure 17: Decomposition of the development of CO_2 emissions from iron and steelmaking in the Romania



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 18: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in Romania

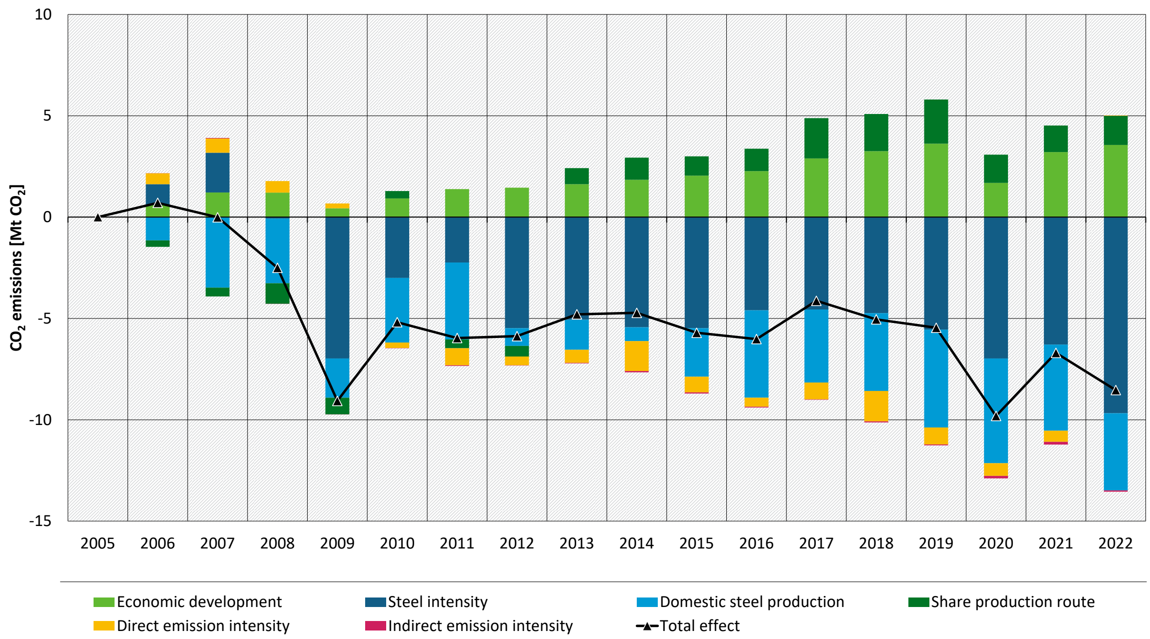


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.4 France

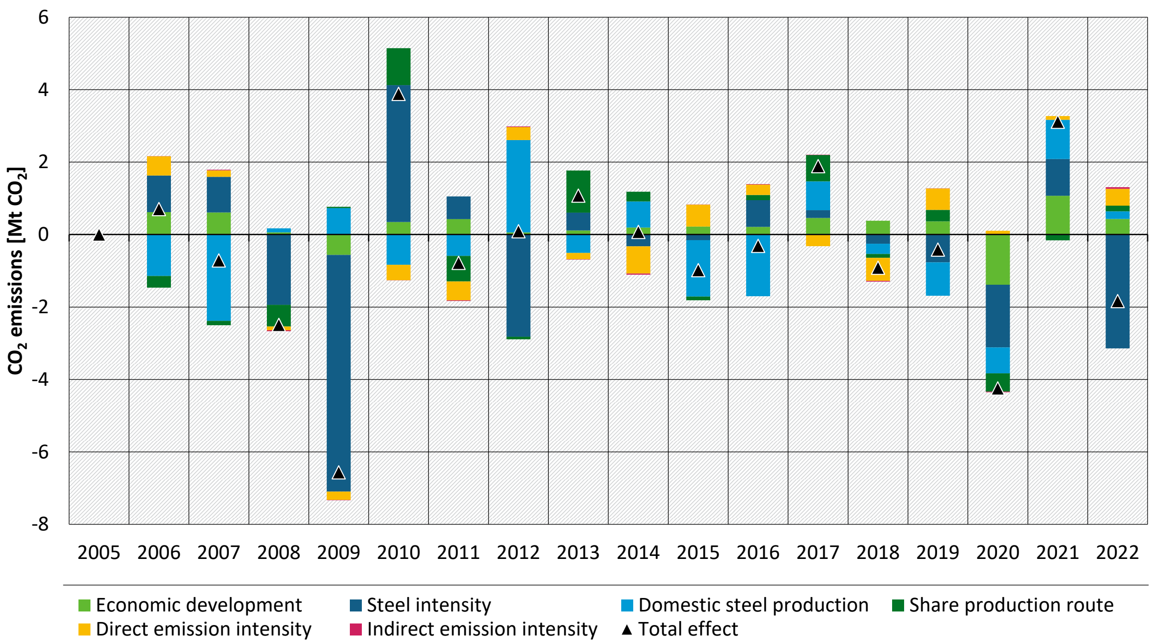
Overall, emissions drivers in France developed very similar to the EU-wide development. The direct emission intensity improved compared to 2005 in almost all years; the return to 2005-levels in 2022 is most likely due to the high gas prices after the Russian invasion of Ukraine. The share of EAF in total production declined somewhat, an atypical development compared to other countries. Indirect emissions did not play a role in the emission development. The French electricity grid already was mainly decarbonised in 2005 with very low emissions from EAF production.

Figure 19: Decomposition of the development of CO_2 emissions from iron and steelmaking in France



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 20: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in France

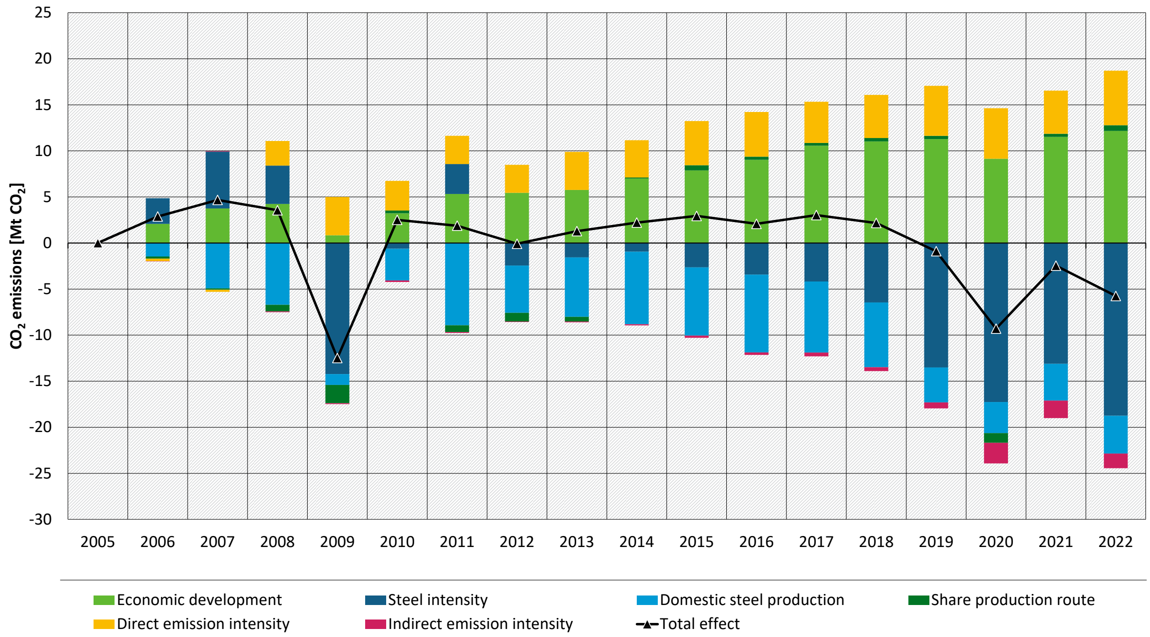


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.5 Germany

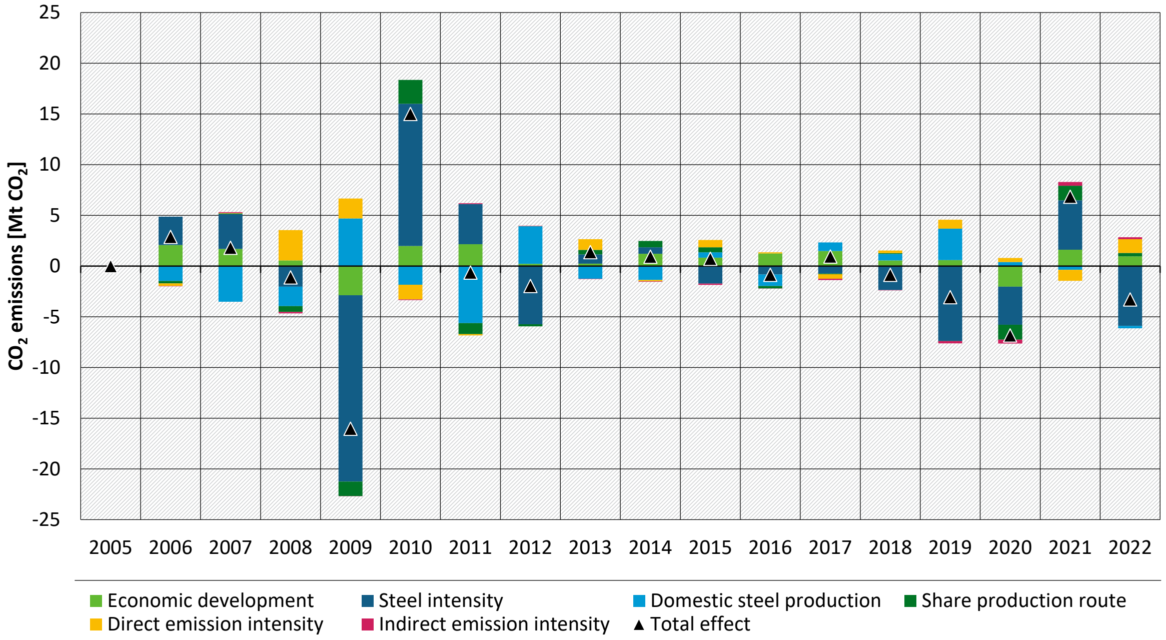
As the largest economy in the EU and also its largest steel producer, the development of the German drivers is very similar to the EU trend. Despite this, emissions from iron and steelmaking in Germany have remained almost stable. The trend for a lower share of domestic steel production is much less pronounced than in other EU Member States and the share of EAF and DRI-EAF has decreased. While the EU-wide steel intensity sharply declined during the economic crisis 2009 and never recovered, the picture is quite different in Germany (Figure 21). In 2011, the steel consumption per GDP peaked and declined gradually thereafter. The steel intensity only really declined from 2018 onwards. The decarbonisation of the electricity grid can also clearly be seen.

Figure 21: Decomposition of the development of CO_2 emissions from iron and steelmaking in Germany



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 22: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in Germany



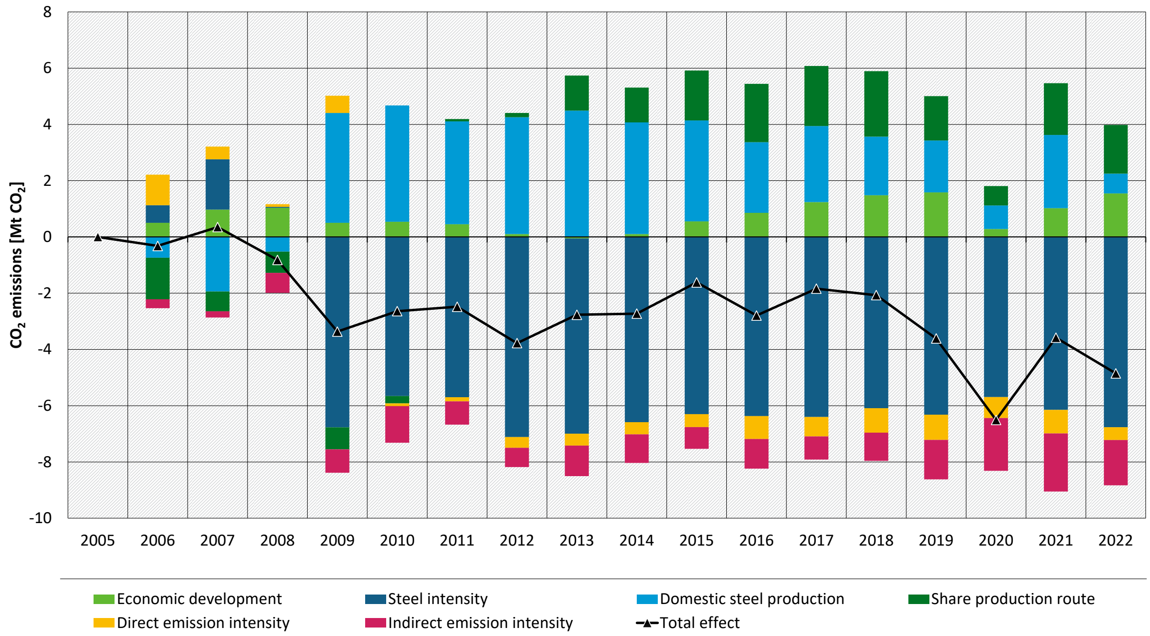
Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.6 Spain

The Spanish economy, and in particular the demand for steel, was hit particularly by the global financial crisis in 2008 and then again by the Euro-crisis 2011/2012. Steel intensity broke down and never recovered. The Spanish steel industry was able to at least partially make up for this by increasing exports to third countries. A similar pattern is visible in the decomposition of the Spanish cement industry (Emele et al. 2022). The export share decreased again at the beginning of the COVID-19 pandemic and again after the Russian invasion of Ukraine.

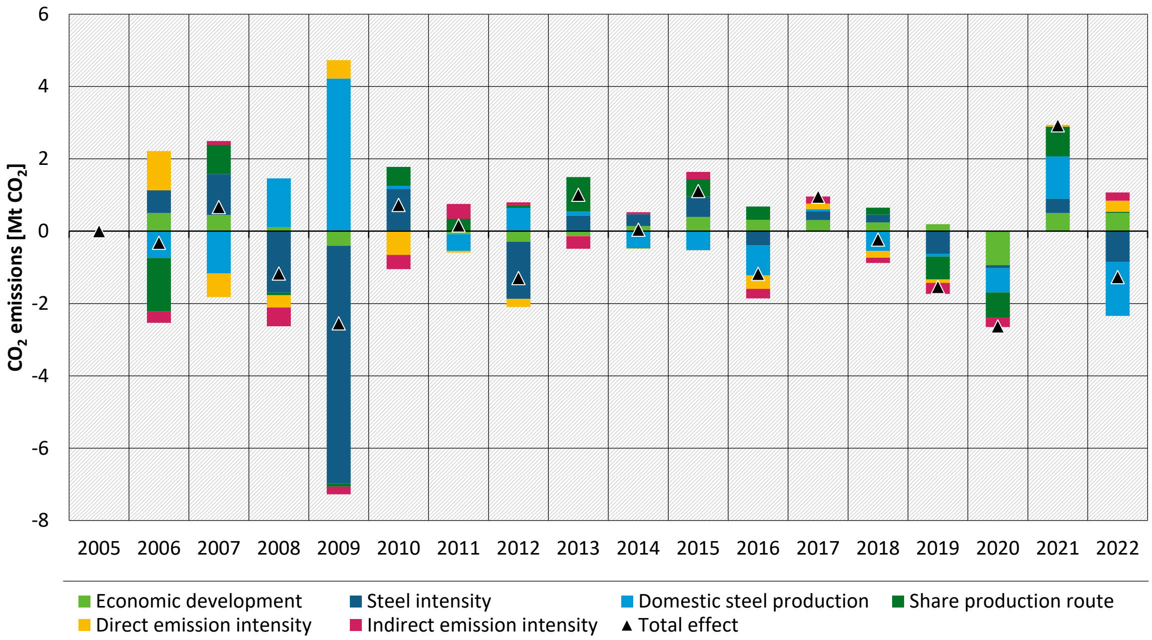
Spain has a large share of the EAF-route of almost 70 %. The decarbonisation of the electricity system can be clearly seen in the overall emission development. In addition, the direct emission intensity has improved somewhat compared to 2005.

Figure 23: Decomposition of the development of CO_2 emissions from iron and steelmaking in Spain



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 24: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in Spain



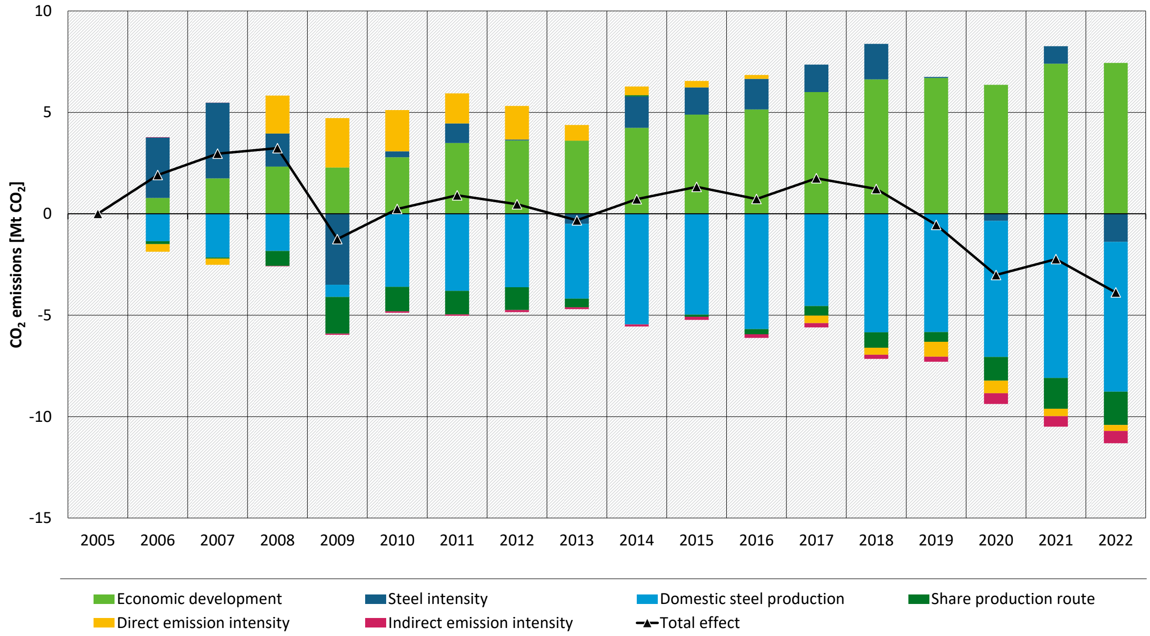
Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.7 Poland

Emissions from iron and steelmaking in Poland remained relatively stable for most of the time period since the introduction of the ETS. The strong economic growth was compensated by a lower share of domestic steel production. Similar to the emission development steel production remained relatively stable; at the same time, steel demand increased which was met by a higher import share. The steel intensity also remains relatively constant, there is no visible trend as in most EU Member States.

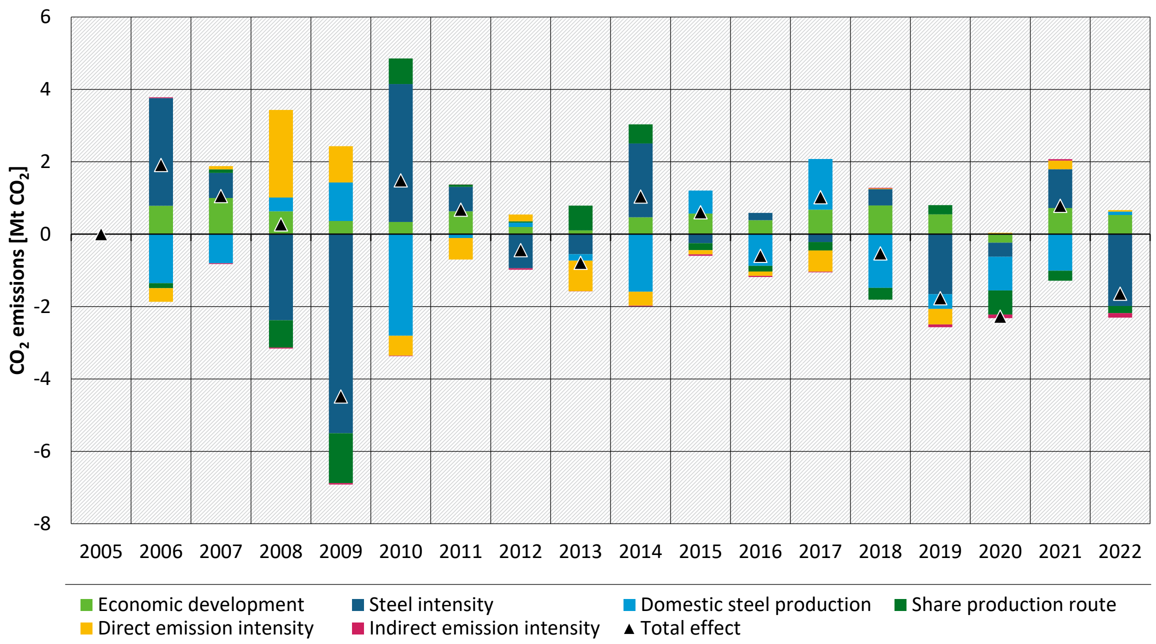
There is a slight improvement of the direct emission intensity in the last five years. This might be linked to the end of operation of one integrated steel works in 2019 (c.f. country level analysis in Mendelevitch et al. (2024)). The graph also shows that – despite a share of almost 60 % EAF steel – the indirect emission intensity has not improved much.

Figure 25: Decomposition of the development of CO_2 emissions from iron and steelmaking in Poland



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 26: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in Poland

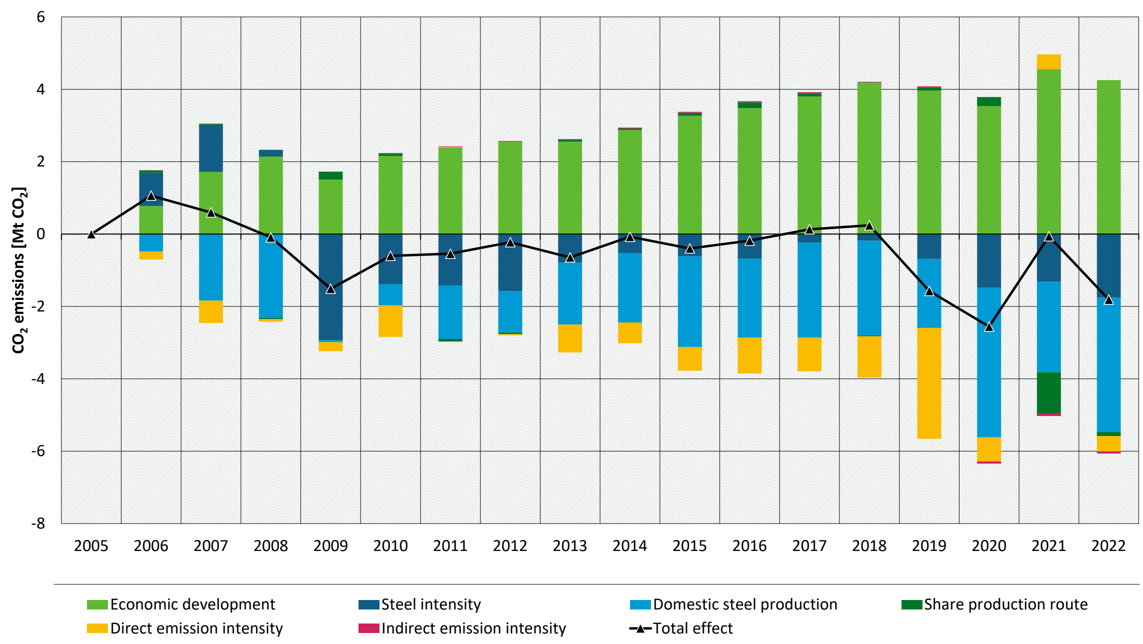


Source: Own calculations using the data sources in Table 4, Öko-Institut

3.2.8 Slovakia

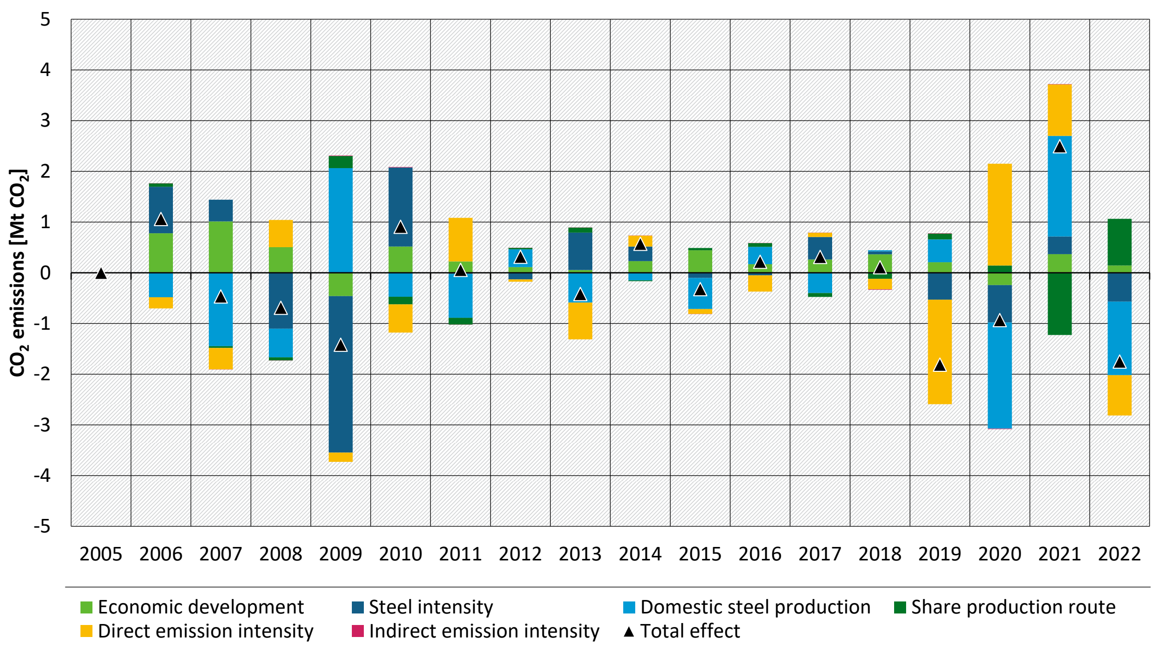
Similar to Poland, emissions from iron and steelmaking in Slovakia remained stable until the latest years. The impact of the strong economic development was offset by a higher import share and – until 2019 – a clear improvement of the direct emission intensity. This improvement was especially high in 2018, but was lost in 2020, during the COVID-19 pandemic and afterwards in 2022 during the Russian invasion of Ukraine. There has been no change in the share of the different production routes. Only around 10 % of total steel production is coming from the EAF route.

Figure 27: Decomposition of the development of CO_2 emissions from iron and steelmaking in Slovakia



Source: Own calculations using the data sources in Table 4, Öko-Institut

Figure 28: Decomposition of the annual change of CO_2 emissions from iron and steelmaking since 2005 in Slovakia



Source: Own calculations using the data sources in Table 4, Öko-Institut

4 Conclusion

With a turnover of about 130 billion EUR and gross value added of 107 billion EUR (direct and indirect), in 2022, iron and steel industry plays an important role for value creation and employment in the EU-27 and induces substantial intra-EU and also international trade (EUROFER 2023). It is also the industrial sector with the highest absolute CO_2 emissions. The share of emissions in the ETS for EU 27+UK was 14% in 2022 (EEA 2023a) and the share of total EU 27+UK emissions is 5%.

Emissions from iron and steelmaking are reported under activity codes 22-25 in the EU ETS. Additionally, emissions from waste gas combustion in power plants is reported under activity code 20. Since the introduction of the EU ETS in 2005, total sector emissions covered by the EU ETS have declined from 235 Mt CO_2 to 178 Mt CO_2, in 2022. With two rounds of scope extensions for the EU ETS, emissions from installations now covered by the scheme have most probably declined even stronger. Note that these figures also do not include indirect emissions from electricity consumption, which are particularly important on the EAF-route, and DRI-EAF-route. In this paper we are able to shed light on the drivers of the declining trend, including both direct and indirect emissions, and with a special focus on the role of the EU ETS.

The decline of emissions from iron and steelmaking covered by the EU ETS in the EU 27+UK was primarily driven by a reduction of production on the emissions intensive BF-BOF-route. There was no major shift in production routes, but rather production was decreased in times of economic downturn, and instead of full recovery due to renewed economic development, increasing demand was partially met with a boost in imports. Most of these reductions in production and production capacity have occurred in periods with very low CO_2 prices in the EU ETS. Hence it seems plausible that the EU ETS did not have had a short-term effect in contributing to production cuts or closures.

The EU ETS might have induced a shift from the BF-BOF-route to the electricity based EAF-route, which would have reduced direct emissions to less than 20%. However, this shift did not occur on a major scale. This could be due to limited scrap resources in the EU, the need for new large-scale investments in EAF installations and large-scale electricity connectors, and the limited substitutability of EAF-based crude steel produced from scrap and crude steel from primary production routes (BF-BOF route, DRI-EAF route). The former mostly comes with impurities which makes it only acceptable for simple, low performance products like construction bars, but not for high-quality steel required for large parts of car manufacturing or appliances. Therefore, primary DRI-based routes are the preferred transformation path for most integrated steelmaking sites.

On the country level, Italy has seen the largest decline in emissions, but even more so in total crude steel production. Total production is about half of 2005 and the low-capacity utilisation results in an inefficient use of the installation and therefore high specific emissions of crude steel production. UK has seen a similar decline in production levels, but in contrast to Italy, where idle capacity has not been closed, it has led to the closure of one integrated site. While the Spanish iron and steelmaking industry was heavily hit by the financial and later by the Euro crisis, the German steel industry was much less affected.

No significant technological advances that would have led to a more efficient production can be found in the data. However, due to the setup of our analysis, effects of a change in the energy mix on a particular route and changes in technology influencing efficiency, cannot be disentangled. Hence, at least the combination of both had no substantial effect on emissions decline. Emission reductions in power generation are clearly mirrored in the data on indirect emissions of the iron and steel production. However, due to the overall small contribution of indirect emissions from electricity to total emissions[6] , they are not a major driver of total emission reductions.

For the future, dynamic times are ahead for the European iron and steelmaking industry, with pressure from international markets, an ageing fleet of integrated steelmaking sites and significant and increasing CO_2 prices expected. In many countries the transition process from the BF-BOF-route to the DRI-EAF route has already started or is about to do so (see Mendelevitch et al. (2024)). One tool to support this transformation which is already applied e.g., in Germany, are Carbon Contracts for Differences (CCfDs). Here the EU ETS will play an important, indirect role: since the subsidy rates depend on the cost differences between new and conventional technologies, the allowance prices affect the subsidy amounts to be paid.

A future analysis will be able to examine the development on the DRI-EAF route, with more units coming online. Also, the role of embedded CO_2 in imported inputs, like coke, DRI, and pig iron should be further assessed. With the Carbon Boarder Adjustment Mechanism (CBAM) unfolding, it will be interesting to analyse whether it will change the relative attractiveness of imports and favour reintegration of the iron and steel industry supply chains.

[6] The industry's emissions are dominated by those of the BF-BOF route which in turn has primarily direct emissions.

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A Annex I: Production processes and technologies

The steelmaking process can be differentiated into three fundamental production routes based on the basic input material and the fuel and reducing agent they use:

- The most common production route, mostly referred to as Blast Furnace and Basic Oxygen Furnace route (BF-BOF), uses coke as the main reducing agent and fuel input. An important additional input in the BOF is steel scrap (typically a share of around 14% per ton of crude steel).
- The Direct Reduced Iron (DRI) production route currently uses syngas (produce from natural gas or coal) as reduction agent. Future DRI concepts rely on hydrogen as a reduction agent. DRI plants produce intermediary products such as iron sponge (DRI) or hot briquetted iron (HBI). In Electric Arc Furnaces, the intermediary product is further processed to crude steel. Other concepts also foresee smelters in order to use the iron sponge in a BF-BOF (tyssenkrupp (17 Mar 2021)).
- Steelmaking on the EAF production route uses recycled steel scrap as material input but can also use intermediary products from DRI in variable amounts up to 100%. Here, the key "fuel" used is electricity.

Table 5 provides an overview on emissions, production levels and specific emissions intensity level of crude steel production by route for the EU 27+UK, as a timeseries from 2005 to 2022. Emissions on the BF-BOF-route has declined by more than 25%, with those on the EAF-route decreased by less than 10%. Emissions from the DRI-route have been stable until 2021, and dropped heavily in 2022, due to high gas prices and a reduction in production in Germany.

Table 5: Emissions, production level and specific emission intensity of crude steel production by route on the EU 27+UK level, 2005-2022

Process	Indicator	Unit	2005	2009	2010	2015	2018	2019	2020	2021	2022
Blast furnaces (BF-BOF-route)	Direct emissions[1]	[Mt CO_2]	215.7	152.9	190.9	186.0	188.4	182.2	150.3	171.9	156.5
	Production	[Mt crude steel]	118.6	77.5	101.1	100.1	100.9	98.1	80.2	91.5	82.3
	Specific emissions	[t CO_2/t crude steel]	1.82	1.97	1.89	1.86	1.87	1.86	1.87	1.88	1.90
Electric arc furnace (EAF-route)	Direct emissions[1]	[Mt CO_2]	9.2	8.2	9.6	9.7	9.7	10.2	8.6	9.7	8.6
	Production[2]	[Mt crude steel]	72.0	60.7	70.5	65.7	64.8	68.9	58.4	67.9	59.8
	Specific emissions	[t CO_2/t crude steel]	0.13	0.13	0.14	0.15	0.15	0.15	0.15	0.14	0.14
Directly	Direct emissions[3]	[Mt CO_2]	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.3

Process	Indicator	Unit	2005	2009	2010	2015	2018	2019	2020	2021	2022
	Production	[Mt direct reduced iron]	0.5	0.5	0.6	0.6	0.7	0.7	0.6	0.6	0.3
	Specific emissions	[t CO_2/t product]	0.84	0.84	0.88	0.86	0.80	0.80	0.77	0.84	1.17
Other	Emissions	[Mt CO_2]	9.7	6.7	8.6	13.7	12.4	12.6	9.6	13.8	12.9
Total	Emissions	[Mt CO_2]	235.1	168.3	209.6	210.0	211.1	205.5	169.1	195.9	178.3
	Share of EAF-route	%	38%	44%	41%	40%	39%	41%	41%	42%	43%

Note: [1] data on emissions from BF-BOF-route and EAF route is gap-filled: Bulgaria and Romania for 2005 and 2006 based on production and average emission factor (2007-2011), for Croatia for 2005-2012 based on production and average emission factor 2013-2015.; [2]excluding EAF steel production from direct reduced iron. [3]Data on emissions from direct iron reduction in Germany are only available from 2013 onwards.
Source: EUTL, Worldsteel

A.1 Steel production in BF and BOF

A.1.1 Process description

Blast furnaces and basic oxygen furnaces are integral part of an integrated steelworks.

The primary process for making steel involves the conversion of iron-ore using coal and other substances into hot metal in a BF. In order to convert hot metal into crude steel, the carbon content of the hot metal is reduced through oxidization in a BOF (e.g. by converting carbon to carbon monoxide and dioxide). The liquid molten steel from the BOF is then cast into crude steel forms (e.g. slabs, blooms, billets) for further processing into finished steel products:[7]

Raw material preparation (important for the even gas flow throughout the blast furnace):

- In a **coking plant** (coking) coal is heated in an oxygen-free atmosphere to produce coke (solid). A major by-product is coke oven gas (COG), which is often used to generate heat and electricity needed at further steps of the process. Coke is used as the major reducing agent in hot metal production. The plant can be located at the site of an integrated steelworks, alternatively coke can also be transported via ship or rail. In integrated steelworks coking plants often use blast furnace gas as a fuel.
- In a **sintering plant**, the iron ore fines are prepared for their use in the BF. Therefore, a mixture of iron ore fines, recycled ironmaking products, fluxes, slag forming agents (limestone), and solid fuel (coke) undergo a thermal agglomeration process whereby the sinter mixture is partially melted to form the sinter cake. After a screening process the agglomerated fines can be loaded into the BF.(D. Fernández-González et al. 2017). Due to the

[7] The following process description in based on (Remus et al. 2013) and https://www.vdeh.de/en/technology/steelmaking/. Additional sources are specified.

fragility of the sinter, the plant is located at the site of the integrated steelworks, close to the blast furnace.

- A **pelletising plant** performs a complementary process for improving the characteristics of the iron ore for the subsequent reduction process: Fine-grained ore mixture is moisturized and combined with biding agents to form pellets, which are dried and burned. These plants are usually located at the ore producer sites.

Iron making process:

- The **blast furnace** is fed from the top by iron-bearing materials (i.e. iron ore lump, sinter and/or pellets), additives (e.g. slag formers such as limestone) and coke. Other reducing agents such as pulverised coal, natural gas or oil are also injected into the blast furnace. To a certain amount they can work as a substitute for the coke. In contrast to coke, they access the furnace in a liquid or gaseous state and thus are not able to substitute the coke's function as a supporting matrix for the solid charge column above.
- A hot air blast produced in the cowper reacts with the reducing agents to produce carbon monoxide (CO). The gas rises binding the oxygen in the iron bearing materials (iron oxides) and oxidizing to CO_2. The rising gases heat the reduced charge of material lying above them which finally melt and gather at the lower part of the furnace. (Remus et al. 2013).
- The liquid iron (referred to as **hot metal** or **pig iron**) and slag gather at the hearth, at the bottom of the BF. After tapping, hot metal and slag are separated, and the hot metal is directed towards further processing for the production of crude steel. After further processing, the slag is largely used as a raw or building material in the cement industry or for road construction (Remus et al. 2013).
- **BF (waste) gases**, i.e. the gases rising in the BF, are collected and treated prior to being used as fuel for the cowper, other processes and electricity production.

Steel making process:

- The process of converting hot metal into crude steel involves: pre-treatment (e.g. desulphurisation), oxidization of the impurities (nowadays performed in a Basic Oxygen Converter), followed by further post-treatment (e.g. secondary metallurgy) to improve the quality of the steel and finally casting (continuous or /and ingot).
- In the **Basic Oxygen Converter/Furnace** hot metal is further purified through oxidization. Through the injected Oxygen the carbon content is reduced to the desired level and impurities such as silicon, sulphur and phosphorus are removed creating a slag that floats on the liquid metal bath.
- **BOF (waste) gas**, i.e. the carbon monoxide gas formed by the injected oxygen reacting with the dissolved carbon, is collected, treated and often used for heat and electricity production in other process steps.

- **Scrap steel** is added into the process in significant amounts of (14% on average) [8] to moderate the exothermal reaction and to balance the temperature at approximately 1 600 to 1 700°C.

A.1.2 Energy and CO_2 emissions balance

According to literature and bottom-up data collected from the EUTL a typical operation producing one ton of crude steel requires the following fuel and electricity inputs:

- Fuel inputs
  - According to He et al. (2017) and Otto et al. (2017) a typical integrated steelworks consumes 1.23-1.43 MWh of steam coal. Additionally, some natural gas is used e.g. in downstream processes (0-0.06 MWh). Inputs of coking coal show a broader range between the two sources: 3.27-3.83 MWh[9]. The variation is due to the different underlying age and technology structure for the two sources. While He et al. (2017) is based on data of the relatively young and modern Chinese steelworks fleet, data in Otto et al. (2017) is based on the EU-level data prepared for the best available technology (BAT)-assessment from 2012 and before. On average this implies around 3.55 MWh per ton of crude steel. The conversion efficiency in terms of MWh output of coke per MWh input of coking coal according to He et al. (2017) is 88%, Otto et al. (2017) implies an efficiency of 80%.
  - Within an integrated steelworks, about 0.7 MWh of coke oven gas (COG), 1.3-1.5 MWh of BF-gas and 0.2 MWh of BOF-gas are produced which are fully consumed in further processes in the integrated works (c.f. He et al. (2017), Otto et al. (2017), Griffin et al. (2016)). The gases are used as a heat source in the process and by on-site powerplants for generating the required electricity.
- Electricity demand and auto-generation
  - Total electricity produced depends on the specific configuration of the steelworks and the employment of additional recovery technologies (such as BF top gas pressure recovery turbines).
  - Total electricity demand (including casting, rolling and further processing steps) is up to 0.41 MWh per ton of crude steel Griffin et al. (2016). If further process steps are not part of the integrated steelworks, on-site electricity consumption equals to about 0.14-0.20 MWh per ton of crude steel (on average 0.17 MWh per ton of crude steel).[10] In order to be able to compare results to emission data on the installation level further

[8]. He et al. (2017) assumes that the production of one ton of crude steel consumes 950 kg of pig iron and 140 kg of scrap steel. For reasons of comparison the same pig iron input per ton of crude steel is assumed for the value in Otto et al. (2017).

[9] Otto et al. (2017) report total coal and natural gas input into the coke oven of 12.5 GJ. Assuming marginal natural gas input into the coke oven, we attribute 12.5 GJ to coking coal input. A share of 14% of coke used in the subsequent process is imported from outside the system boundaries in the analysis by Otto et al. (2017). We assume all coke to be produced in the integrated steelworks and scale the energy input accordingly. Finally, values in Otto et al. (2017) are calculated on a per ton of pig iron basis, whereas in this report we use a per ton of crude steel basis. Following He et al. ((2017)) we assume 950kg of pig iron per ton of crude steel.

[10] Cf. He et al. (2017) and Otto et al. (2017).

calculations are based on 0.2 MWh per ton of crude steel. At the same time, on-site electricity generation is in the range of 0.28-0.37 MWh per ton of crude steel, depending on the system configuration (on average 0.33 MWh per ton of crude steel).

- CO_2-balance
  - The balance covers direct emission from fuel inputs at a typical integrated steelwork (comprising a coking plant, a sintering plant, a blast furnace and a basic oxygen furnace). Upstream emissions are not included. The oxidisation of coking coal and steam coal (and some natural gas) leads to specific emissions from fossil fuels of about 1.7 t CO_2 per ton of crude steel in this example.
  - Additionally, there are CO_2 emissions from the calcination of limestone. Data on emissions from limestone in Germany suggest average specific emissions of 0.07 t CO_2 ton of crude steel production.[11]
  - Total direct emissions add up to 1.72 t CO_2 ton of crude steel. This is 8% lower than the EU average of 1.86 t CO_2/t of crude steel.

Table 1: Fuel use, direct emissions and electricity balance of a typical integrated steelworks

	Fuel use MWh/t	Emission factor T CO_2/TJ	Emissions T CO_2/t
Coking Coal	3.55	94	1.20
Steam Coal	1.33	94	0.45
Natural Gas	0.03	56	0.01
Total fuel use	4.91		1.72
Process emissions from limestone			0.07
Total direct emissions			1.72
Electricity demand[1]	0.20	104[2]	0.06
Auto-generation	-0.33	104[2]	-0.12
Total electricity	-0.13		-0.06

Note: [1]If further process steps are included (casting, rolling and further processing steps) total electricity demand sum up to 0.41 MWh per ton of crude steel Griffin et al. (2016). [2] An average emission factor for electricity of 0.376tCO_2 per MWh is used here, in line with regulations for the new product benchmarks for the first half of phase 4 of the EU ETS (EU 2019).
Source: He et al. (2017), Otto et al. (2017), own calculations.

[11] Total emissions from limestone were 2 Mt CO_2 in Germany in 2018 Source: German Inventory Report, Table 204 on page 343, UBA (2020)

A.2 Electric arc furnace

A.2.1 Process description

The Electric Arc Furnace uses heat generated from electricity to melt scrap, DRI or HBI and produces liquid steel. The electric arc is ignited using graphite electrodes which burn off during the process and need to be replaced periodically. Temperatures reach up to 3500°C in the arc and 1800°C in the steel melt. The melting process can be accelerated by adding oxygen or other fuel-gas mixtures into the furnace. Pre-treatment (e.g. scrap pre-heating) can reduce energy electricity demand(Remus et al. 2013).

Explain: Relation liquid steel and crude steel: my guess: liquid steel highlights the additional energy input required to make the intermediary products liquid and suitable for further processing in subsequent processing steps. Therefore, the two terms refer to the same product in same conditions but highlights the different production routes. For easier understanding we use the term crude steel for both routes.

A.2.2 Energy and CO_2 balance

- The energy demand of the EAF is dominated by electricity. (Remus et al. 2013) report values between 0.4 and 0.8 MWh per ton of crude steel. Accordingly, Otto et al. (2017) calculate electricity input equal to 0.6 MWh per ton on crude steel (including 0.01 MWh for auxiliary demand e.g. for oxygen provision).
- Additionally, heat is provided from fossil fuels such as natural gas, and to a smaller extend also from coal Otto et al. (2017). Remus et al. (2013) report a wide range of realized values between 0.04 and 0.7 MWh per ton of crude steel, with an average of 0.22 MWh of natural gas and 0.13 MWh of coal. The same average values are reported by Otto et al. (2017). Hölling et al. (2017) who look at the particular example of the Hamburg DRI-EAF plant, report natural gas input for about 0.3 MWh per ton of crude steel[12].
- Direct CO_2 emissions comprise of:
  - emissions from fossil fuels (natural gas and coal combustion) account for about 0.05-09 tCO_2 per ton of crude steel;
  - and process-related emissions from electrode burn-off and foam coal with account for about 0.08tCO_2 per ton of crude steel according to Otto et al. (2017). Hölling et al. (2017) report respective emissions at 0.03 tCO_2 per ton of crude steel for the Hamburg DRI-EAF plant.

The following Table 2 summarises the energy use and emissions of an EAF. Direct emissions sum up to 0.1-0.2 tCO_2 per ton of crude steel. Indirect emissions can be calculated applying a specific emission factor. The benchmark for the 3rd trading period in the EU ETS where based on a value of 0.465tCO_2per MWh with benchmarks for the first half of the 4th trading period are based on a

[12] This facility combines an EAF with a DRI unit. As the DRI is produced on-site, some energy savings can be realized reducing the demand for preheating in the EAF.

value of 0.376 tCO_2per MWh.[13] Values on total specific emissions can be compared to values reported for the update of benchmark values for the phase 4 of the EU ETS (EC 2021). Two benchmarks exist for EAF steel which both also take into account indirect emissions for electricity consumption: the EAF carbon steel and the EAF high alloy steel benchmark. Calculated values based on figures from the literature are well in the range of reported numbers for 2016/2017 (EC 2021).

Table 2: Fuel use and emissions of a typical EAF

	Fuel use MWh/t	Emission factor T CO_2/TJ	Emissions T CO_2/t
Coal	0-0.13	94	0-0.04
Natural Gas	0.22-0.30	56	0.04-0.06
Electrodes and foam coal			0.03-0.08
Total direct emissions			0.09-0.17
Electricity total	0.59	104[1]	0.22
Total including electricity	0.8-0.9		0.31-0.39
EU ETS benchmarks	**Average GHG emissions intensity of all installations in 2016/2017**	**Weighted average GHG emissions intensity of all installations in 2016/2017**	**Benchmark value for 2021-2025**
EAF carbon steel	0.320	0.255	0.215
EAF high alloy steel	0.382	0.323	0.268

Notes: [1] An average emission factor for electricity of 0.376tCO_2 per MWh is used here, in line with regulations for the new product benchmarks for the first half of phase 4 of the EU ETS (EU 2019).
Source: own calculations based on Otto et al. (2017), Hölling et al. (2017)

A.3 Direct Reduced Iron

The crucial difference of the direct reduced iron (DRI)-EAF route to the conventional primary route via the BF and BOF is the reduction agent. DRI does not require coke but the reducing agent is syngas (a mixture of hydrogen and carbon monoxide) which can be produced from natural gas or non-coking coal.[14] The reduction process operates at lower temperatures than the blast furnace. Therefore, instead of producing liquid hot metal, it produces sponge iron, also referred to as direct reduced iron or – after briquetting - hot briquette iron.[15] Iron produced as DRI or HBI needs further treatment to be converted into steel. The sponge iron can either be processed into liquid steel in an Electric Arc Furnace (see below) or be used as additional feedstock in the BOF. Depending on the extent to which hydrogen is provided from other sources than natural gas, CO_2 emissions can be reduced significantly. If green hydrogen is used

[13] Indirect emissions were calculated with an emission factor of 0.465 t CO_2/MWh.

[14] In the EU 27+UK, two DRI sited were in operation in 2019. One in Hamburg, Germany using natural gas a reducing agent, and one in Höganäs, Sweden using non-coking coal as a reducing agent.

https://doi.org/10.1016/B978-1-78242-156-6.00016-2 Chapter 16

[15] https://www.vdeh.de/en/technology/steelmaking/

as reducing agent, the iron sponge is carbon free, and might require additional carbon sources in the EAF to produce the desired crude steel qualities.

Rotary kilns account for about 24% of DRI production in 2019. which can use low quality non-coking coal are widely used in regions with low quality domestic coal reserves, in particular in India and South Africa. Midrex (60%) and Energiron (12%) are the other two most widely applied technologies. Among other things, a decisive difference between the two is the flexibility in terms of feedstock. While Midrex (currently installed at the Hamburg DRI plant) is can only take up to 30% of hydrogen before a reconfiguration becomes necessary, Energiron (currently planned for the Salzgitter SALCOS Project) is more flexible and accepts up to 100% hydrogen but also mixing with COG without the need for reconfiguration (Hölling et al. 2017; Pauluzzi et al. 2021).

A.3.1 Energy and CO_2 balance

Natural-gas-based DRI MIDREX and ENERGIRON DRI process

- According to Hölling et al. (2017) the required gas input in the MIDREX process equals to 2.69 MWh per ton of cold DRI; electricity demand of the DRI contributions 0.08 MWh per ton of DRI; in the ENERGIRON DRI process, natural gas input is 2.66 MWh per ton of hot DRI and electricity demand equals 0.10 MWh per ton of hot DRI .
- Direct CO_2 emissions from natural gas amount to 0.54 tCO_2 per ton of DRI.

Green hydrogen-based DRI

- In case green hydrogen is used, fossil fuel demand is substituted by electricity demand. Based on current technology levels, electrolysers work at an efficiency of around 65%. If assumed technological progress is realized, efficiency can increase to 70% by 2030 (Matthes et al. (2020). The theoretical minimum demand of hydrogen in the reduction reaction is 1.80 MWh Lower heating value (LHV) per ton of iron. Additionally, the reaction gas required preheating.
- Running the installation on pure hydrogen requires 1.90 MWh H_2 (LHV) per ton of HBI. Assuming current efficiency results in an electricity demand of 2.92 MWh per ton of HBI for hydrogen production[16] .
- The additional electricity demand for preheating equals to 0.23 MWh ton of HBI (Hölling et al. 2017). No direct emissions are associated with DRI or HBI production in case green hydrogen is used as a reducing agent.

For information only, indirect emissions[17] are also reported in Table 3. This illustrates how important it is to use hydrogen produced from additional renewable energy sources to reduce the carbon footprint of steel production.

[16] Marc Hölling, Matthias Weng, Sebastian Gellert (2017) report hydrogen demand of 635Nm^3 per ton of HBI. Otto et al. (2017) report a similar hydrogen demand per ton of HBI (1.94 MWh H_2 (LHV)); assuming a LHV of 3 kWh/Nm^3 and an efficiency of 65% yield an electricity input of 2.92 MWh per ton of HBI.

[17] Indirect emissions were calculated with an emission factor of 0.376 t CO_2/MWh.

Table 3: Fuel use and emissions of different DRI plants

	DRI Gas	DRI electrolysis-based hydrogen (current mix)
Energy use	***MWh LHV /t***	
Natural Gas	2.69	
Electricity total	0.08	3.24
Auxillary processes	0.08	0.08
Pre-heating		0.23
Hydrogenelectrolysis		2.93
Emissions	***t CO_2/t***	
Natural Gas	0.54	0.00
Direct emissions	0.54	0.00
Indirect emissions (electricity)	0.03	1.22
Total	**0.57**	**1.22**

Source: Hölling et al. 2017, Matthes et al. (2020)

A.3.2 Combined DRI and EAF

The values presented in Table 3 show an energy and CO_2 balance based per ton of HBI/DRI. However, in order to allow for a comparison with the BF/BOF route specific emissions per ton of crude steel were calculated in Table 4. In this calculation the following aspects are taken into account:

- an HBI input of 1.03 ton of HBI per ton of crude steel is necessary Otto et al. (2017).
- HBI produced from green hydrogen is carbon-free. Depending on the mixture of inputs into the EAF, an additional carbon source is required to achieve the carbon content desired for standard liquid steel. To avoid additional emissions, biomass can be used as carbon feedstock.
- DRI, HBI and scrap can be mixed as input for liquid steel production in the EAF. To allow comparability between the BF-BOF route and the DRI-EAF route, we assume the scrap share to be the same as in the BOF (16.7% also see A.1.1). Hence, we assume DRI/HBI provides a share of 86% in liquid steel and the remainder is supplied from scrap.

Table 4: Specific fuel use and specific emissions per ton crude steel produced with DRI/HBI plant and a scrap share of 16.7%

	DRI Gas		DRI electrolysis-based hydrogen (current mix)
Energy use DRI (86%)[1]			
Natural gas	2.31		0.00
Electricity total	0.07		2.78
Auxiliary processes	0.07		0.27
Hydrogen electrolysis	0.00		2.51
Energy use EAF			
Electricity EAF	0.59		0.59
Total electricity	0.66		3.37
Total energy input	2.97		3.37
Emissions		***t CO_2/t***	
Direct emissions DRI (86%)	0.49		0.00
Direct emissions EAF	0.08		0.08
Total direct emissions	0.57		0.00
Indirect emissions (electricity)	0.25		1.27
Total emissions	**0.82**		**1.35**

Note: [1] Taking into account that a an HBI input of 1.03 ton of HBI per ton of crude steel is necessary Otto et al. (2017).
Source: Hölling et al. 2017, Matthes et al. (2020).

For the standard natural gas-based DRI-EAF route this results in total direct emissions of 0.49 t CO_2/ton of crude steel (mainly from the DRI-plant) and specific electricity consumption of 0.66 MWh/t (mainly from the EAF).

For the DRI-EAF route with green hydrogen total electricity consumption is 3.37 MWh/t.