IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

27/06/2025

D4.8 Sectoral and cross-sectoral analysis – Update

WP4: Modelling – Quantitative evidence in support of post-2030 Paris-compliant climate action

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

The results of the work documented in this Deliverable D4.8 will be presented to stakeholders during the final conference of IAM COMPACT and in a policy brief.

Parts or all of the content of this deliverable will be disseminated to the scientific community via research articles and/or scientific conferences.

3. Short summary of results (<250 words)

This report covers the results of Task 4.4, 'Sectoral and Cross-Sectoral Analysis', of the IAM COMPACT project. First, it presents the findings of Study 9 of the 2nd cycle of the project's Policy Response Mechanism (PRM2) on the decarbonisation of the EU steel industry, which builds upon the findings of Study 4 of PRM1. The report analyses the influence of various policy instruments, such as the Carbon Border Adjustment Mechanism (CBAM), trade of direct reduced iron (DRI), and subsidies for green steel production, on the relocation of iron and steel production, as well as on costs and emissions. To do so, it utilises several modelling frameworks, including GCAM, MARIO and ITOM. Second, it documents a study building on six scenarios aimed at examining the impact of financing costs on global hydrogen markets, trade flows, and hydrogen-related investments in the year 2050.

4. Evidence of accomplishment

This report.

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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Executive Summary

This Deliverable D4.8 serves as an update and continuation of the sectoral and cross-sectoral analyses conducted under Task 4.4 of the IAM COMPACT project, building on Deliverable D4.7. It is part of the work conducted under Work Package WP4: Modelling – Quantitative evidence in support of post-2030 Paris-compliant climate action.

The Deliverable presents work from two main areas: the transformation of the EU steel sector and the impact of financing costs on the future international trade of renewable hydrogen. The work on the transformation of the EU steel sector was conducted as part of the second Policy Response Mechanism cycle (PRM2) of the IAM COMPACT project, under "Study 9", and expands upon initial investigations into climate policies and international trade dynamics on the EU steel sector from PRM1 (Study 4), incorporating stakeholder feedback for refinement of the analysis.

Steel production is a significant contributor to global and EU greenhouse gas emissions. The sector is currently dominated by the emissions-intensive blast furnace/basic oxygen furnace (BF/BOF) route, which is complemented by electric arc furnaces (EAF) using scrap for secondary steel production. The upscaling of low-CO_2 technologies for primary steel production, such as hydrogen-based direct reduction (DRI) hinges on supportive policy frameworks. The EU's tightening emissions trading system and the phasing out of free CO_2 allowances are creating economic incentives for low-emission production but also raise concerns about carbon leakage, where production might relocate to global regions with lower carbon costs. Moreover, the availability of green electricity and hydrogen could shift steel production towards regions rich in renewable energy, a phenomenon known as "renewables pull".

In this context Study 9's overarching research question was: ***"How do policies shape the pathways towards a decarbonised European steel industry and its impacts on energy demand and CO_2 emissions, considering spatial relocation, globally and within the EU?".*** This question is addressed through several sub-studies using a combination of models: a modified version of GCAM, a global, partial equilibrium Integrated Assessment Model was used to model global steel pathways and trade. MARIO, a Python-based framework for scenario and economic-environmental impact assessment and footprint analyses using input-output tables, was used to characterise environmental impacts of steel production processes and steel consumption. The linear optimisation model ITOM was utilised to derive pathways for the EU steel industry with high technological and sub-EU-level detail.

In a baseline scenario derived from GCAM that does not consider trade restrictions, the EU's comparably high climate ambitions put pressure on EU steel competitiveness, leading to a drop of EU steel production around 2030 and increased imports. Over the long term (2035-2050), EU steel competitiveness improves as other regions implement effective CO_2 pricing, allowing EU production to return to 2020 levels. The Carbon Border Adjustment Mechanism (CBAM) significantly softens the intermediate production decline and reduces steel imports by replacing them with domestically produced low-carbon steel, but it has no effect on losses of exports. Subsidies for green steel production in the EU show significant additional positive effects on steel production levels only when subsidies are high and maintained in the long term. Including global trade of hydrogen-based DRI into the analysis shows only a small effect on overall EU steel production, consumption, and trade. While it slightly improves EU steel competitiveness by leading to higher production, increased exports, and fewer imports, this is achieved by partly substituting domestic hydrogen-based DRI production with imports.

The greenhouse gas (GHG) footprint of EU steel production technologies calculated with MARIO and using GCAM scenario results as inputs varies widely. Conventional BF-BOF routes have a high footprint, which can be sharply reduced with Carbon Capture and Storage (CCS). The hydrogen-based DRI route currently has a higher GHG intensity than the natural gas-based one due to scope 2 emissions (based on the EU's 2020 electricity mix). But technologies relying heavily on electricity, such as electrolysis-based and DRI-EAF-based routes, show a pronounced decline in GHG footprint over time due to the rapidly decarbonising EU electricity mix. Overall, the GHG emissions embedded in EU steel consumption are projected to decline significantly due to a substitution of the coal-based BF/BOF route and the decarbonisation of the electricity sector. However, while policy measures like CBAM and green subsidies influence this trajectory, their overall transformative impact appears limited unless accompanied by broader structural shifts in trade patterns and more ambitious decarbonisation efforts in exporting countries.

The analysis of EU steel transformation pathways with ITOM reveals that even without additional steel-specific policies, the EU steel industry undergoes a swift transformation to low-carbon production, being almost CO2-neutral by 2035 in a scenario with CBAM. This is primarily driven by strongly increasing effective CO_2 emission costs that reflect a combination of rising EU ETS-1 certificate costs and a phase-out of free emissions allowances. Iron production tends to shift from established regions (e.g., Germany, BeNeLux) to areas with more competitive energy prices for DRI and secondary steel production (e.g., EU_North, EU_Southwest, EU_Southeast). Crude steel production relocation is less pronounced due to incentives for production closer to target markets. The analysis of additional CAPEX and hydrogen subsidies suggests that (in the context of the scenario) their impact on accelerating the uptake of low-carbon steel production beyond the swift transformation driven by rising effective CO_2 prices is relatively small (2-6% additional cumulative emission reduction). A low-level, time-stretched CAPEX subsidy is the most efficient in terms of CO_2 avoidance costs but least effective in total CO_2 avoided. High, targeted CAPEX subsidies around 2030 are more effective in reducing cumulative CO_2 emissions but come with higher CO_2 avoidance costs and risk subsidising investments that would have occurred later regardless. Untargeted hydrogen subsidies are found to be inefficient, with the low-cost hydrogen primarily being used for hot-rolling instead of hydrogen-based DRI and high CO_2 avoidance costs. Hydrogen subsidies specifically targeted to DRI production show moderate CO_2 avoidance costs and are effective in saving fossil CO_2 storage capacity, potentially freeing up capacity for unavoidable emissions or negative emissions for permanent CO_2 removal from the atmosphere.

The analysis of the impact of financing costs on the future international trade of renewable hydrogen presented in the second part of the deliverable recognises renewable hydrogen as a crucial energy carrier for decarbonising hard-to-abate sectors, with global demand expected to grow significantly to meet climate goals. Regions with abundant, inexpensive renewable energy can produce hydrogen competitively, making it a potential globally traded commodity. However, low-carbon technologies are capital-intensive and highly sensitive to the weighted average cost of capital (WACC), which varies drastically across countries due to macroeconomic and political factors. A key determinant for competitiveness in hydrogen production, therefore, is financing costs, reflected in the WACC. High financing costs in developing economies may thus limit their ability to produce hydrogen competitively. The study uses a global framework that integrates country-specific renewable hydrogen supply curves, regional demand curves, global supply chains, and a market equilibrium model to simulate the development of hydrogen markets and international trade by 2050 under six scenarios, differentiating the future development of WACC in world regions and whether main importers seek to diversify their imports or not. The shares of hydrogen transportation modes and the role of world regions vary significantly across scenarios. The study confirms that the capital-intensive nature of renewable hydrogen projects means that financing costs are a crucial determinant of competitiveness. While developing countries in Latin America and North Africa possess substantial renewable resource potential to become major exporters, high financing costs hinder their competitiveness in some scenarios. This allows countries with lower financing costs, such as China, Australia, and certain European nations to become leading producers and exporters. The total cumulative investment required for hydrogen varies between $8 trillion and $6.8 trillion between scenarios. Investment in shipping significantly increases in scenarios with a shift in funding towards Australia and Western Europe. The research suggests that policies aimed at de-risking energy investments and lowering financing costs in developing countries would be critical to fostering a more cost-effective global supply of renewables.

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1 Introduction

This Deliverable presents an update and continuation of the sectoral and cross-sectoral analyses conducted under Task 4.4 of the IAM COMPACT project (see Deliverable D4.7 "Sectoral and cross-sectoral analysis")[1]. Parts of the work presented in this Deliverable have been conducted during the second round of stakeholder engagement – the second Policy Response Mechanism cycle (PRM2) of the IAM COMPACT project (see Deliverables D2.3: Scoping policy relevant Research Questions[2] and D4.6: National, regional, global mitigation pathways – Update[3]) – under "Study 9" and expands on the investigation of the implications of climate policies and international trade dynamics on the EU steel sector that have been taken up during PRM1 under "Study 4". This is complemented by an analysis of the impacts of financing costs on the future hydrogen trade across world regions.

1.1 Brief summary of D4.7

Deliverable D4.7 included work conducted under Study 4 on the risk of relocation of EU steel production to other world regions due to high energy and CO_2 costs under current EU climate policy conditions and the transformation of the EU steel industry under such conditions. A multi-model framework was applied—combining three Integrated Assessment Models (GCAM, TIAM, WILIAM), a sectoral bottom-up model (ITOM, then WISEE-EDM-I), and an Input-Output model (MARIO)—to assess global scenarios with different steel trade constraints, assuming all countries implement their current climate policies and meet their NDC targets. The analysis provided policy-relevant insights into emissions leakage, competitiveness, and the design of effective trade and climate policy interactions. It also helped identify potential for further model harmonisation and extension of the scope of analysis, including Direct Reduced Iron (DRI) trade, analysis of policy instruments and analysis of the dynamics on the sub-EU level.

Three furthers studies conducted under Task 4.4 were reported in D4.7: a study that analyses the impacts of implementing an increasing amount of wind and solar power technologies in terms of raw material demand. The analysis covers four global regions, including the EU. Results from one IAM regarding renewables upscaling have been processed with another one to derive raw material demands.

A study that analysed the capacity and flexibility requirements of future electricity systems to meet carbon neutrality for the case of Greece. It soft-linked a cost-optimising energy system model (OSeMOSYS-GR) with a short-term power system model (FlexTool) and analyses two scenarios for a carbon-neutral Greek electricity system up to 2050.

Finally, a study addressed the uptake of small-scale PV by the residential sector in Greece, using an agent-based model (ATOM) to analyse how consumers' investing behaviour affects the adoption of small-scale PV systems by 2030 by comparing the effects of different policies; uncertainty about the effects of policies that emerges from agents' adoption behaviour was quantified and presented.

1.2 Overview of work conducted in PRM2

Building on D4.7 and in line with the description of Task 4.4, sectoral and cross-sectoral analyses were conducted during the time period of PRM2. The work on the steel transformation was continued under "Study 9" and is presented below in section 3. Furthermore, hydrogen trade across world regions was investigated, which is presented in section 4.

Other potential topics for sectoral and cross-sectoral analyses that are mentioned in the Task description, and

[1] DOI 10.5281/zenodo.13839232
[2] DOI 10.5281/zenodo.13132343
[3] DOI 10.5281/zenodo.15593966

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which were not covered in D4.7 include: the role of international transport and bunker fuels in global mitigation, biophysical constraints and impacts on land-energy-water nexus and land-use requirements, and finance.

Biophysical constraints and impacts on land-energy-water nexus and land-use requirements were addressed as part of Study 15 about Land-use and Renewables. This research combines two different studies: (i) the effects of ambitious bioenergy policies in the EU on land demand, forest biomass and ecological boundaries; and (ii) the land-use implications of large-scale solar PV deployment in the EU. Both exercises compare the results obtained from business-as-usual and NDC-LTT scenarios, as well as NDC-LTT scenarios with additional land-based policies. Outputs are mostly measured in terms of carbon emissions and forest area changes. The study will be reported under D5.9 "Climate action in the sustainability spectrum – Update".

The role of finance will be analysed in Study 12, which aims to explore how governance frameworks, funding mechanisms, and international coordination can be improved to enhance the impact of climate finance, specifically focusing on infrastructure development, cross-border financial flows, loss and damage compensation, and the potential impact of international investment funds. It will be reported under D5.7: "Behaviour, social and disruptive innovation – Update."

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2 Study 9: EU Steel Transformation

2.1 Introduction to topic and summary of Study 4

Steel production accounts for approximately 7% of global and around 5% of EU greenhouse gas emissions (IEA 2020). In the EU, 57% of crude steel is produced via the blast furnace/basic oxygen furnace (BF/BOF) route, emitting about 2.1 tonnes of CO_2 per tonne of finished steel. In contrast, 43% is produced via electric arc furnaces (EAF), with average emissions of only 0.22 tonnes CO_2 per tonne, which primarily uses scrap steel as feedstock. Emerging low-CO_2 production technologies – such as hydrogen-based direct reduction – are technically viable and nearing commercial deployment (Zelt et al. 2025), but their diffusion depends heavily on policy frameworks, infrastructure readiness, and regional energy system characteristics. As the EU tightens its emissions trading system and phases out free allocation of CO_2 allowances in the time period from 2025 to 2035, economic incentives for low-emission production are strengthening. However, this shift increases the risk of carbon leakage, where production may relocate to regions with lower carbon costs. Simultaneously, the use of green electricity and hydrogen alters the locational logic of steel production, favouring regions with abundant renewable energy potentials – a phenomenon sometimes described as the "renewables pull."

These dynamics create complex systemic challenges for EU industrial policy. Modelling studies and scenario analyses highlight the need for spatially differentiated approaches, cross-sectoral coordination, and targeted infrastructure planning (Nykvist et al. 2025; Agora Industry and Wuppertal Institute, 2023; Bellona, 2023). EU policy must navigate these trade-offs to ensure that industrial decarbonisation reinforces, and not undermines, economic sovereignty, climate targets, and regional cohesion.

Against this background, Study 4 focussed on the EU steel industry and a potential relocation thereof to other world regions because of high energy and CO_2 prices in the EU. Five different models including three IAMs (GCAM, TIAM, WILIAM), one sectoral bottom-up model (ITOM) and one Input-Output (I/O) model (MARIO) have been (soft-) linked to assess the potential impact of different degrees of trade restrictions for steel. Three scenarios were analysed. In all scenarios, countries implement their current climate policies and achieve the GHG emissions reduction targets aimed at in their respective NDCs and in their long-term targets. But different steel-related trade constraints were assumed for the scenarios, including the Carbon Border Adjustment Mechanism (CBAM). The analysis showed that the EU steel industry faces tendencies for off-shoring in the period around 2030, if no additional measures are taken. However, it also shows that the comparably fast decarbonisation of the EU electricity sector entails competitive advantages for steel after 2040. Low-emissions primary steel technologies will scale only after 2030, according to the models and this process will not be accelerated through keeping additional production capacity within the EU. Because of increasing CO_2 prices and the transformation of the steel sector towards low-emission technologies, specific costs of steel production increase from about 500€/t in 2020 to about 700€/t in 2050, in all scenarios. If trade is restricted, EU steel related CO_2 emissions, GVA and employment are higher in line with higher production volumes around 2030, while the effects on global steel related CO_2 emissions are small and differ between models (GCAM, TIAM). Parts of the analysis have been broken down to the EU member state level. This reveals that differences in renewable energy prices between member states affect locational factors, which creates a tendency for production to shift toward those states which feature the lowest renewable energy costs.

2.2 Stakeholder feedback on Study 4

The results of Study 4 were presented to stakeholders as part of PRM1 and feedback was gathered. Among other aspects, stakeholders expressed interest in a more in-depth analysis with regards to a) Analysis of dynamics on the sub-EU level such as the Member state level; b) the role of imports of intermediate products; c) policy instruments for supporting green steel and their effects; and d) energy demands of a decarbonised EU industry. These aspects are taken up in Study 9, which is described below.

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Stakeholders were also interested in other topics that cannot be addressed with the methods and models available in IAM COMPACT. These include:

- Normative questions on the desirable level of steel production in the EU for security vs. competitiveness vs. cost reasons: Differences in CO_2 and energy costs create a tendency for re-location of steel production from the EU to other world regions. Different scenarios are analysed using GCAM (see section 3.1, but an assessment of their security impacts was not conducted, and a normative evaluation was not part of the stakeholder process of PRM2.
- Questions on potential benefits of more circular solutions in green steel production: Scrap availability and its use are modelled with ITOM (see section 3.5). The results show that the role of scrap and secondary steel increases, compared to the current state, what contributes to CO_2 reduction of the sector. Beyond that, model capabilities did not allow for deep dives in circularity solutions.
- Questions on the best instruments for driving innovation in the steel sector: the available models were used to analyse the upscaling of innovations available on the market as a result of implementing various policy instruments. However, the timing of when innovations will reach the market and how the innovation process itself can be fostered is outside the scope of the available models.
- A question on Net Zero Industry Act and how realistic its targets for European manufacturing: a study conducted during PRM1 touched upon the raw material demand for net-zero technologies covered by the Net Zero Industry Act. But this study was not continued in PRM2 because capacity in the project was dedicated to other studies and aspects.

A full list of stakeholder questions that were put forward as a response to Study 4 is provided in the Appendix, while a summary can be found here[4].

[4] https://iam-compact.eu/news-events/core-working-group-workshop-modelling-clean-industrial-deal

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3 Study 9 – Research questions and study outline

3.1 Overview

Study 9 was part of the second Policy Response Mechanism cycle (PRM2) and includes an update and continuation of the work conducted in Study 4. Based on the stakeholder feedback and the capabilities of the models involved, the overarching research question of Study 9 was *"How do policies shape the pathways towards a decarbonised European steel industry and its impacts on energy demand and CO_2 emissions, considering spatial relocation, globally and within the EU?"*

This overarching research question is underpinned by three more fine-grained questions:

- How do various policies (such as CBAM) influence the EU steel production levels in a global context, considering global spatial relocation of the production of steel and intermediate products? (Sub-studies 9.0 and 9.1)
- What are the indirect effects (e.g. carbon leakage) of EU steel transformation pathways in a global context under different policies? (Sub-study 9.2)
- How do various policy instruments influence EU and EU member state steel transformation pathways, costs and emissions, considering spatial relocation of production of steel and intermediate products within the EU? (Sub-study 9.3)

These research questions were approached in three sub-studies (9.1 – 9.3), each dedicated to one of the questions. All three sub-studies were based on an update of global and EU steel pathways from GCAM (sub-study 9.0). Figure 3-1 outlines the sub-studies along the topics addressed, the models used and the main data flows.

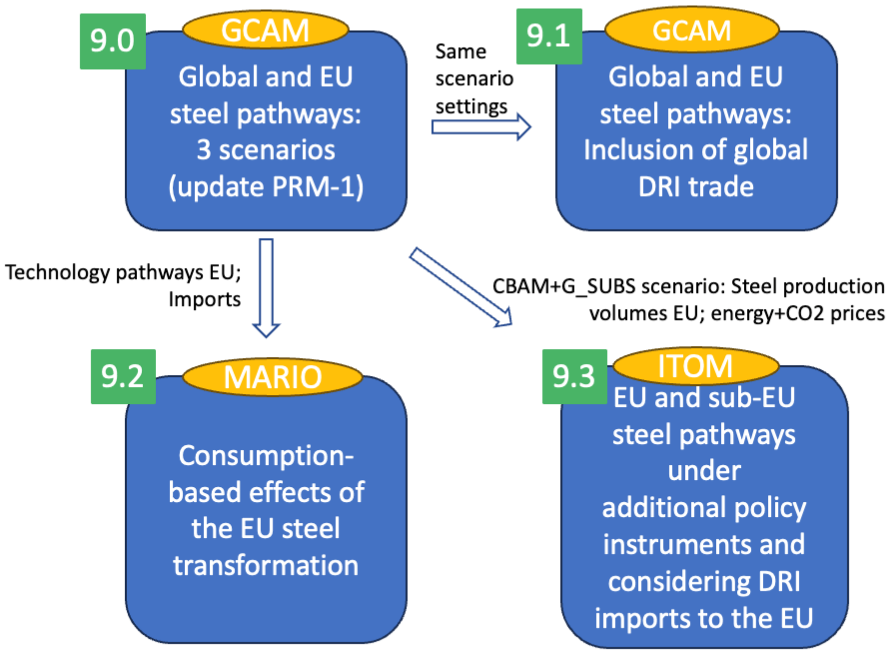

Figure 3-1: Outline of Study 9 with sub-studies 9.0 to 9.3, main topics of sub-studies and models used

Sub-study 9.0 is an update of the work conducted as part of PRM1, addressing stakeholder feedback. A major part of this is the replacement of the "INDEPENDENCE" scenario from PRM1 – which pre-defined a minimum level of steel production in the EU but did not underpin this with specific policy instruments – by a scenario called CBAM_G_SUBS that builds on the CBAM scenario and adds subsidies for green steel production within the EU. Sub-study 9.1 added global trade of Direct Reduced Iron (DRI) – an intermediate product of steel production –

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and analysed the effects on EU steel production levels and transformation pathways, using GCAM. Sub-study 9.2 analysed the consumption-based energy and CO_2 impacts of the European steel transformation with MARIO. Sub-study 9.3 used ITOM to model various types of green subsidies and to investigate their effects on EU steel transformation pathways and relocation within the EU, including also intra-EU DRI trade.

The models used in Study 9 include GCAM, MARIO and ITOM. **GCAM** is a global, partial equilibrium IAM that represents human-Earth dynamics by exploring the behaviour and interactions between the energy system, agriculture and land use, the economy and climate to model GHG emissions, energy use, energy prices, and trade patterns (Calvin et al. 2019). It operates by looking for cost-efficient energy system solutions in a specific period and then moves on to the next time period to repeat the optimisation exercise. In this study a modified version of GCAM 7.0 was used, which includes global iron and steel trade, with modifications to socioeconomic pathways and iron and steel production technologies to harmonise with the other models used in this study. Details of the modifications of GCAM are provided in section 3.2.1.

MARIO is a versatile modelling framework for easy input-output analyses and models handling. It is programmed in Python and comes with a set of useful features which are of paramount relevance to perform scenario and economic-environmental impact assessment and footprint analyses adopting input-output tables. In this study, MARIO was adopted to enrich the raw version of the Exiobase dataset, to account for novel steel production processes environmental impact. With respect to Study 4 many more steel production routes have been characterised, to match the same technological granularity of GCAM, to which MARIO has been linked in this modelling exercise.

ITOM is a framework for the modelling of transformation processes in single basic industry sectors in the middle-to long-term. The model was previously (including PRM1) referred to as WISEE EDM-I and has been further developed and renamed to ITOM (Industry Transformation Optimisation Model). ITOM is a linear optimisation model designed to derive detailed technological pathways for the production of basic materials, including energy and material demand, CO_2 emissions, investments and production costs. It features high technological detail including differentiation of production by product types, a differentiation of the production chain into various steps, an explicit representation of individual sites and plants, and an endogenous optimisation of the production network across sites and production steps.

3.2 Study 9.0 Update of EU steel pathways and trade in a global context

3.2.1 Methodology

For modelling global steel pathways and trade, the iron and steel sector from GCAM 7.0 was modified. This includes an expansion of steel production technologies and the steel trade market. The typical 9 iron and steel production technologies were expanded to 22 technologies in this version, based on technology data from Witeka et al. (2024). These new technologies include more diversity of options for carbon capture and sequestration, more specific fuel and finishing technologies for secondary steel from electric arc furnaces, the ability to combine direct reduced iron with smelting and a basic oxygen furnace, as well as novel technologies such as molten oxide electrolysis and alkaline iron ore electrolysis. We also employ a global limit to the use of scrap-based technologies, to better align with estimates of availability and feasible usability. Total global scrap-based production – including secondary steel and an (assumed) use of 0.19 t scrap / t crude steel in primary steel production routes – are capped at approximately the scrap-production of the Stated Policy Scenario in IEA's Iron and Steel Technology Roadmap (IEA 2020), reaching 1,090 Mt in 2050. Similarly scrap-based production in the EU specifically is limited, assuming secondary steel production is limited to 94 Mt in 2020, growing to 111 Mt in 2050.

Furthermore, the steel trade market was modified to allow for greater tracing of a traded products' carbon content and region of production. This is particularly relevant for the modelling of CBAM (see scenario descriptions below). For all traded commodities GCAM utilises an Armington trade approach, with one global trade pool that holds exports from all regions. Regions then choose between consuming the domestically produced commodity versus imports from the global trade pool. Here we expand the single global trade pool into six pools – based on the

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emissions intensity of production of the iron and steel technology and the region of production. Iron and steel exports and imports are separated into three markets – "low emissions", "medium emissions", and "high emissions" – based on the direct emissions associated with production (see Figure 3-2). The direct emissions and categories for each steel technology are included in Table 3-1. This market separation allows regions to place a tax on imported iron and steel based on the average direct emissions associated with each steel market, favouring imports from the "low emissions" trade pool. As well, since CBAM policies in these scenarios are implemented in the EU, the trade market was further broken into exports from the EU vs. non-EU. Each GCAM region can then import from one of six categories, based on the emissions intensity and EU vs. non-EU origin of production. A schematic of this new trade market is shown in Figure 3-2. For each region, the split between EU and non-EU steel imports in 2015 are calibrated with Chatham House's resourcetrade.earth data on iron and steel trade (Chatham House, 2023). Historical exports and imports by emissions group (low, medium, high) are assumed to follow the same proportions as production. For example, if Region A is in a non-EU region and produces 60% high-emissions steel and 40% low-emissions steel in 2015, it is also assumed that it exports 60% to the non-EU high-emissions trade pool and 40% to the non-EU low-emissions trade pool. Similarly, if the non-EU high-emissions trade pool receives twice as many exports as the low-emissions trade pool, then the EU will import twice as much non-EU high-emissions steel than non-EU low-emissions steel.

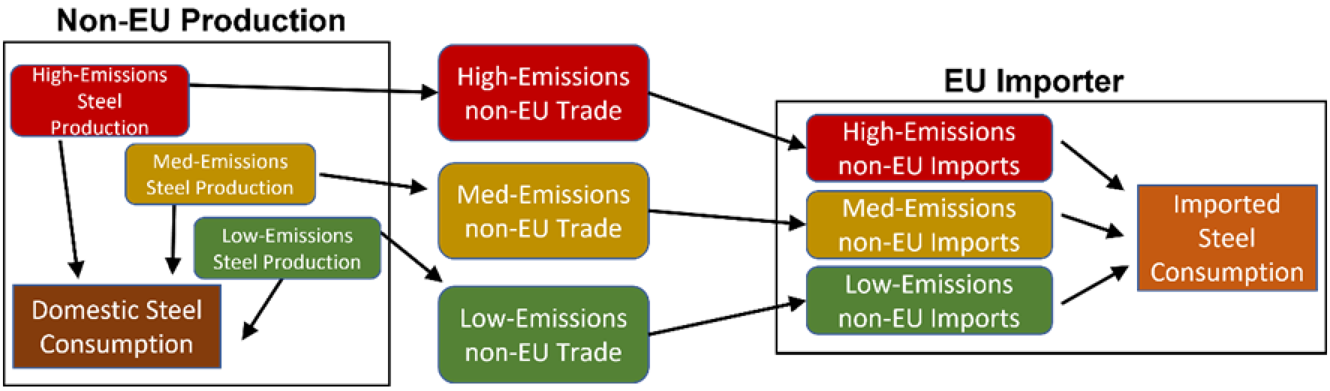

Figure 3-2: Trade structure in GCAM to account for steel emissions at border

Some additional small changes were made in GCAM assumptions for PRM2:

- Recognition of free allowances, which remove steel emissions from all foreign CO_2 prices through 2030, while pricing EU steel emissions at a percentage of ETS price. Based on announcements for DRI plants according to the Green steel tracker[5] and the rule that the number of allowances is calculated from the best-performing 10% of plants in the EU it has been estimated that free allowances cover 55% of CO_2 emissions in 2025 and 40% of CO_2 emissions of the steel industry in 2030. From 2035 onwards no free allowances are provided.
- Removing industrial fuels from "energy efficiency policy" which puts a cap on total final energy use, to prevent an excessive fuel tax limiting steel production. In addition, a small electricity tax was included because EU electricity was excessively cheap due to how renewable energy policy is modelled.
- An economy-wide CO_2 tax was added in the EU in 2030 because it was required to activate CCS for model-internal reasons. But the tax level is so low that it has no effect on the scenario as such.

[5] https://www.industrytransition.org/green-steel-tracker/

Table 3-1: Steel production technologies in GCAM, and their associated direct emissions, and grouping into high (red), medium (yellow), and low (green) emissions steel production

Technology	Direct Emissions ($kg\ CO_2$/ton finished steel)
DRI_EAF_coal	2286
BF_BOF	2183
SR_BOF	1476
DRI_EAF_NG	736
DRI_SAF_BOF_NG	704
BF_BOF_CCS_73%	590
DRI_EAF_coal_CCS	320
BF_BOF_CCS_86%	306
SR_BOF_CCS	207
EAF_scrap_fossil_NG_finish	199
DRI_EAF_NG_CCS	199
EAF_scrap_bio_NG_finish	136
EAF_scrap_fossil_elec_finish	64
DRI_EAF_H2	0
EAF_scrap_bio_elec_finish	0
AEL_EAF	0
MOE	0
DRI_SAF_BOF_H2	0
BF_BOF_BECCSmin	<0
BF_BOF_BECCSmax	<0
DRI_SAF_BOF_BECCS	<0
DRI_EAF_BECCS	<0

3.2.2 Scenarios

This modified version of GCAM 7.0 was used to model four scenarios, as outlined in Table 3-2.

NDC_LTT is a baseline scenario with no restrictions on global trade. I.e. all countries interact in a global market and each sets boundary conditions (CO_2 price) that allow to achieve climate goals. The countries leave it to the market to decide where steel is produced and with which technologies. The regionally different CO_2 prices also affect the steel industry (with varying intensity between regions), which leads to global relocation of steel production.

CBAM: In this scenario the EU introduces a CBAM with the aim to create a level playing field for its steel industry – that faces comparably high CO_2 costs compared to other world regions – on the European market and to prevent carbon leakage. All other regions behave identical to NDC_LTT, i.e. maintain open trade.

CBAM+G_SUBS: These scenarios build on the CBAM scenario, but the EU aims to accelerate the transformation to green steel production by providing financial support to low-carbon primary steel production.

Table 3-2: Scenario description for updated global steel pathways and trade

Scenario	Details
NDC_LTT	• Free steel emissions in all non-EU regions until 2035 • EU steel emissions priced at 30% of ETS in 2020, 45% of ETS in 2025, 60% of ETS in 2030
CBAM	NDC_LTT + • EU CBAM for steel starts in 2030, priced at 60% of ETS, then 100% ETS in 2035 • CBAM modelled with low-/med-/high emissions steel markets and CBAM based on average CO_2 footprint
CBAM_G_SUBS	CBAM + • EU subsidies for capital costs for low-carbon (non-scrap), from 30% in 2030 to 10% in 2040
CBAM_G_SUBS_ HI	CBAM + • EU subsidies for non-energy costs for low-carbon (non-scrap), 20% from 2030 to 2050

3.2.3 Results

The transformation of the global and EU steel industry happens in a global setting in which the climate ambitions of the EU are initially high, compared to the rest of the world. This becomes apparent from the total and steel related CO_2 emissions (see Figure 3-3). From the beginning of the simulation period (2015) until 2030, EU CO_2 total emissions already drop by almost 50%, while those of the rest of the world remain approximately stable and start to drop only afterwards when long-term targets dominate the development in the scenario. Similarly, EU steel related CO_2 emissions drop until 2030, while steel related CO_2 emissions increase in the same time period in non-EU.

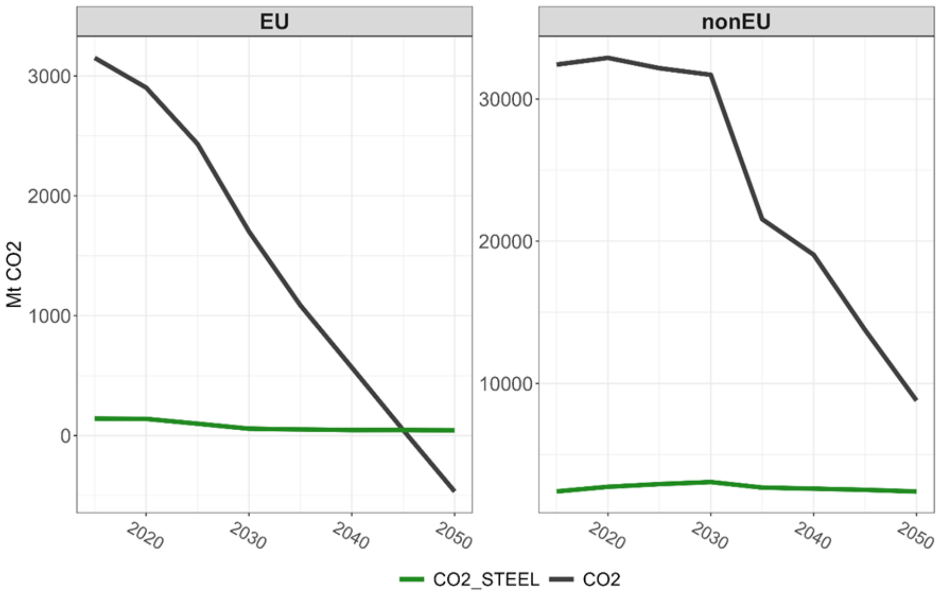

Figure 3-3: Total and steel related CO_2 emissions in the EU and in the rest of the world (non-EU)

In the NDC_LTT scenario, the divergent climate ambitions of global regions and associated CO_2 prices – without additional policy measures – put pressure on the competitiveness of the EU steel industry. As a consequence, EU

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steel production drops by 28 Mt between 2020 and 2030 (see Figure 3-4). In a context of decreasing EU consumption (-5 Mt) imports to the EU increase sharply, by 17 Mt and exports drop by 7 Mt. In the longer term, between 2030 and 2050, the competitiveness of the EU steel industry increases when other world regions introduce (effective) CO_2 pricing on the CO_2 emissions of their steel industries. In all scenarios, EU steel production is back to at least 2020-levels by 2050, despite of reduced EU consumptions levels. This is facilitated by both low import levels and high export volumes. The drop in EU steel production levels between 2020 and 2040 is significantly softened in the scenarios with CBAM. This is achieved through replacing imports by consumption of domestically produced steel, while exports from the EU do not benefit from CBAM. Subsidies to EU green steel production show significant effect in the CBAM_G_SUBS_HI scenario, which features high levels of subsidies, while the more modest subsidies in CBAM_G_SUBS have limited impact on EU steel production levels.

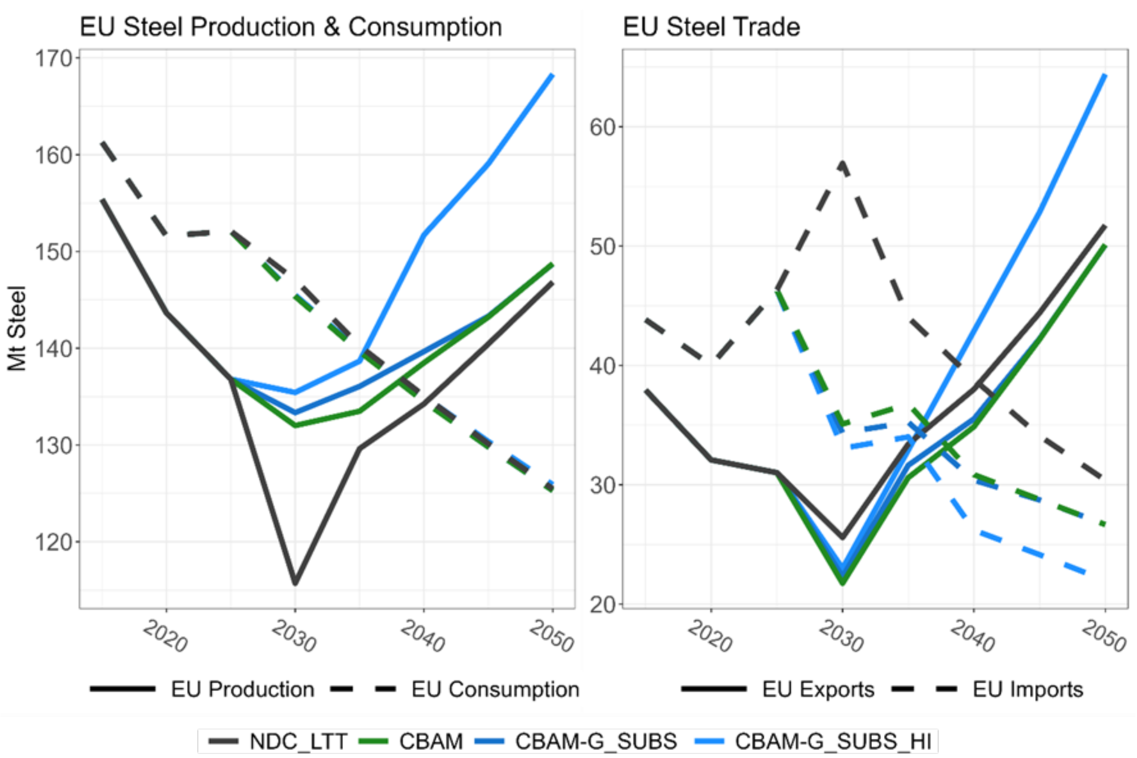

Figure 3-4: EU steel production, consumption and trade in four scenarios

Steel production, consumption and trade develop differently between steel of different emission levels (cf. Table 3-1). Production and consumption of high and medium carbon steel drops sharply between 2020 and 2030. Production and exports fall close to zero in all scenarios due to high CO_2 costs (see Figure 3-5). CBAM significantly lowers imports of high and medium carbon steel and through this also reduces consumption levels of these steel categories. This is mirrored by EU production and consumption levels of low carbon steel (see Figure 3-6) which increase strongly between 2020 and 2030 and continue to grow later on. The growth of low carbon steel production from 2035 onwards is driven by exports, while domestic consumption levels off.

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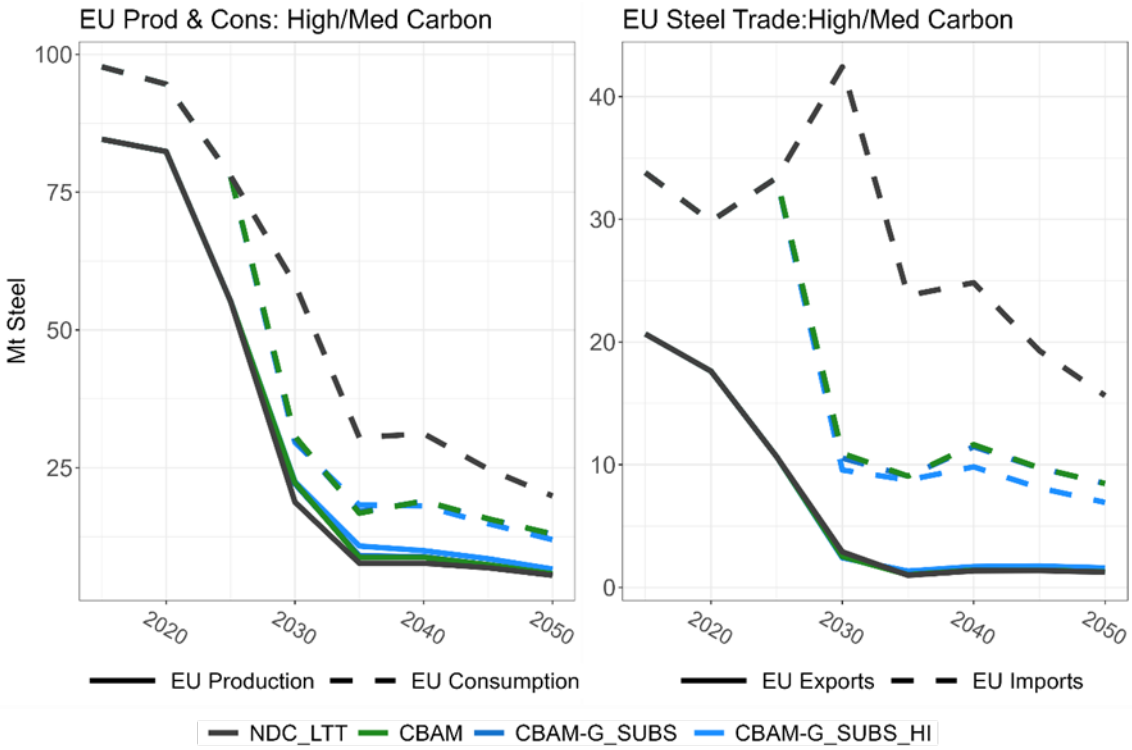

Figure 3-5: EU steel production, consumption and trade of high and medium carbon steel in four scenarios

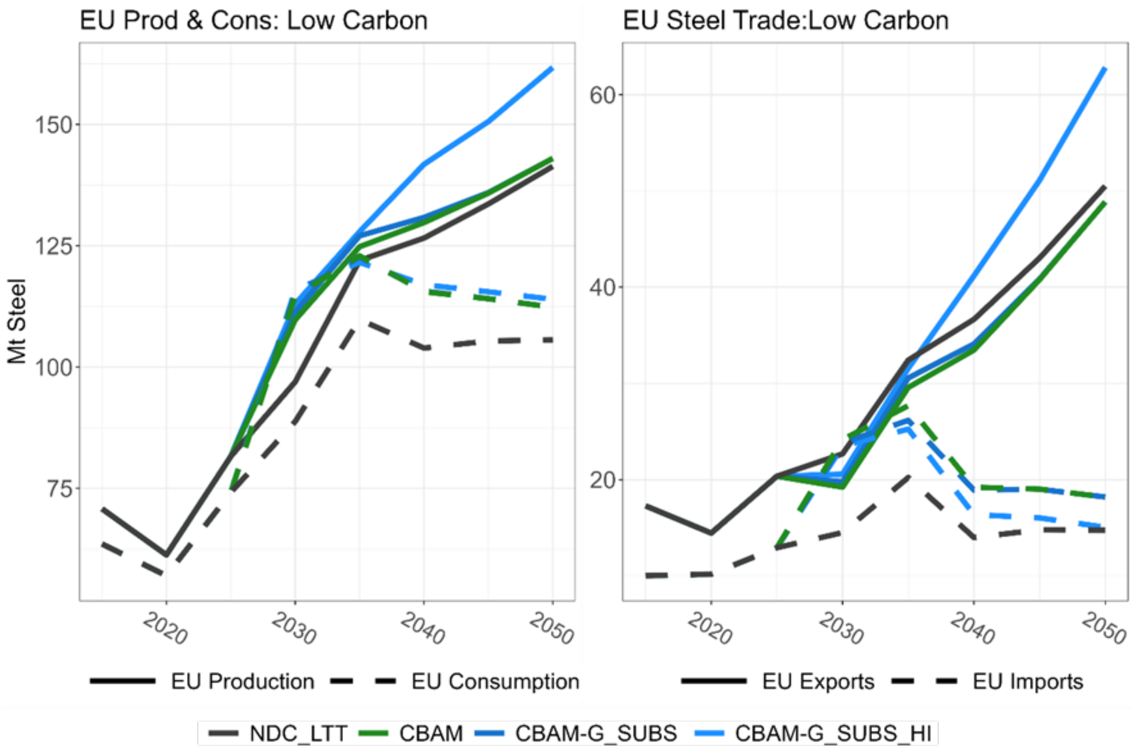

Figure 3-6: EU steel production, consumption and trade of low carbon steel in four scenarios

Figure 3-7 provides a closer look at the technologies by which steel is produced in the EU in the four scenarios. It becomes apparent that secondary steel production in electric arc furnaces is the dominant technology in all four scenarios. The production of secondary steel increases from 61 Mt in the year 2020 to approximately 105 Mt in the year 2050, making use of (almost) all scrap available to secondary steel production. In the same time period, primary steel production drops from 82 Mt around 42 Mt, except for the CBAM_G_SUBS_HI scenario in which the production volume of primary steel amounts to 64 Mt in the year 2050. The production of primary steel production is distributed among a broad set of (low carbon) production technologies.

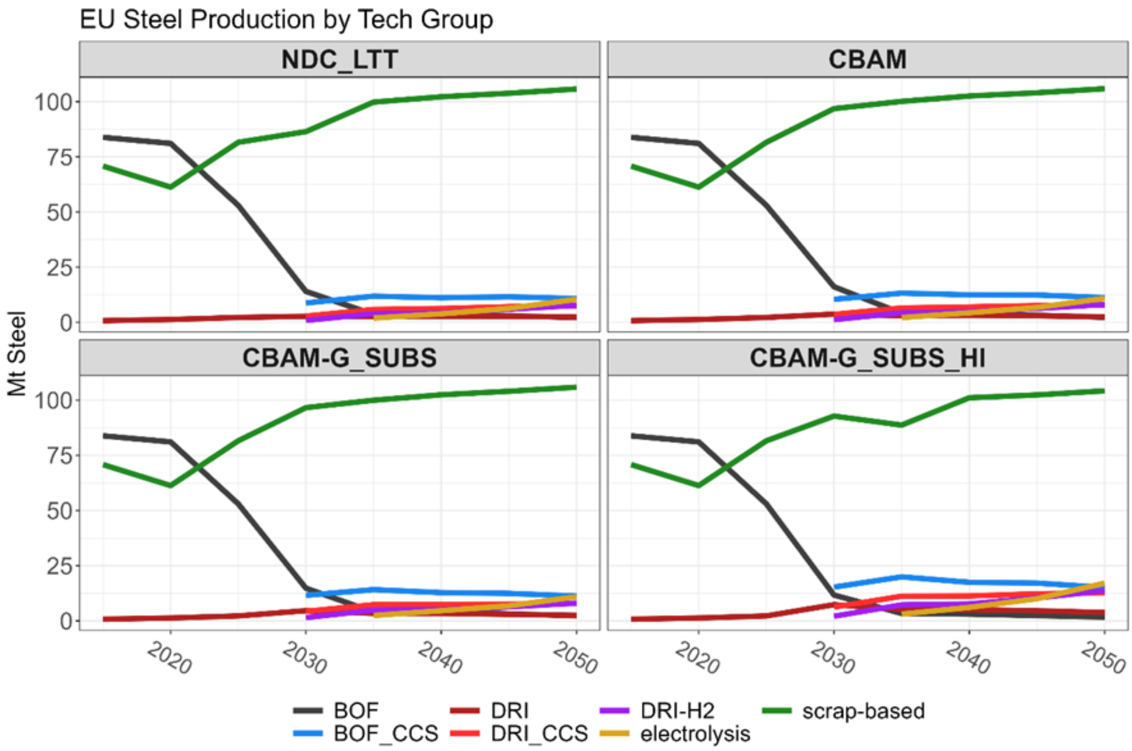

Figure 3-7: EU steel production by technology in four scenarios

Figure 3-8 compares the low carbon steel production in the EU and on a global level. While CBAM and green subsidies achieve to accelerate the upscaling of low carbon steel production in the EU to some extent in the time period around 2030, this remains a temporal effect (except for the CBAM_G_SUBS_HI scenario, which provides massive support for the long term). CBAM, however, does not incentivise additional low carbon steel production in non-EU regions.

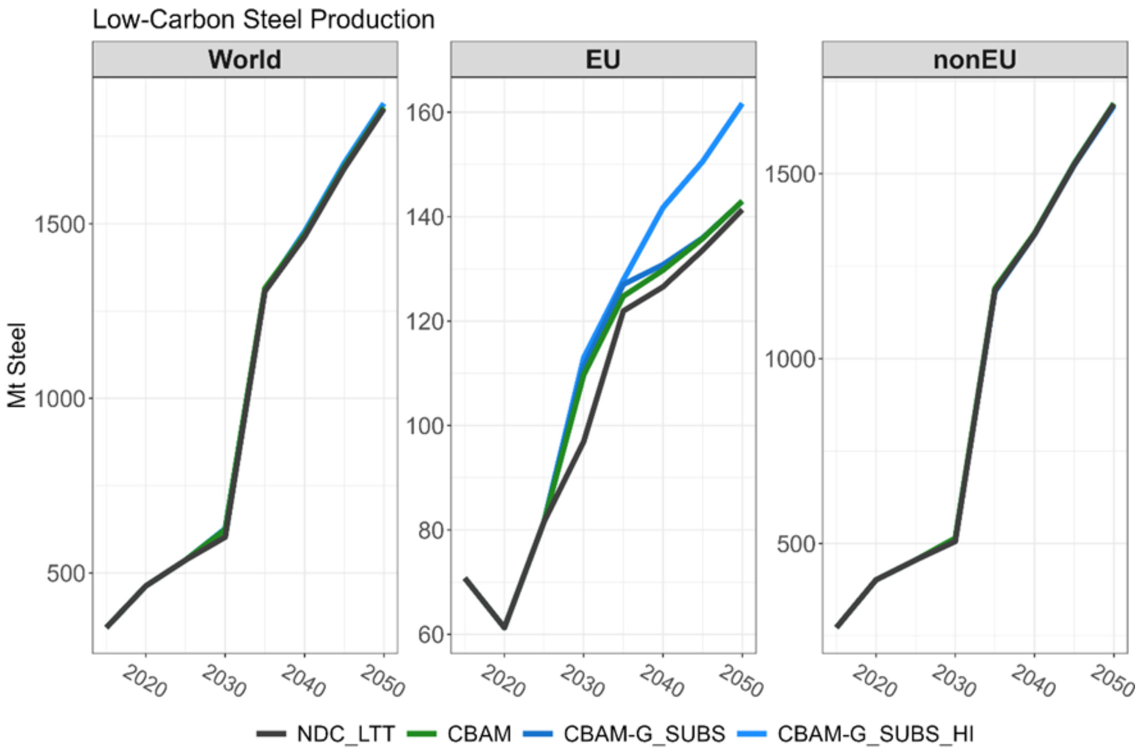

Figure 3-8: Global, EU and non-EU low-carbon steel production by technology in four scenarios

3.2.4 Discussion and conclusions

The scenario analysis shows that the divergent climate ambitions in global regions around 2030 reduce the competitiveness of the EU steel industry and lead to significantly reduced production levels in the time period around 2030, if no policy measures are implemented. The analysis furthermore shows that CBAM is an effective measure to soften these impacts on the EU steel industry and to limit imports of high carbon steel to the EU market. CBAM instead increases the EU production of low carbon steel for the domestic market. However, it has no effect on exports and thus cannot circumvent production losses completely.

The analysis also suggests that the EU steel industry becomes competitive (again) in the long-term and production levels increase to 2020 levels, independent of policy support. This is facilitated by increasing CO_2 prices in other global regions and is achieved by producing low-carbon steel in the EU and exporting it to other global regions. It should be noted, however, that the competitiveness of low carbon steel production in the EU is (in the scenario) mostly achieved through high levels of secondary steel production and competitive electricity prices due to support for renewable energy.

Subsidies for green steel have a limited additional effect except if they are very high and provided also in the long term.

3.3 Study 9.1 Global DRI trade

3.3.1 Methodology

To allow for DRI trade, the iron and steel sector in GCAM has been further adapted, separating iron and steel production into different steps, and allowing for the import of foreign produced DRI in domestic steelmaking facilities. The main differences to the previous version of the model (described in section 3.1) include a restructuring of the of iron and steel sector: rather than having 22 combined iron and steel technologies, the restructured version includes only 8 combined iron and steel routes (EAF_scrap_*, AEL_EAF, MOE, SR_BOF, and

SR_BOF_CCS), while the rest of the routes are split between iron production technologies and steel making technologies. There are 11 iron production technologies (BF_coal, BF_CCS_73%, BF_CCS_86%, BF_BECCSmin, BF_BECCSmax, DRI_NG, DRI_NG_CCS, DRI_coal, DRI_coal_CCS, DRI_BECCS, DRI_H2), 3 smelter technologies (Smelter_NG, Smelter_H2, Smelter_Electric)[6] and 4 steel making technologies (EAF_coal_NG, EAF_charcoal_H2, EAF_charcoal_elec, BOF).

In total these structural changes result in the same 22 iron and steel technology routes, where 8 have the exact same cost/energy-input structure as before, while the other 14 combine the costs/lifetimes/energy-input of the associated iron techs and steel techs (and smelter techs for DRI_SAF steel).

For the inclusion of DRI trade the following assumptions and changes have been made: regions can either import DRI_H2 or produce it domestically. This new "regional DRI_H2" can then be used in DRI_EAF_H2 and DRI_SAF_BOF_H2. DRI produced using fossil energy is not included as a tradable good, as it circumvents the purpose of modelling DRI in a CBAM context, which should only be beneficial when it makes use of more economical H2 in regions with high renewable endowments. All global regions can import DRI_H2, but exporters are limited to current iron ore exporters: Africa_Western, Australia_NZ, Brazil, Canada, China, India, Mexico, South Africa, South America_Southern, USA.

In addition, several smaller changes have been made based on learnings from the scenario exercise presented in section 3.2. In Study 9.0, hydrogen turned out to be very cheap in the EU because of the use of BECCS for its production. In Study 9.1 hydrogen production is not allowed from biomass or fossil fuels with CCS. Furthermore, all H2 policies of individual regions were removed. Instead, a global H_2 subsidy was implemented to align H_2 prices better with existing studies (Bilici et al., 2024). The use of biomass in the EU was constrained to the bioenergy use in the EU in the base year (2015) and a limited growth of 3% per 5 years. Also, the maximum production volume of secondary steel was amended to 94 Mt in 2050. The EU solar and wind targets for 2030 required very high subsidies, which were continued forward to 2050 in sub-study 9.0. This resulted in very low electricity prices, benefiting H_2 production from electrolysis. In study 9.1 these subsidies taper to 0 by 2040, which made EU H_2 prices much less competitive, potentially fostering imports of DRI.

3.3.2 Scenarios

Four scenarios are modelled and compared, two of which are basically identical to study 9.0 (but include the above-described changes): NDC_LTT_NoDRI mirrors NDC_LTT from Study 9.0 and CBAM_NoDRI mirrors CBAM_G_SUBS. The other two scenarios add the option for DRI trade to these. Table 3-3 outlines the scenario elements.

Table 3-3: Description for global DRI trade scenarios

Scenario	Details
NDC_LTT_NoDRI	• Free steel emissions in all non-EU regions until 2035 • EU steel emissions priced at 30% of ETS in 2020, 45% of ETS in 2025, 60% of ETS in 2030
NDC_LTT_DRI	NDC_LTT + • Allowing imports of DRI (from currently existing exporting regions, see methodology) as input for steelmaking facilities
CBAM_NoDRI	NDC_LTT +

[6] Smelters are always electric. For reasons of the model's structure after separating iron and steel production, the smelter steps also include energy for hot-rolling, which can be natural gas, hydrogen or electricity.

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	• EU CBAM for steel starts in 2030, priced at 60% of ETS, then 100% ETS in 2035 • CBAM modelled with low-/med-/high emissions steel markets and CBAM based on average CO_2 footprint • EU subsidies for capital costs for low-carbon (non-scrap), from 30% in 2030 to 10% in 2040
CBAM_DRI	CBAM_SUBS + • Allowing imports of DRI (from currently existing exporting regions, see methodology) as input for steelmaking facilities

3.3.3 Results

The EU steel consumption (see Figure 3-9) shows a continuous decline from 2025 onwards and is very similar to the result of sub-study 9.0. The steel production level develops similar to Study 9.0 until 2030 but then continues to decline after 2030 in line with consumption, while imports and exports approximately level off. The overall pattern of steel production in the whole simulated time period is thus significantly different from Study 9.0. The difference is driven by structural model differences, including the split between iron and steel production, and assumptions regarding secondary steel production and electricity subsidies.

DRI trade, which is the focus of this sub-study has a very small effect on overall steel production, consumption and trade which becomes discernible only in the long term. EU steel production and consumption are slightly increased in the scenarios with DRI trade, compared to their counterparts without DRI trade, imports are decreased and exports increased.

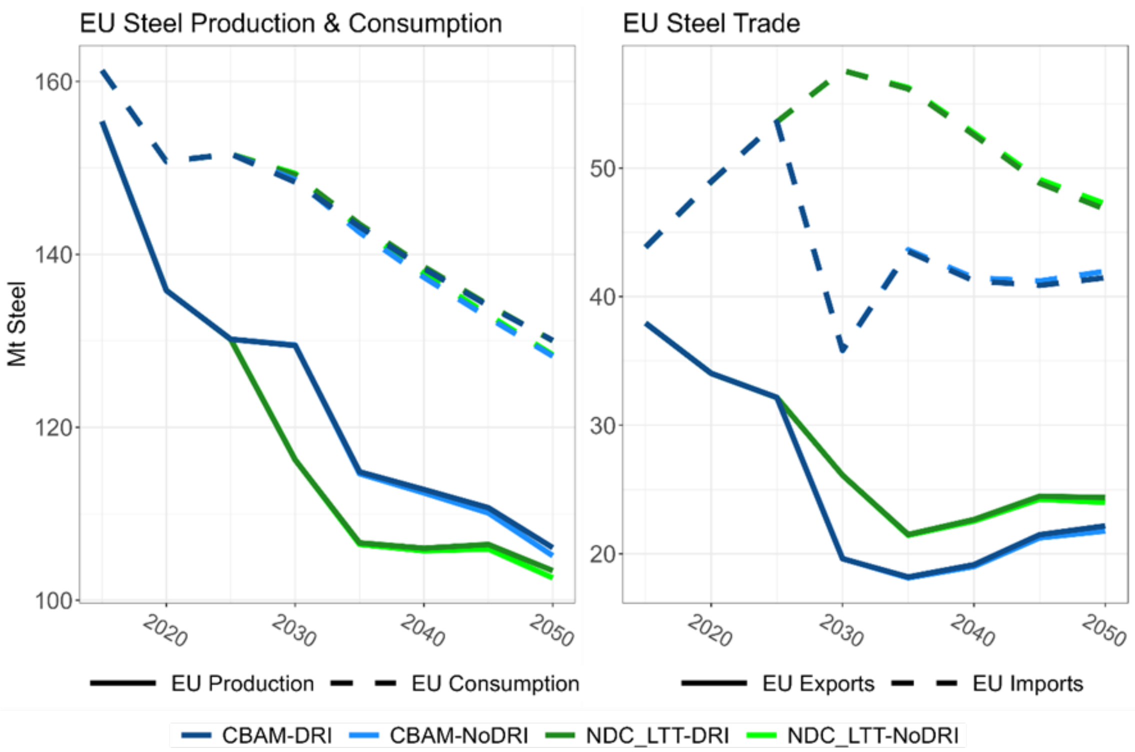

Figure 3-9: EU steel production, consumption and trade in four scenarios

The share of various steel production routes (see Figure 3-10) appears to be very similar to the results of Study 9.0: secondary steel is the dominant route while primary steel production is distributed across a broad portfolio of production routes. In comparison of the scenarios with and without DRI trade, DRI-H2 has a slightly higher production volume when DRI trade is included.

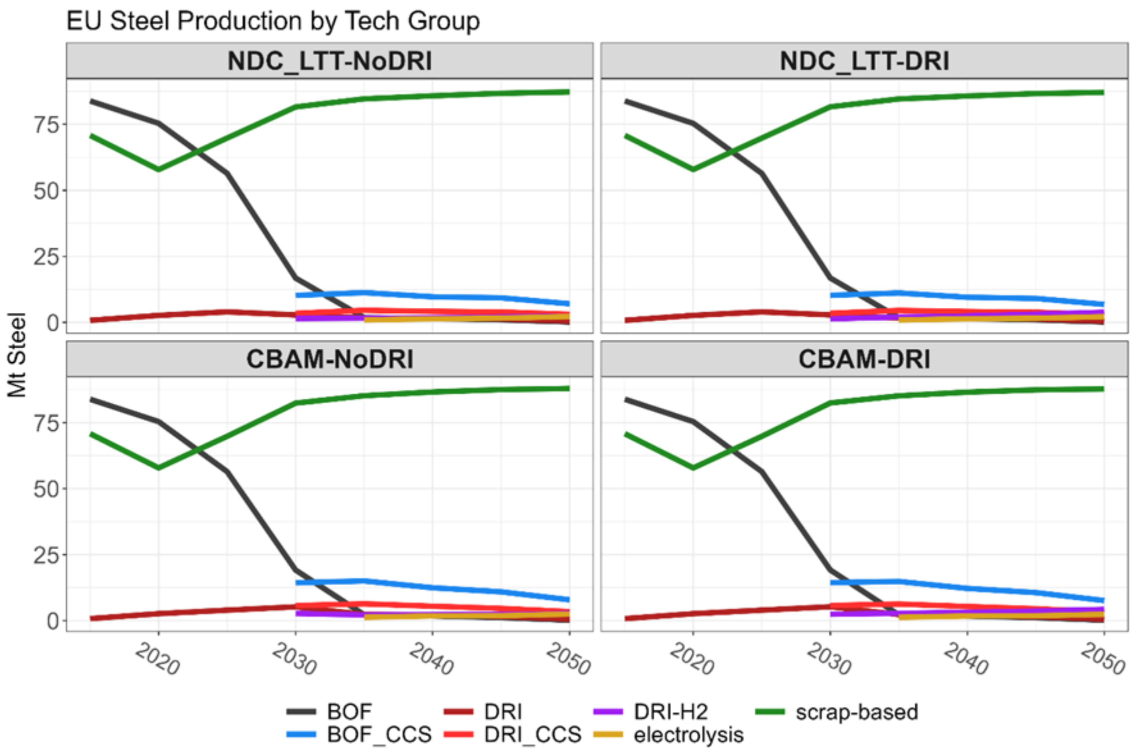

Figure 3-10: Production by technology in four scenarios

While DRI_H2 trade slightly increases steel production and the shares of DRI_H2 among primary steel production (see above), it leads to a reduced domestic production of DRI (see Figure 3-11). In 2030, around half the DRI used for steelmaking is imported. This share of imported DRI_H2 increases to approximately 2/3 over time. In scenarios with DRI trade, EU DRI production is about half the amount of it in the scenarios without DRI trade. In comparison of the scenarios with and without CBAM, it can be observed that CBAM secures DRI_H2 production to the EU.

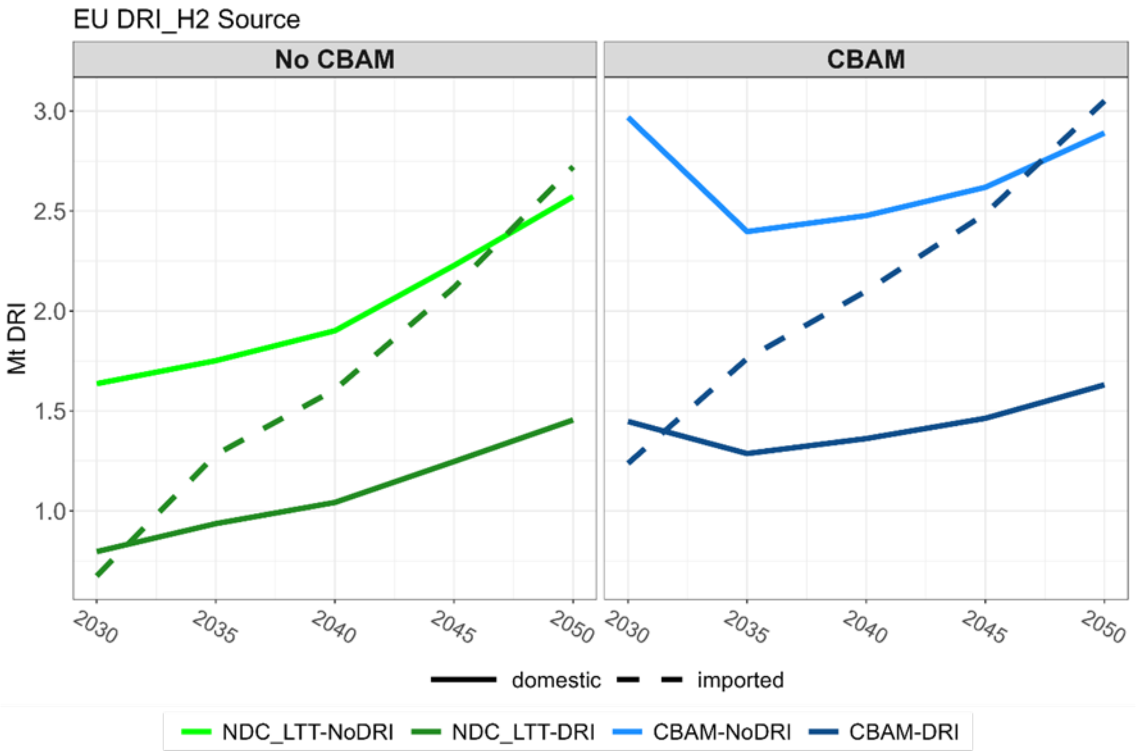

Figure 3-11: Sources of DRI_H2 over time in four scenarios

On a global scale, the effects of DRI trade on low carbon steel production are negligible (see Figure 3-12). While a small difference is made on the EU level as described above, these changes are not discernible on the global level.

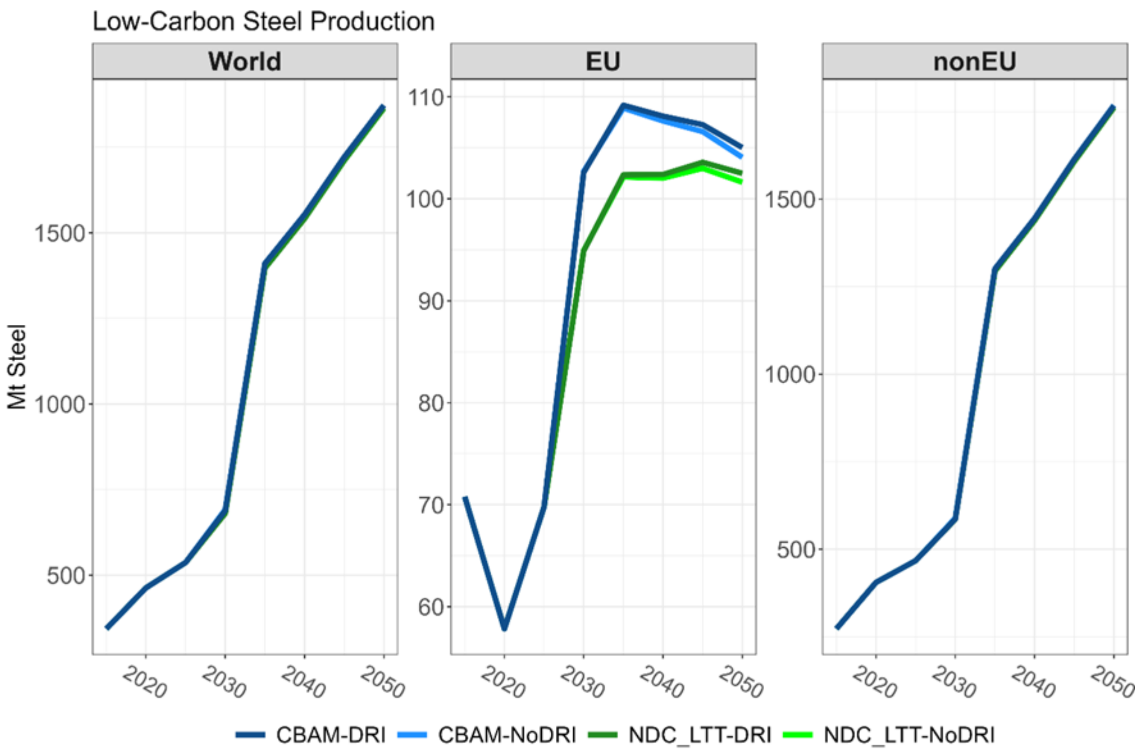

Figure 3-12: Global, EU and non-EU low-carbon steel production by technology in four scenarios

3.3.4 Conclusions

According to the scenario results, global trade of DRI_H2 improves the competitiveness of EU steel production to some extent, leading to (slightly) higher production, increased exports and less imports. This is achieved through the use of imported DRI_H2, which, however, partly substitutes DRI_H2 produced in the EU. These results show a trade-of between competitiveness of steel produced in the EU and maintaining all production steps within the EU. In relation to total steel production in the EU, the magnitude of these effects is, however, small and the effect on the global steel transformation is negligible.

3.4 Consumption-based environmental impact of the European steel transformation

3.4.1 Introduction to the modelling approach

A comprehensive exploration of the indirect (i.e., consumption-based) effects of carbon and energy impacts associated with the EU steel transformation relies on a soft-linked modelling approach that integrates GCAM with MARIO. As shown in Figure 3-1, GCAM, an Integrated Assessment Model, endogenously generates region-specific projections for future energy and steel supply mixes. These GCAM outputs are then fed into MARIO, an input-output modelling environment based on the Exiobase hybrid database, which has been technologically enriched in this study to align its steel production technology layer with GCAM's granularity.[7] This approach builds directly upon the methodology established in Rinaldi et al. (2024), but is extended here to cover a broader set of innovative steelmaking options.

Input-output models intrinsically enable precise quantification of both direct and indirect (i.e., upstream and supply chain) impacts. In this analysis, such capabilities have been leveraged to assess the GHG and energy footprints associated with a range of steel production technologies and future European steel production scenarios.

Finally, the analysis offers additional insights by quantifying the environmental implications of shifting the balance between domestic steel production and imports, specifically by calculating the total GHG emissions embedded in the EU steel consumption in each scenario.

3.4.2 Greenhouse gases and primary energy footprints for steel production technologies

The model calibration is referred to the year 2020**.** The GHG footprints for steel via all identified production technologies, ranging from conventional BF-BOF and emergent DRI-EAF-based steel making routes, to breakthrough techniques such as AEL-EAF and the MOE methods are shown in Figure 3-13. Values for the conventional (BF-BOF, EAF) and DRI-EAF routes fall well within published reference ranges (IEA, 2020), while there is a limited availability of literature for comparing results for emergent technologies, due to their current limited adoption.

[7] https://zenodo.org/records/15586337

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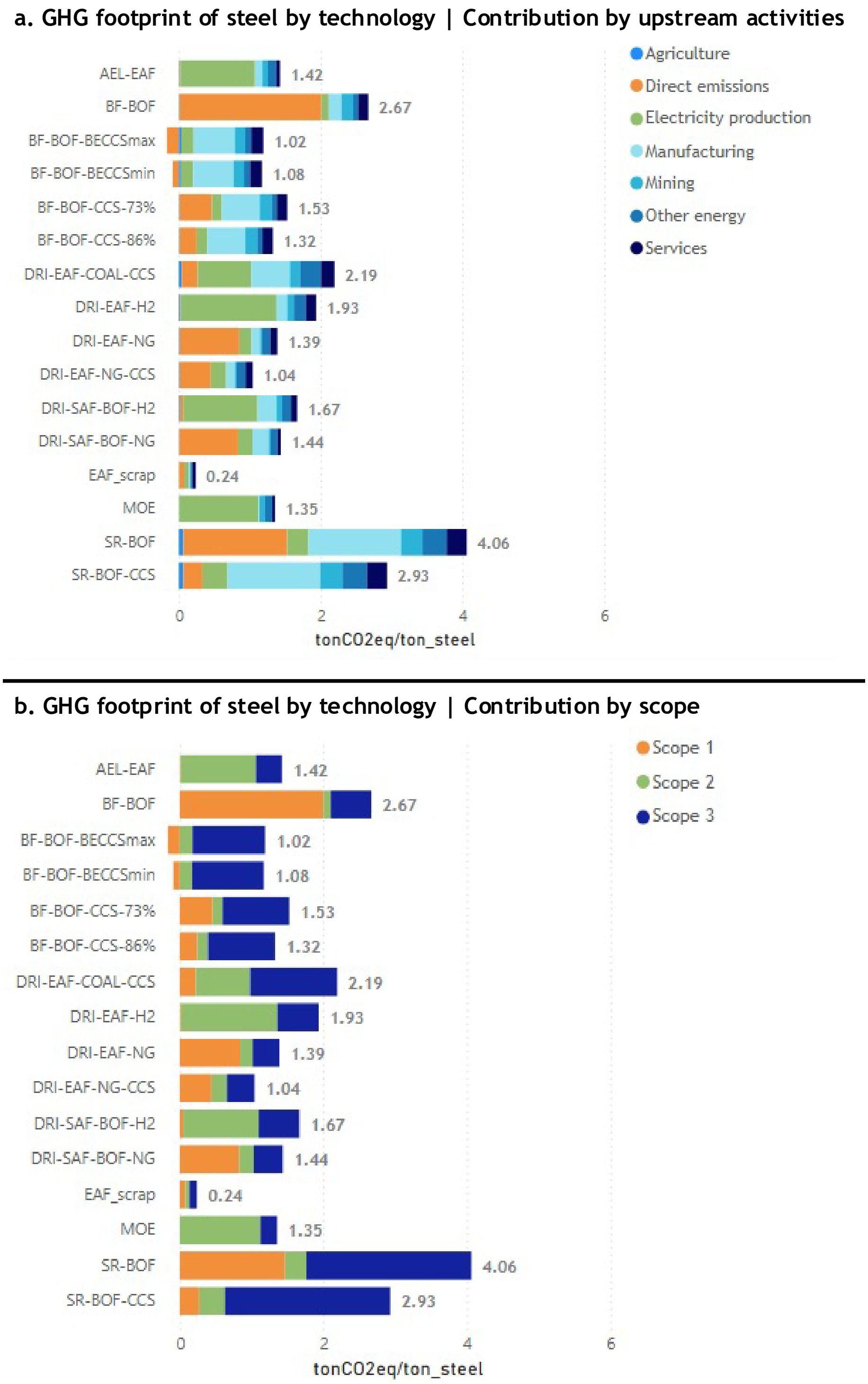

Figure 3-13: GHG footprint by steel production technology in the EU, 2020, (a) by origin upstream activity and (b) by impact scope

By decomposing emissions by both economic sector (such as mining, electricity supply, and upstream manufacturing) and impact scope (where scope 1 refers to direct emissions of the technology, scope 2 to emissions embedded in electricity consumed, scope 3 to all remaining other emissions), Figure 3-13 reveals the "anatomy" of the greenhouse gases contained in a ton of steel produced by each route in the EU.

Within a single plant type, substantial variation emerges based on fuel choices or the deployment of CO_2 abatement strategies. In the case of BF-BOF plants, the "standard" configuration posts a high GHG intensity at

2.67 tCO_2eq/ton steel, but when carbon capture and storage (CCS) is implemented, emissions fall sharply—to 1.53 tCO_2eq/ton steel for partial CCS (73%) and 1.32 tCO_2eq/ton steel for a higher direct emissions removal rate (86%). This decline in the GHG footprint is attributed to the reduction in direct emissions from the steel plant (Scope 1), which is able to offset the increase in Scope 2 and Scope 3 emissions resulting from the increased electricity consumption required by the CCS technology. Further adoption of bioenergy with CCS (BECCS) can decrease the footprint to as low as 1.02 tCO_2eq/ton steel (maximal BECCS), or 1.08 tCO_2eq/ton steel (minimal BECCS application), highlighting the compounded mitigation offered by combining fuel shifts and negative-emissions technology.

The fuel choice effect is also evident in the DRI-EAF routes. Switching from natural gas (1.39 tCO_2eq/ton steel) to hydrogen (1.93 tCO_2eq/ton steel) presently increases GHG intensity: despite DRI-EAF-H_2 technology employs only green hydrogen, it requires larger amounts of electricity from the grid than DRI-EAF-NG for the heating process in the shaft furnace, resulting in a higher GHG footprint – at least with the 2020 EU electricity mix considered for the calibration (roughly 300 gCO_2eq/kWh). Integrating CCS with the natural gas-based DRI-processes brings emissions down to 1.04 tCO_2eq/ton steel.

Among innovative electrolysis-based steelmaking routes, MOE and AEL-EAF yield to similar emissions levels (1.35 and 1.42 tCO_2eq/ton steel, respectively), with the majority of these emissions arising from electricity production. Consequently, as for DRI-EAF-H_2, their GHG footprint is strictly associated with the EU electricity supply mix.

Additional considerations can be drawn from the primary energy embedded in each steel production route, shown in Figure 3-14 with contributions by impact scope. The most energy-efficient pathway is the secondary route (EAF), requiring only 7.09 GJ/ton steel, underscoring the very low energy demand associated with recycled steel. In contrast, advanced routes relying heavily on electricity, such as DRI-EAF-H_2 (83.48 GJ/ton steel), AEL-EAF (60.88 GJ/ton steel) and MOE (61.08 GJ/ton steel), require higher energy inputs with respect to traditional routes (all BOF-based technologies require around 49-52 GJ/ton steel of energy), largely due to their reliance on the electrolysis process and to current EU electricity supply mixes.

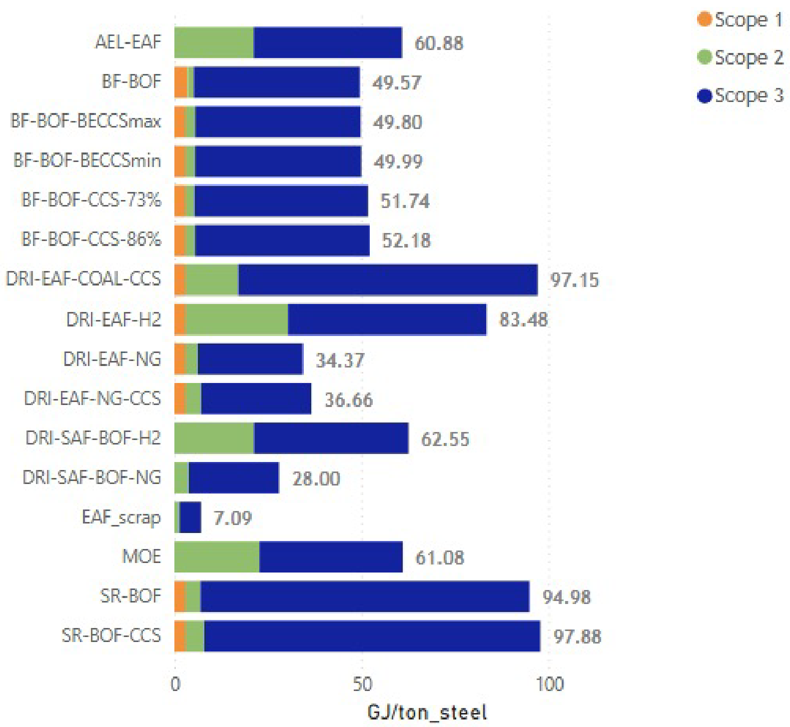

Figure 3-14: Total energy footprint by steel production technology in the EU, 2020, by impact scope

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3.4.2.1 Temporal dynamics and technology clusters

As mentioned in the previous section, the electricity supply mix has a significant impact on the final GHG footprint of steel production technologies such as DRI-EAF-H_2, AEL-EAF and MOE. The scenarios envisaged in the GCAM model for the period 2025-2050 project a global energy transition process, which will consequently affect the future environmental impacts of steel production routes. Figure 3-15 illustrates how the increasing share of renewable energy in the EU electricity mix will influence the GHG footprint of different technologies clusters.

A first cluster of routes, comprising electrolysis-based (AEL-EAF, MOE) and DRI-EAF-based production routes, demonstrates a pronounced decline in the GHG footprint over time (see Figure 3-15a for DRI-based, and Figure 3-15b for electrolysis-based routes). These technologies benefit strongly from a rapidly decarbonising EU electricity mix, with renewables shares rising from just under 50% in 2020 to up to 90% by 2050. For example, the GHG intensity of AEL-EAF falls from 1.42 in 2020 to 0.25 tCO_2eq/ton steel in 2050, and MOE essentially reaches zero emissions by 2050 thanks to clean power inputs.

Meanwhile, BOF-based routes show only marginal improvements over the same horizon, mainly concentrated in CCS-equipped technologies. Being more reliant on electricity than the traditional BF-BOF technology, these routes can indeed benefit more from the decarbonisation of the European electricity sector (see Figure 3-15c).

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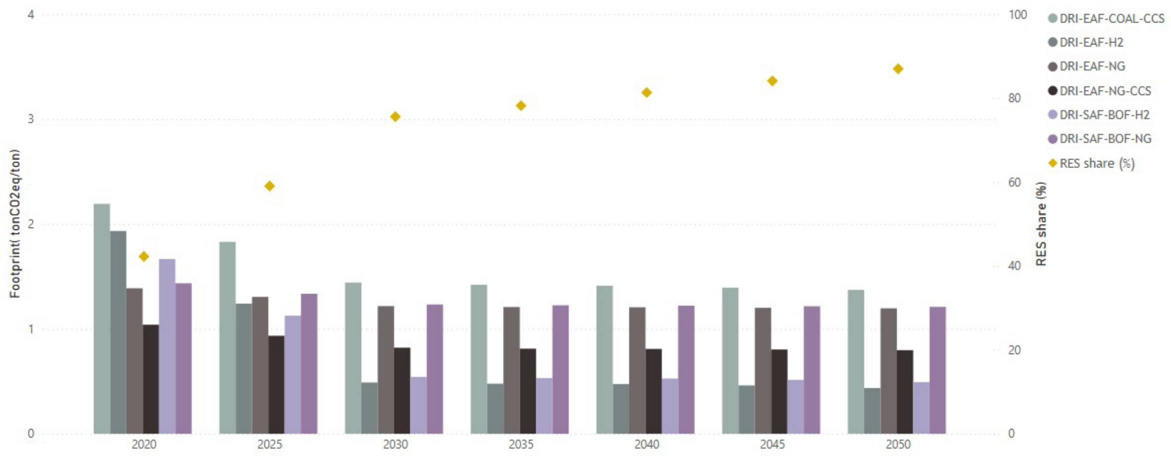
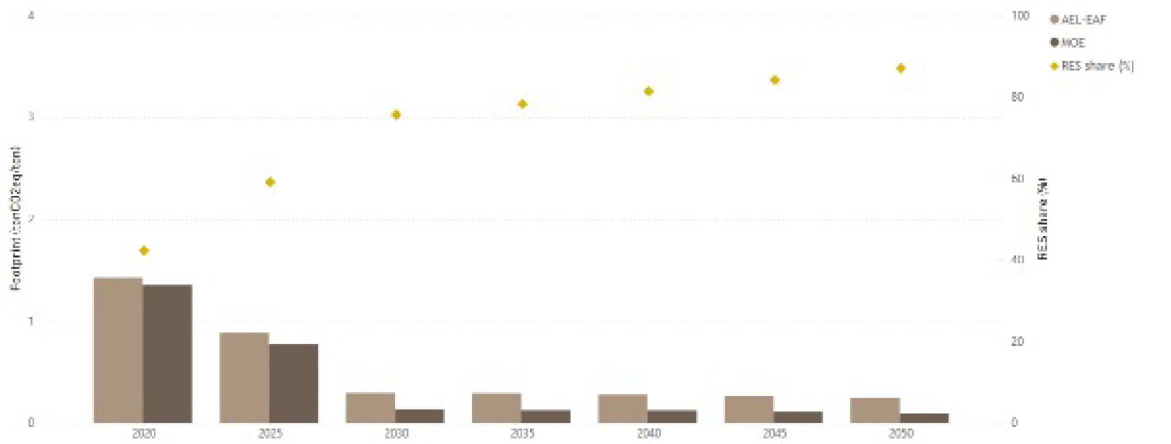
a. DRI-based technologies



b. Electrolysis-based technologies



c. BOF-based technologies

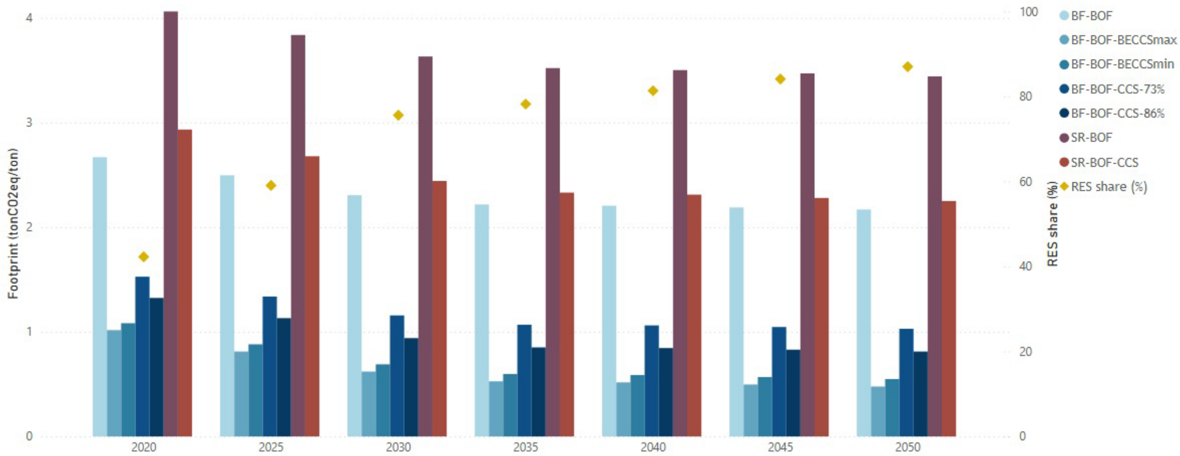


Figure 3-15: GHG footprint evolution over time in NDC_LTT scenario. a) DRI-EAF-based technologies. b) Electrolysis-based technologies. c) BOF-based technologies

3.4.3 Environmental implications of EU steel decarbonisation scenarios

By implementing the future steel supply mixes provided by GCAM in MARIO, it is possible to analyse how the different scenarios affect the GHG footprint of the steel produced in the EU over time. With the reduction of the dependence on traditional blast furnace and the adoption of a plurality of technologies (especially EAF), together with the simultaneous decarbonisation of the electricity sector, the GHG footprint of steel produced in the EU decreases significantly in all analysed scenarios. As the steel supply mix in the EU differs only marginally between scenarios, the GHG footprint is also very similar in the different pathways, declining from 1.56 tCO_2eq/ton steel in 2020 to approximately 0.30 tCO_2eq/ton steel in 2050.

Nevertheless, in order to derive a precise overview of the effects that various scenarios have on the EU steel consumption-based emissions, it is necessary to consider the balance between domestic and imported steel, which varies across the different analysed pathways. This impact is measured in terms of total GHG footprint related to the consumption of steel in the EU and is shown in Figure 3-16.

In particular, all scenarios exhibit a significant decline in the GHG emissions embedded (Scope 1, 2, 3) in the EU steel consumption, from over 220 $MtCO_2eq$ in 2025 down to approximately 65 $MtCO_2eq$ by 2050. The variation across scenarios remains moderate, though not insignificant. As expected, the observed divergences are closely linked to the dynamics of EU steel imports, as also shown in Figure 3-9, which illustrates trends in consumption and trade across the four scenarios. In particular, the NDC_LTT scenario projects a sharp increase in imported steel by 2030, which explains the higher level of consumption-based emissions observed in that year. By 2050, the gap across scenarios narrows, with a maximum difference in consumption-based GHG emissions of approximately 12% between NDC_LTT and CBAM_G_SUBS_HI. This suggests that the policy measures under examination—namely the Carbon Border Adjustment Mechanism (CBAM) and varying levels of green subsidies—can influence the decarbonisation trajectory of steel consumption in the EU. However, their overall impact appears limited, indicating that while such interventions contribute to emissions reductions, they are not transformative unless accompanied by broader structural shifts in trade patterns and more ambitious decarbonisation efforts in exporting countries.

In summary, the scenario analysis reveals that the ability of current policy mechanisms to meaningfully reshape the GHG footprint of the EU steel consumption, especially through trade, is limited. For a deeper impact, these instruments would need to drive either a more substantial restructuring of steel trade flows or promote transformative decarbonisation abroad, in addition to domestic efforts.

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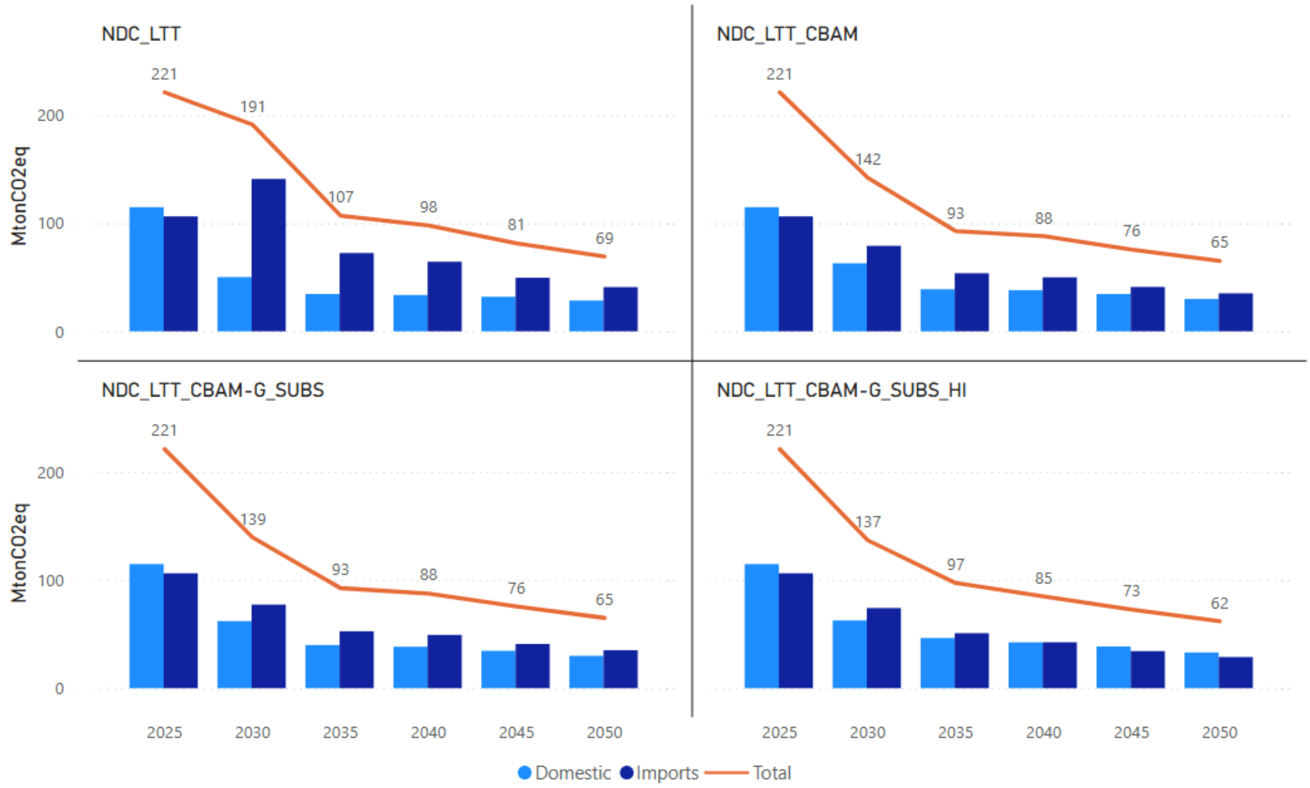

Figure 3-16: GHG emissions embedded in steel consumed in the EU by scenario. Contribution split by domestic and imported steel

3.5 Policy instruments and their effects on intra-EU relocation

3.5.1 Introduction

The bottom-up, techno-economic, steel sector-specific model ITOM-Steel (see section 3.1) is used to create and analyse scenarios to answer the third research question: "How do various policy instruments influence EU and EU member state steel transformation pathways, costs and emissions, considering spatial relocation of production of steel and intermediate products within the EU?"

The scenario work uses results of the *CBAM+G_SUBS* scenario (see section 3.2.2) as inputs to ITOM and analyses the technological transformation pathway on the EU-level, relocation of iron and steel production between EU regions, CO_2 emissions, and average crude steel production costs. Imports of HBI[8] from non-EU countries are also considered within the scenario.

Then, various model experiments are conducted to explore additional policy measures for steering the steel transformation and to analyse their effects. The policy measures have been defined in a stepwise manner, starting from the CAPEX subsidies assumed in *CBAM+G_SUBS* as modelled with GCAM, then exploring hydrogen subsidies as an alternative OPEX based instrument for accelerating the transition to green steel and finally – building on the learnings – analysing refined CAPEX- and hydrogen subsidies as alternatives.

[8] Hot briquetted iron, a transportable form of direct reduced iron (DRI)

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3.5.2 Scenario design, input data and policy measures

The scenarios modelled with ITOM build on the results of *CBAM+G_SUBS* modelled by GCAM. The steel production volumes, the prices of the most important energy carriers (hydrogen, natural gas, electricity, coal, biomass) and the CO_2 emission costs are taken from GCAM results and translated into the data input structure of ITOM as explained in the following. Furthermore, additional scenario assumptions are made with regards to the maximum upscaling speed of electrolysis and DRI technologies, CCS costs, HBI import costs and limits and limits to the use of biomass. First, a scenario *GSUBS_base* which does not include additional policy measures is modelled based on these inputs and assumptions and used as a reference for scenario variants with policy instruments.

To explore the effectiveness of various policy instruments, several distinct scenarios have been designed. These scenarios represent different approaches to accelerate the transition to low-carbon steel production, each with unique implications for technology adoption, costs, and emissions. They are intended to provide policymakers with insights into how specific instruments can shape the future of the EU steel sector. The following policy measures, which are explained in greater detail below, are explored:

- **GSUBS_Capex-low:** This scenario examines the impact of CAPEX subsidies for DRI plants, offering a phased reduction of investment costs from 30% in 2030 to 10% in 2040 to stimulate early adoption.
- **GSUBS_Capex-high:** This ambitious scenario investigates the effects of substantially higher CAPEX subsidies for DRI plants (90%) around 2030, designed to provide a stronger, more immediate financial incentive for early transformation.
- **GSUBS_H2:** Here, the focus shifts to reducing operational burdens for new technologies through the provision of low-cost green hydrogen to the steel industry.
- **GSUBS_H2-DRI:** This variant refines the hydrogen subsidy by restricting its application exclusively to the production of DRI, ensuring targeted support for a key decarbonisation pathway.

Each of these scenarios is designed to shed light on how specific policy instruments can influence the technological mix, emissions trajectory, and economic viability of the EU steel sector, moving beyond the baseline.

3.5.2.1 Production volumes

ITOM endogenously models the UK in addition to EU27. Finished steel production volumes in the period from 2020 to 2050 are based on empirical values for 2020 and extrapolated using EU production volumes from the *CBAM+G_SUBS* scenario modelled with GCAM. Table 3-4 shows the resulting total steel production.

Table 3-4: EU 27+UK production volumes of finished steel

	2020	2025	2030	2035	2040	2045	2050
Production volume finished steel (EU27+UK); Mt	145.6	138.6	135.0	137.9	141.5	145.2	150.7

While GCAM models aggregate steel production for the EU27, ITOM disaggregates steel production to EU regions and steel products to reflect the regionally divergent demand for finished steel and cast products, further differentiated by steel grades and demand sectors. First, production for non-EU exports were allocated to an abstract model region "Europe" based on the assumption that such exports can be supplied by all model regions at the same costs (see below). Domestic demand of EU regions for steel produced within the EU was then allocated to the respective region, what creates incentives for production close to customers. To achieve this disaggregation of production volumes, Eurostat data for total production[9] and trade statistics[10] for the base year[11] were used were available and complemented with proxy data derived from steel mill production capacities (own data). Those data were related to each other and to ITOM product categories by mapping each of them to ten product categories. The distribution of more specific products and product qualities within each product category was taken from existing (own) data for the EU27+UK. The resulting distribution of products and product qualities among EU regions is held constant over time and scaled in line with the GCAM-projected total volumes, enabling a region- and product-specific evolution of steel and cast-iron production.

Model Regionalisation – Overview

ITOM covers all 27 EU Member States. Additionally, to the EU27 the United Kingdom (UK) is also endogenous modelled but is excluded from the analysis. To enable regional differentiation while maintaining analytical clarity and reducing the computational burden, countries are aggregated into nine distinct regions. These groupings reflect geographical proximity and relevance in steel production. Some regions therefore consist of multiple Member States, while others – such as Germany and France – are represented individually due to their important role in the European steel sector. In addition to these regions, the model includes a synthetic "Europe" region, which accommodates production volumes dedicated for export to non-EU countries as well as production volumes that could not be allocated to a specific EU region based on the empirical data.

The mapping of EU Member States into the nine regions used in ITOM is as follows:

- **DE** – Germany
- **FR** – France
- **EU_South** – Austria (AT), Italy (IT)
- **EU_Southeast** – Bulgaria (BG), Greece (EL), Croatia (HR), Romania (RO), Slovenia (SL)
- **EU_Southwest** – Spain (ES), Portugal (PT)
- **BeNeLux** – Belgium (BE), Netherlands (NL), Luxembourg (LU)
- **EU_North** – Sweden (SE), Finland (FI), Denmark (DK)
- **EU_East** – Czech Republic (CZ), Estonia (EE), Hungary (HU), Latvia (LT), Lithuania (LV), Poland (PL), Slovakia (SK)
- **UK** – United Kingdom, Ireland (IE)

3.5.2.2 Prices of energy carriers

In addition to production volumes, GCAM endogenously calculates EU averages of energy costs for the EU steel industry, which are also used as exogenous data input by ITOM. This includes the most relevant ones for today and future steel making: hydrogen, natural gas, coal, electricity and biomass (see Table 3-5). For those energy carrier prices that are required by ITOM on a member state level the table also includes minimum and maximum values in member states. The member state prices have been derived from EU average values (from GCAM) and additional considerations as explained below.

[9] https://ec.europa.eu/eurostat/databrowser/view/ds-056121__custom_15778687/default/table?lang=en&page=time:2021
[10] https://ec.europa.eu/eurostat/databrowser/view/ds-045409/default/table?lang=en
[11] The year 2021 was used as a proxy because production volumes in the year 2020 were very peculiar due to the Corona crisis.

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Table 3-5: Energy prices for the EU steel industry

Fuel	2020	2025	2030	2035	2040	2045	2050
Elect. (€/MWh) (Min / Max in MS)	115 (51/233)	104 (66/170)	83 (55/106)	92 (61/137)	85 (57/127)	73 (49/109)	60 (40/89)
Natural gas (€/GJ) (Min / Max in MS)	7.7 (5.7/14.6)	9.4 (7.1/18)	8.6 (6.5/16.4)	9.4 (7.1/18)	9.1 (6.8/17.4)	8.7 (6.5/16.6)	8.5 (6.4/16.2)
Hydrogen (€/GJ) (Min / Max in MS)	-	-	32.7 (24.5/40.9	22.6 (19.2/26)	22.0 (19.8/24.2	19.4 (17.4/21.3	16.6 (14.9/18.2
Coal (€/GJ)	2.5	3.4	2.4	3.0	3.0	3.2	3.2
Biomass (€/GJ)	7.4	7.2	7.3	10.1	10.3	12.2	13.8

ITOM uses EU-wide prices for coal because it is generally purchased on the global market and imported into the EU for similar prices independent of the destination. Also, the prices for biomass were assumed to be the same across the EU, due to a lack of data on the member state level. Electricity prices are based on the average prices from GCAM but varied per country based on a pattern of differences between marginal electricity costs of EU member state. The latter was derived from data from ACER (2020) for 2019 in combination with analyses conducted with the EXPANSE model for three scenarios on the energy crisis conducted in IAM COMPACT, each run by three IAMs (D4.5 "National, regional, global mitigation pathways"; Sasse & Trutnevyte 2023). The results of the EXPANSE model were used for 2035 onwards while 2025 and 2030 have been linearly interpolated between 2020 and 2035, for each country. Hydrogen prices for ITOM are derived based on average hydrogen prices of the EU as calculated by GCAM and varied between countries according to the same pattern as electricity prices. However, deviations from the EU average hydrogen price are capped by a maximum deviation of 25% in 2030, 15% in 2035 and 10% from 2040 onwards, assuming that a growing hydrogen infrastructure provides possibilities for hydrogen imports and exports and an according reduction of price spreads. The spread of prices for natural gas around the EU average is taken from Eurostat data (average for the years 2023 and 2024) and kept constant over time. The years 2023 and 2024 are chosen to reflect the changed pattern of EU gas purchases since the Russian war on Ukraine.

3.5.2.3 CO_2 emission costs

GCAM also provides "effective" average CO_2 prices[12] per ton of CO_2 emitted by the steel industry. These "effective" CO_2 prices take into account that the steel industry receives free emissions allowances in the period up to 2035 and are calculated from three factors:

- The EU ETS-1 price for CO_2 certificates
- Then number of free allowances is phased-out while CBAM is phased-in
- The number of free allowances is calculated based on a benchmark which changes in line with the

[12] GCAM values were given in USD2010 and were translated into €2020.

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emissions of the most efficient[13] 10% of the plant fleet.[14]

The phase-out of free allowances in line with the introduction of CBAM and the decrease in the benchmark for their calculation thus add to the increase of the (effective) CO_2 price, besides the increasing ETS price. Consequently, between 2020 and 2050, the effective CO_2 price increases significantly, from € 2.6/t CO_2 in 2020 to € 311/t CO_2 in 2050 (see Table 3-6). The steepest absolute increases occur between 2030 and 2035. The sharply increasing effective CO_2 price provides strong incentives for companies to cut emissions and invest in low-carbon technologies. Furthermore, if negative emissions are achieved through the use of BECCS in steel production, this creates the opportunity to generate revenue by selling CO_2 certificates for negative emissions. It is assumed that these certificates can be sold at prices equivalent to those of standard ETS CO_2 emission allowances.

Table 3-6: Effective CO_2 price per ton of CO_2 emitted by the EU steel industry, considering free allowances

	Unit	2020	2025	2030	2035	2040	2045	2050
ETS CO_2 certificate price	€/t CO_2	8.8	38.4	176	234	239	273	311
Free allowances	% of emissions	70	55	40	0	0	0	0
Effective CO_2 price	€/t CO_2	2.6	17.3	105	234	239	273	311

3.5.2.4 CO_2 transport and storage costs

CO_2 storage costs are calculated endogenously by GCAM. However, CO_2 transport costs are not considered. Therefore, CO_2 transport and storage costs for ITOM are taken from Malz et al. (2025) instead, choosing the average of the cost spread of the average scenario modelled by Malz et al. (see Table 3-7). It is assumed that CCS becomes legally and technically possible in the 2030 time period.

Table 3-7: Transport and storage costs per ton of CO_2 stored

	Unit	2020	2025	2030	2035	2040	2045	2050
Transport and storage costs	€/t CO_2	-	-	63.5	60.9	58.4	55.8	55.8

3.5.2.5 Maximum upscaling speed of electrolysis and DRI

A major bottleneck in the transition of the steel industry to low-carbon steel could be the limited engineering capacity for the construction of DRI plants. Currently, there is around 135 Mt of DRI capacity worldwide (Midrex 2024). Assuming a maximum growth rate of 10% in capacity expansion, which corresponds to the expected targets or expansions in other future technologies such as EV batteries or electrolysers (Agora Industry and Wuppertal Institute 2023), a global DRI capacity expansion of 15-20 Mt capacity per year seems possible in the mid-term. Parts of DRI upscaling will take place in growing regions in which (fossil-based) DRI-based steel production is already established, in particular MENA, India and Northern America. Furthermore, regions with

[13] In terms of specific CO_2 emissions

[14] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation_en
The resulting change in the benchmark has been estimated based planned DRI plant installations listed in the green steel tracker (https://www.industrytransition.org/green-steel-tracker/).

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favourable renewables conditions and iron ore reserves such as Australia and Brazil aim at the production of green DRI. Based on these considerations, ITOM incorporates a constraint on capacity addition per production site and time slice. This limit is set to 2.5 Mt (the capacity of a typical DRI plant) per location and five-year step.

Compared to DRI, direct iron ore electrolysis routes are significantly lacking in development and will only be available as an alternative in the medium to long term. While MOE[15] is expected to be available from 2035, the AEL_EAF route will not be available until 2040. Since these technologies use only electricity for steel production with no energy losses from converting electricity into hydrogen, they are by far the most energy-efficient renewables-based primary steel production methods. Accordingly, production costs are relatively low, offering considerable potential advantage over DRI for future steelmaking. However, the assumptions regarding energy use and technological readiness over time are subject to a high degree of uncertainty. Therefore, their use is limited in ITOM, with constraints on possible capacity addition. This is reflected in ITOM by limiting capacity addition of MOE and AEL to 2035 onwards and to 0.25 Mt per production site.

3.5.2.6 HBI import costs and limits

As the steel production cost of H2-DRI is heavily dependent on the cost of electricity production (for H2), it should be considered that global sweet-spots with favourable renewable energy conditions (and, advantageously, large iron ore deposits) are well suited to producing H2-DRI at low cost. Such global sweet spots could be in Australia or Brazil, for example, which not only have high potential for renewable energy but are also already among the largest exporters of iron ore due to their abundant domestic iron ore reserves. The average EU hydrogen price from GCAM for 2030 (3.7 €/kg) and 2050 (1.9 €/kg) are high, compared to those expected for Brazil and Australia (1.5 €/kg and 0.9 €/kg respectively; Bilici et al. 2024). It may therefore be cheaper for the European steel industry, to import DRI from global sweet-spots and only carry out the steelmaking step domestically. The option to import DRI in the form of hot briquetted iron (HBI) is therefore also considered by ITOM.

When importing DRI, however, a distinction must be made between two qualities of DRI: DRI_for_EAF and DRI_for_BOF, which differ mainly in the iron ore used, with DRI_EAF having a higher iron content and DRI_BOF a lower one. In addition, the quantity of high-grade DRI pellets needed for DRI_EAF is limited, as only a small proportion of the world's iron ore mined is currently of sufficient quality. Iron ore beneficiation and rising prices for high-quality iron ore pellets may increase this proportion in the future. Low-quality BF-pellets, on the other hand, already account for a significantly larger share of the iron market today, which is why there should be no restrictions here in the long term.

The prospects of a global DRI trade in terms of costs and volumes are very uncertain from today's perspective. For the scenarios, assumptions are made as shown in Table 3-8. For both qualities of DRI, two price levels have been defined, with import limits to each of the four resulting categories. The maximum import amounts are kept deliberately low to keep the focus of the analysis on the domestic steel transformation pathway, while imports play a minor role. This is in line with results of GCAM, as presented in section 3.3.

Table 3-8: Limits to DRI imports and import prices by type

	Unit	2030	2035	2040	2045	2050
HBI_EAF_1	Mt	1.05	1.3	1.5	1.8	2
HBI_EAF_2	Mt	0.85	1.0	1.2	1.3	1.5
HBI_BOF_1	Mt	1.8	2.3	2.7	3.2	3.6

[15] Molten oxide electrolysis

HBI_BOF_2	Mt	1.4	1.8	2.2	2.5	2.9
HBI_EAF_1	€ / t HBI	406	397	386	376	365
HBI_EAF_2	€ / t HBI	427	419	411	402	393
HBI_BOF_1	€ / t HBI	369	361	352	343	334
HBI_BOF_2	€ / t HBI	387	381	373	366	358

3.5.2.7 Use of biomass

The use of biomass in ITOM is also limited, as it is only available to a limited extent and the demand from the steel industry competes with that of other industries, particularly the chemical industry, which will continue to rely on carbon as a feedstock in the future which may be sourced from climate neutral sources such as biomass and atmospheric CO_2 instead of fossil feedstocks (Jones et al. 2025). In ITOM, biomass is used either in the form of raw biomass, which is converted into biogas in a gasification plant, which can then be used as a reducing gas in DRI plants as an alternative to natural gas or hydrogen. Another option is the use of charcoal, which is required for carburisation or slag formation in various processes, for example in the smelter or EAF. In the scenario, biomass use for the steel industry will not begin until 2030, as it is assumed that no biomass will be made available to the steel industry prior to this point in time. The actual limits of available biomass are aligned with the biomass use of the steel industry in GCAM and shown in Table 3-9.

Table 3-9: Limits to DRI imports and import prices by type

Product	Unit	2020	2025	2030	2035	2040	2045	2050
biomass	PJ	0	0	61.5	126.4	130.7	135.7	142.7
charcoal	PJ	0	0	36.2	74.4	76.9	79.8	83.9

3.5.2.8 Steel scrap

To reflect limitations in scrap availability, ITOM includes a limit for scrap use of the EU27+UK steel industry (see Table 3-10). This estimate is based on own data from a material flow analysis (unpublished) for future scrap supply and assumes that all scrap generated is used domestically for steel production and there are no scrap imports to the EU27+UK. Scrap is furthermore differentiated by five degrees of copper contamination, with copper contamination limiting the usability of scrap depending on the required steel product quality. Scrap is allocated endogenously by ITOM to primary steel production routes and secondary steel production, thereby considering required scrap qualities when producing steel products.

Table 3-10: Scrap available to EU27+UK steel industry

EU27 + UK	2020	2025	2030	2035	2040	2045	2050
Available scrap (Mt/a)	112.8	115.8	118.6	121.8	124.6	127.1	129.5

3.5.2.9 Policy measures

The above presented input data and assumptions are the same for all scenarios modelled with ITOM and result in the GSUBS_base scenario (see below). Derived directly from the GCAM model results, this scenario illustrates the sector's inherent trajectory under the context conditions of the *CBAM+G_SUBS* scenario and serves as a reference point for steel production volumes, CO_2 emissions and costs. It provides a benchmark against which the effects of proposed policy measures can be assessed. On top of that, the other four scenarios include additional policy instruments, explained in the following.

GSUBS_Capex-low: As a first policy measure, the provision of CAPEX subsidies for Direct Reduced Iron (DRI) plants is proposed to accelerate the decarbonisation of the EU27 steel industry beyond the pace of GSUBS_base.

The structure of these subsidies is aligned with the values assumed in the *CBAM+G_SUBS* scenario as modelled by GCAM: a 30% reduction in Capital Expenditure (CAPEX) is to be provided in 2030, followed by a 20% reduction in 2035, and a 10% reduction in 2040. The strategic focus on DRI plants is chosen, as Electrolysis (MOE) is highly competitive even without subsidies and BF/BOF+CCS is not competitive against DRI in the long-term (see Figure 3-17) and features comparably high residual emissions. Moreover, DRI plants provide flexibility with regards to the fuel used (natural gas, hydrogen, biogenic syngas) and therefore greater resilience against future energy cost variations.

GSUBS_CAPEX-high: Building on the previous discussions regarding CAPEX support and learning from the implementation of GSUBS_Capex-low (see below), a more ambitious and focused policy measure is explored: High CAPEX Subsidies for DRI Plants (90%) are provided in the critical period around 2030. In contrast to the initial GSUBS_Capex-low scenario, which offered a phased reduction of CAPEX support, this measure provides a more immediate and profound financial incentive. By front-loading the financial support, this policy seeks to overcome initial investment barriers more decisively and thereby accelerate the scale up and deployment of climate-neutral steel production technologies.

GSUBS-H2: This policy instrument focuses on operational expenditure (OPEX) support by providing the EU27+UK steel industry with 134 PJ/year of low-cost hydrogen during the crucial period from 2030 to 2040. The hydrogen prices are set at €15/GJ in 2030, €12/GJ in 2035, and €11/GJ in 2040. This subsidised amount of hydrogen is, in principle, sufficient to enable the annual production of 20 Mt of H2-DRI (hydrogen-based Direct Reduced Iron). This measure aims to accelerate the transition to climate-neutral steel production by significantly reducing operational costs for a key decarbonisation technology.

GSUBS-H2-DRI: Building on the previous measure of providing low-cost hydrogen and the learnings from its simulation with ITOM, a more targeted scenario variant is explored. This approach refines the hydrogen subsidy by restricting its application exclusively to the production of Direct Reduced Iron (DRI). While the overall volume and prices of subsidised hydrogen (134 PJ/year for EU27+UK steel industry from 2030 to 2040 at €15/GJ in 2030, €12/GJ in 2035, and €11/GJ in 2040) remains consistent with the GSUBS_H2 variant, this targeted approach aims to support what is currently often considered being the most promising decarbonisation pathway within the steel sector.

3.5.3 Results

3.5.3.1 GSUBS_base without policy measures

Figure 3-17 (left) shows the transformation of crude steel production in the EU27 in the GSUBS_base scenario without steel-specific policy instruments. It can be observed that primary steel production is primarily done via the DRI-route and electrolysis from 2035 onwards. The share of secondary steel increases significantly from 51% in the year 2020 to 66% in the year 2050, with an intermediate peak of 70% in the year 2035.

From 2035 onwards, iron is mainly provided by the DRI routes, with around 60% of the domestic iron production using natural gas as reducing gas, while bio-syngas has a share of around 25%. The import of HBI starts in 2035 and complements domestic production of iron. Blast furnaces equipped with CCS play some role until 2045 and are then replaced by hydrogen-based DRI and higher imports (see Figure 3-17, right).

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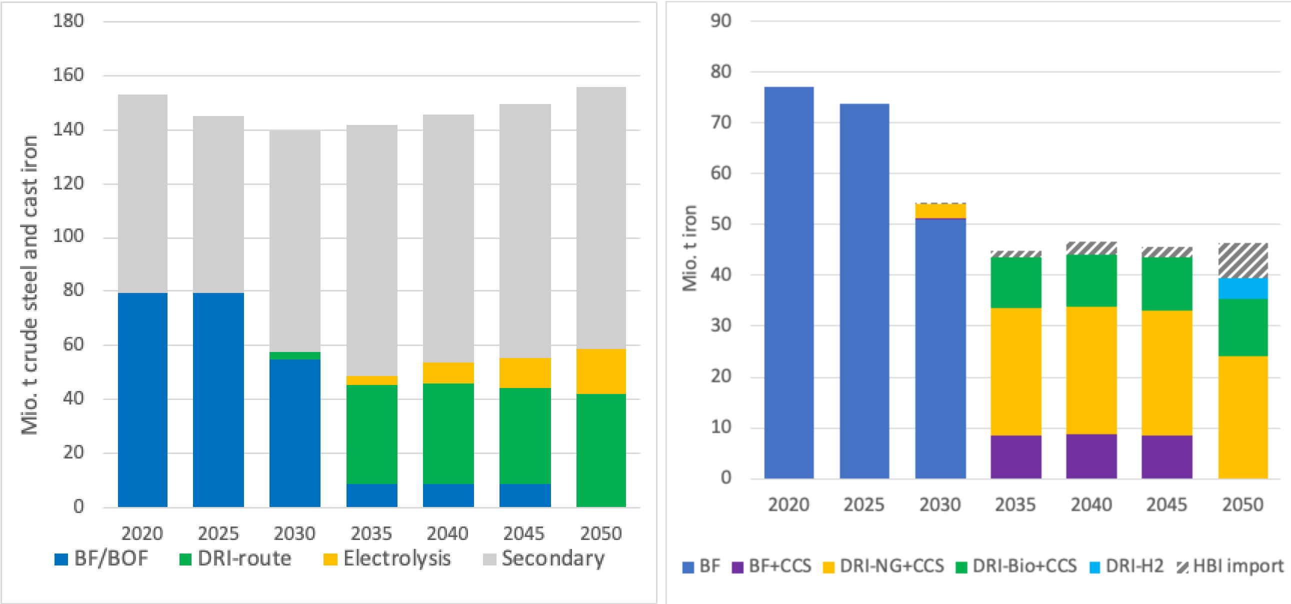

Figure 3-17: Crude steel production (incl. cast iron) in the EU27 per production route (left); iron provision in the EU27 (right).

A striking aspect of the transformation pathway is the swift switch from the unabated BF/BOF-route to low-carbon production technologies between 2030 and 2035. This can be understood against the background of strongly increasing effective CO_2 emission costs that rise from 105 $€_{2020}$ to 234 $€_{2020}$ in that period (see section 3.5.2.3 3). Figure 3-18 shows the specific crude steel production costs in EU major steel producing countries for the unabated BF/BOF route in comparison to low-carbon routes. It becomes apparent, that in the year 2030, the BF/BOF-route is cheapest in all these countries, while it becomes one of the most expensive options by 2035. The latter holds true even if only costs for a retrofit of the blast furnace instead of full Investment are considered and CAPEX of the coke-oven and the basic oxygen furnace are considered sunk costs and not included in the cost calculation. The DRI route with natural gas but without CCS – which if often considered being a "bridge" to near-zero-CO_2 steel production – does not play a role in this scenario as it is not cost-competitive to other routes in the year 2035 due to comparably high CO_2 emissions in combination with high CO_2 certificate costs. It should be noted, though, that the model runs in 5-year steps and in the period between 2030 and 2035 the DRI-NG route without CCS may still play a temporary role in the real world – even if boundary conditions would develop as in the scenario. With further increasing CO_2 emission costs after 2035 the cost differences that render DRI-NG without CCS uncompetitive even increase in later years.

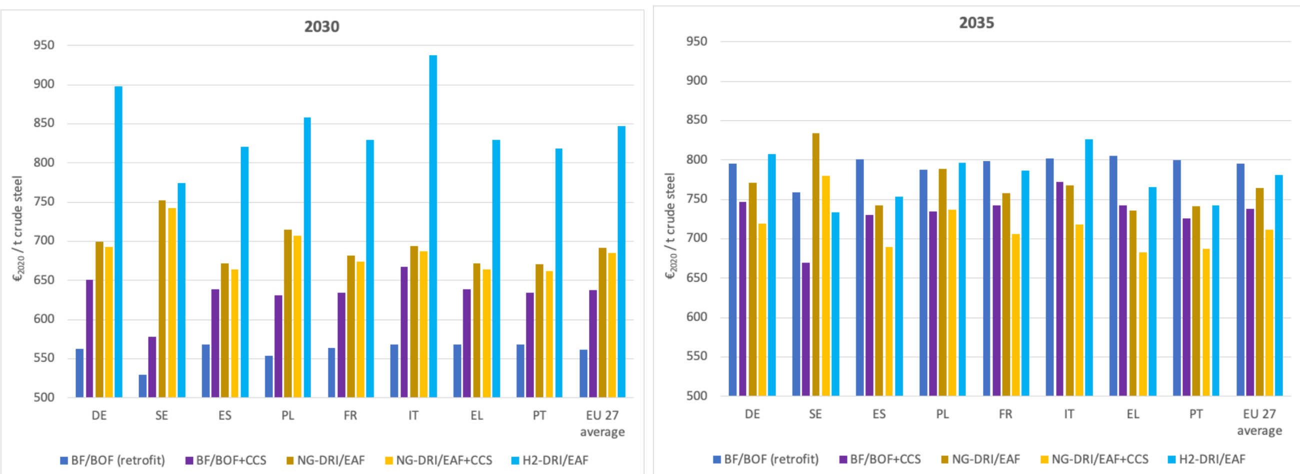

Figure 3-18: Specific crude steel production cost for BF/BOF and DRI-routes in major EU steel producing countries in the years 2030 (left) and 2035 (right)

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Figure 3-19 (left) displays the CO_2 emissions associated with the GSUBS_base scenario. The CO_2 emissions drop significantly in the period from 2025 to 2035, due to the swift shift to secondary steel and low-carbon primary routes described above. The bio-based DRI-route in combination with CCS creates negative emissions and as a result the EU steel industry is almost CO_2-neutral by 2035, already. When the energy provision for hot-rolling from natural gas is gradually replaced by hydrogen and electricity after 2035 and the associated CO_2 emissions of hot-rolling are avoided, the net emissions of the EU27 steel industry even become net-negative around 2045.

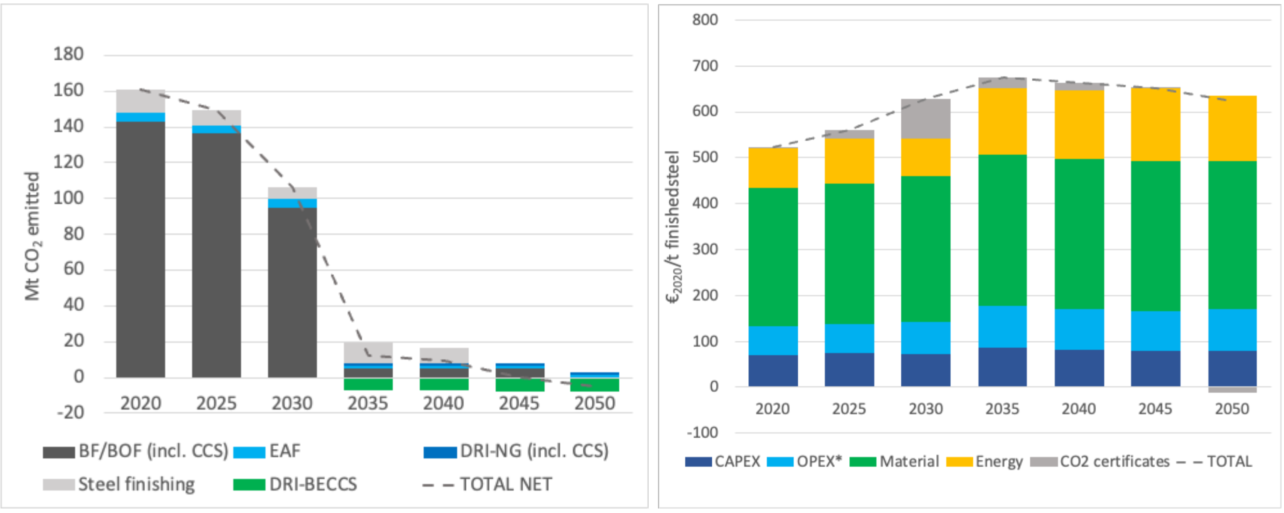

Figure 3-19: CO_2 emissions of the EU27 steel industry in the GSUBS_base scenario (left) and average costs of finished steel production in the EU27 in the GSUBS_base scenario (right)

The average costs of the production of finished steel in the EU27 increase from 524 €$_{2020}$ / t finished steel to around 620 €$_{2020}$/t in the long-term, with an intermediate peak of 674 €$_{2020}$/t in the year 2035. The main part of the long-term increase results from higher energy costs. In the medium term around the year 2030 CO_2 certificate costs play a significant role, before the steel industry switches to low-carbon production routes and negative emissions generate some revenues. Material costs remain comparably stable in the scenario, but CAPEX and OPEX increase in the mid-term when new plants are built while existing plants have not yet reached the end of their lifetime.[16]

While the transformation unfolds, iron and steel production partly re-locate within the EU27 (see Figure 3-20). With regards to iron production (see Figure 3-20, right), most blast furnaces in established steel regions such as Germany (DE), BeNeLux and EU_East are shut down, while DRI production is being build-up where local energy (electricity, natural gas, hydrogen) prices make this most competitive, in particular in EU_North. The picture is similar but less pronounced for crude steel production (see Figure 3-20, left). The difference results from regions with decreasing iron production increasing their secondary steel production, importing HBI, or establishing molten oxide electrolysis steel production (which does not require pig iron production as an upstream production step).

[16] In the model the economic lifetime and payback period is identical to the technical lifetime which is assumed to be 40+ years for most plant types. Fixed OPEX must be paid for all existing plants, be they in use or not.

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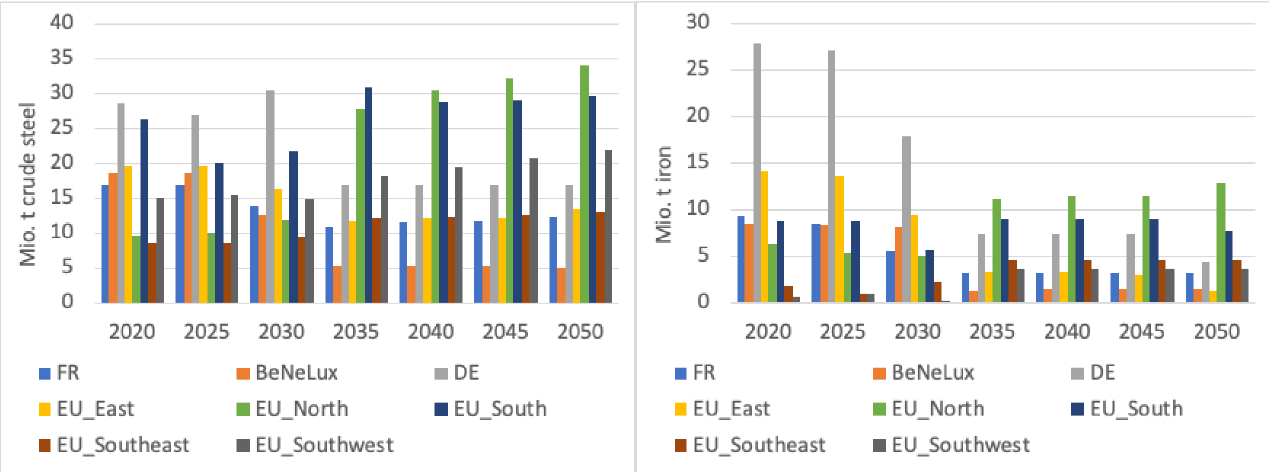

Figure 3-20: Crude steel (left) and iron (right) production in European regions over time

3.5.3.2 CAPEX subsidies

As a first policy measure (GSUBS_Capex-low), CAPEX subsidies are provided to DRI plants in line with the CAPEX subsidies in GCAM in the scenario CBAM+G_SUBS, i.e. CAPEX is reduced by 30% in 2030, 20% in 2035 and 10% in 2040. Subsidies are focussed on DRI plants as these are most competitive in the long-term (see Figure 3-17) and – in case of H2-DRI and NG-DRI+CCS – have lower residual CO2 emissions, compared to BF/BOF+CCS. This policy measure has some minor effects on the modelled scenario. Figure 3-21 (right) shows that 4 Mt of blast furnace capacity are substituted by DRI kilns. However, mostly one low-carbon route (BF/BOF+CCS) is substituted by another one (DRI-route), while the effect on upscaling of low-carbon steel in total is very small. In the year 2030, (only) 1 Mt of primary steel production in the unabated BF/BOF route is substituted by DRI-NG+CCS.

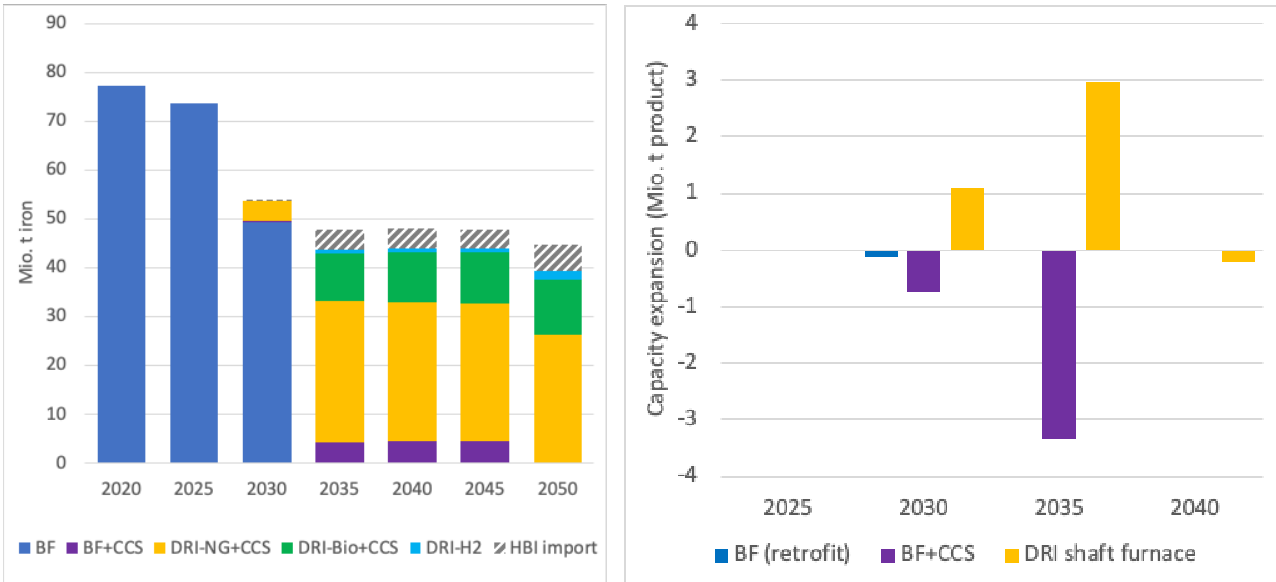

Figure 3-21: Iron provision in the GSUBS_Capex-low scenario variant (left) and difference in new capacity built between GSUBS_basis and GSUBS_Capex-low (right)

A more focussed policy measure thus could try to accelerate the shift towards low-carbon steel production by providing high CAPEX subsidy for DRI plants (90%) in the time period around 2030. Figure 3-22 shows that this measure indeed has a stronger effect on the substitution of blast furnaces by DRI kilns. Over the simulation period, around 9 Mt BF/BOF capacity (including such with CCS) is replaced by DRI kilns, compared to GSUBS_basis (see Figure 3-22, right). In the year 2030, 6 Mt iron production in blast furnaces is substituted by the DRI-route

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(see Figure 3-22, left). However, a side-effect of this policy measure is that investments in DRI plants are massively advanced from 2035 to 2030; i.e. subsidies are provided for DRI plants that would have been built anyway, but later.

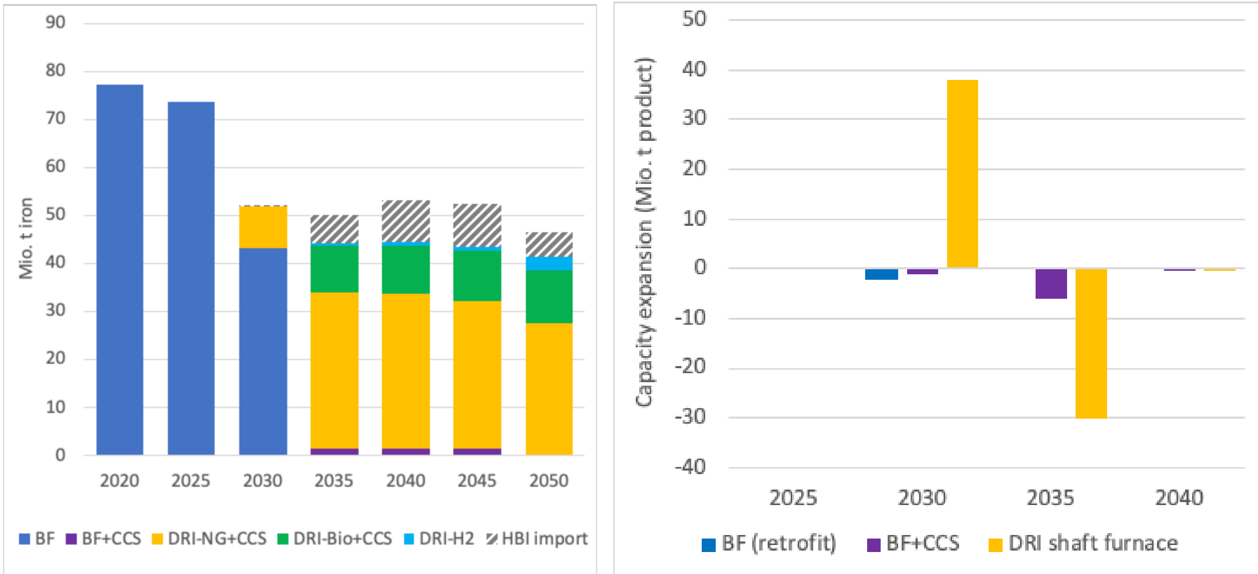

Figure 3-22: Iron provision in the GSUBS_Capex-high scenario variant (left) and difference in new capacity built between GSUBS_base and GSUBS_Capex-high (right)

Table 3-11 compares the effectiveness and the costs of CO_2 avoidance for both Capex-based policy measures. The provision of high, targeted subsidies in the time period around 2030 (GSUBS_Capex-high) proves more effective and reduces the cumulative CO_2 emissions up to 2050 in the scenario by 116 Mt CO_2, compared to GSUBS_basis. The lower level and more timely stretched provision of subsides (GSUBS_Capex-low) achieves only one third (40 Mt CO_2). But GSUBS_Capex-high also creates a lot of free-riding with plants being subsidised that would have been built anyway (but later). Presumably that is the reason why the costs of CO_2 avoidance in GSUBS_Capex-high are 75% higher, compared to GSUBS_Capex-low.

Table 3-11: Performance indicators of scenario variants with CAPEX subsidies, compared to GSUBS_basis

	CO_2 avoided (cumul.); Mio. t CO_2	CO2 storage capacity saved; Mio. t CO_2	Subsidies paid; Billion €	Cost of CO_2 avoidance; €/ t CO_2
GSUBS_Capex-low	40	45	3.3	83
GSUBS_Capex-high	116	72	16.8	145

3.5.3.3 Hydrogen subsidies

The GSUBS_base scenario heavily relies on the use of CCS. The CO_2 emissions associated with steel production decrease rapidly in the scenario (see Figure 3-19) and in the long-term, the steel industry even generates net-negative CO_2 emissions. Nevertheless, the reliance on the capture and storage of fossil CO_2 for a production process for which renewables-based alternatives exist (bio-/hydrogen-based DRI and electrolysis) may nevertheless be questioned for reasons of unaccounted upstream emissions associated with the use of coal and natural gas (methane leakage) and the use of CO_2 storage and injection capacities which may be needed for carbon dioxide removal from the atmosphere (through BECCS) or for so-called unavoidable[17] emissions from processes for which there are currently no renewable alternatives. For example, large parts of the German organised civil society demand that CCS be only allowed for such unavoidable emissions (Kreul et al. 2024).

Against this background, a scenario variant GSUBS_H2 is explored. In this variant 134 PJ/year of hydrogen are provided to the EU27+UK steel industry at low costs in the time periods 2030 to 2040 (2030: 15€/GJ, 2035: 12€/GJ, 2040: 11€/GJ). The subsidised amount of hydrogen is (in principle) sufficient for producing 20 Mt of H2-DRI per year. Some part of this hydrogen (11 PJ max) is used in the UK, which is excluded from the analysis. The remaining amount of hydrogen is used by the EU27 steel industry, but almost entirely for hot-rolling.[18] This was not anticipated during scenario design but is understandable from a comparison of cost savings achieved when using 1 GJ of subsidised hydrogen for H2-DRI, compared to using it for hot-rolling: cost savings from using hydrogen for hot-rolling include avoided costs for natural gas (5 to 18 €/GJ) and associated CO certificate costs (13 to 18 €/GJ$_{natural\ gas}$ in the period 2035 to 2050). Cost savings when using hydrogen for H2-DRI can be defined as the cost difference to the otherwise cheapest route (dependent on country, see Figure 3-18, right) normalised to 1 GJ hydrogen used – which is 7 €/GJ$_{hydrogen}$, at maximum.

A more targeted variant of hydrogen subsidies restricts these to the production of DRI (scenario GSUBS_H2-DRI). In this variant, again 134 PJ/year of hydrogen are provided to the EU27+UK steel industry at low costs in the time periods 2030 to 2040, but these may only be used in DRI shaft kilns. According to the model, about 45% of the subsidised hydrogen is used in the UK and excluded from the further analysis.[19] Figure 3-23 shows the effects of this policy measure on the EU27 iron provision: the share of H2-DRI increases compared to GSUBS_base (see Figure 3-17, right), to 19% in the years 2035 and 2040 (when subsidies are provided). The share of H2-DRI then drops to some extent from 2045 onwards to levels comparable with the other scenario variants explored.

Table 3-12 compares key indicators for the scenario variants with hydrogen subsidies. The cumulative societal costs for the hydrogen subsidies in the EU27 and in time period up to 2050 amount to around 15 billion € in the GSUBS_H2 scenario and to 5.8. billion € in the GSUBS_H2-DRI scenario.

[17] The definition of "unavoidable" is not completely sharp but typically refers to emissions from cement and lime production and to emissions from waste incineration plants.

[18] In ITOM it is not possible to trace subsidised hydrogen to single processes, but only to sites. But in comparison to GSUBS_basis, the amount of hydrogen used for hot-rolling increases by a maximum of 106 PJ in 5-year time period around 2035, while the amount of hydrogen used for H2-DRI increases by only 3.4 PJ in a 5-year time-period.

[19] The large share of subsidised hydrogen going to the UK was not anticipated and this result is assumed to be sensitive to parameter variations.

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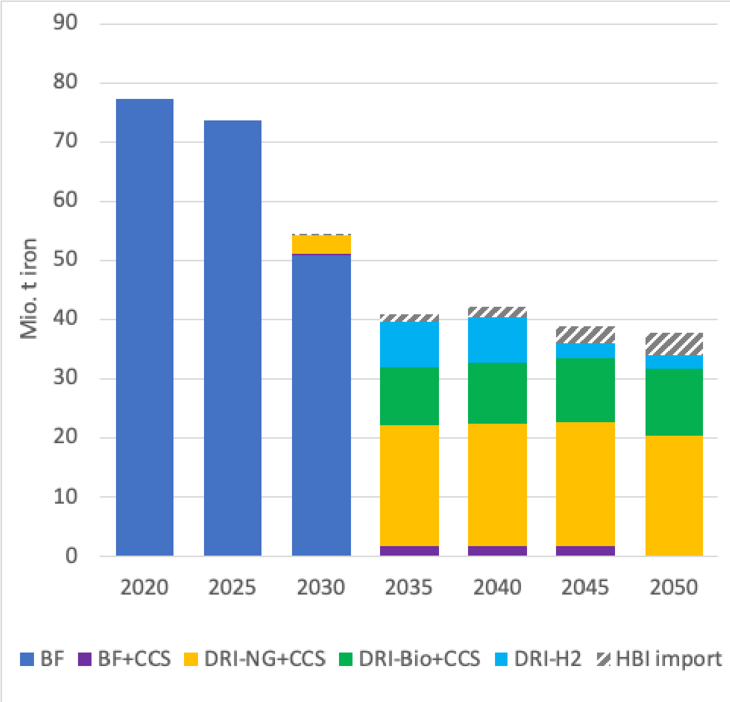

Figure 3-23: EU 27 iron production by type with hydrogen subsidies targeted to DRI production.

Table 3-12: Performance indicators of scenario variants with hydrogen subsidies, compared to GSUBS_basis

	(Direct) CO_2 emissions avoided (cumulative); Mio. t CO_2	Upstream emissions avoided (cumulative); Mio t CO_{2eq}	CO_2 storage capacity saved; Mio t CO_2	Subsidies paid in EU 27; Billion €	CO_2 avoidance costs; €/t CO_2 (direct CO_2 only)
GSUBS_H2	67	2.6	34	15	226
GSUBS_H2-DRI	47	5.7	159	5.8	125

3.5.4 Discussion and conclusions

The scenario features a swift switch to low-carbon steel making even in the base case, without dedicated policy instruments. The main driver is the effective CO_2 price, which combines effects from increases in the EU ETS-1 price and the phase-out of free allowances. It strongly increases in the time period until 2035 and makes unabated iron and steel production uncompetitive. In such a context, the considered additional policy instruments to accelerate the uptake of low-carbon steel production technologies have only small impact. The additional reduction of the cumulative emissions of the EU27 steel industry in the period from 2020 to 2050 vary from 2% to 6% between policy instruments, compared to base case.[20] The most effective policy instrument is the provision of high CAPEX[21] subsidies in the 2030 time period, but this instrument involves comparably high CO_2 avoidance

[20] 40 / 116 Mt CO_2 avoided, compared to 1857 Mt cumulative emissions in GSubs_base.

[21] With regards to CAPEX subsidies, it should be noted that ITOM assumes the same CAPEX in all modelled years. The costs

costs of 145€/t CO_2. According to the modelling results, the provision of lower CAPEX subsidies over a more extensive time period is the most efficient instruments, in terms of CO_2 avoidance costs (83 €/t CO_2). At the same time, it is the least effective one, leading to only 40 Mt CO_2 avoided. Untargeted hydrogen subsidies in the period 2030 to 2040 have the highest CO_2 avoidance cost and do not stand out otherwise as being most effective in terms of emissions avoidance or saving CO_2 storage capacities. Subsidies for hydrogen use targeted to the DRI route feature moderate CO_2 avoidance costs (125 €/t CO_2) and stand out through the strongest effect on avoiding fossil CO_2 storage and thus saving storage capacities for negative and otherwise unavoidable emissions.

All scenarios feature a similar level and similar dynamics of relocation of iron and crude steel production between EU regions as in the base case (see Figure 3-20; not shown for other scenarios). Overall iron production volumes are shrinking due to higher shares of secondary steel and the introduction of molten-oxide electrolysis as a steel production technology that does not require pig iron production as an upstream production step. In addition, established iron production regions – in particular Germany but also France, BeNeLux and EU_EAST – lose parts of their iron production to EU_North, EU_Southwest and EU_Southeast which feature better cost conditions for DRI-based iron reduction, in particular lower electricity, natural gas and hydrogen costs. As a results, some regions such as Germany lose most of their iron production during the simulated time period. The picture is similar but less pronounced for crude steel production because the model includes incentives[22] for production close to target markets and thus losses of the integrated steel production route are partly compensated by higher volumes of secondary steel, HBI imports and electrolysis-based steel production. The modelled policy instruments do not differentiate between member states or regions. It would require further research to explore the effects on intra-EU relocation that policy measures with a focus on particular member states could have.

and subsidies hence refer to "nth-of-a-kind" technologies. In reality, CAPEX subsidies are typically provided to reduce high costs of "first-of-a-kind" technologies. This case is not covered by the modelling exercise.

[22] The larger share of demand is located within EU regions. In combination with transport costs which are set higher for more specialised products, compared to uniform intermediate products (HBI), this creates advantages for steel production that is close to target markets. This reflects longer lead times for production distant from target markets.

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4 Impact of financing costs on the future international trade of renewable hydrogen

4.1 Introduction

Renewable hydrogen is emerging as a key energy carrier with the potential to decarbonise hard-to-abate sectors. The processes in heavy industry include energy use and heavy-duty transportation that are challenging to electrify, making the transition to renewable power difficult (Staffell et al. 2019). Additionally, many industrial processes rely on fossil fuels for chemical feedstocks. Global demand for hydrogen is expected to grow significantly over the next three decades to meet climate goals, especially to decarbonise the hard-to-abate sector.
Currently, about 95% of global hydrogen is produced from fossil fuels, releasing significant CO_2 emissions and contributing to global warming (IEA 2023). Low-carbon production methods have emerged, with renewable-powered water electrolysis and fossil fuel-based hydrogen production with carbon capture and storage (blue hydrogen) being the most notable. Blue hydrogen is seen as a near term solution towards a low carbon hydrogen economy, with projections suggesting more than 85% of hydrogen supply could come from renewable sources by 2050. To meet climate targets, a 6000-fold increase in electrolysis capacity is needed by 2050 (Shirizadeh et al. 2023). While advancements in electrolysis technology may lower production costs, the primary factors influencing the levelised cost of hydrogen (LCOH) are electricity costs and electrolyser efficiency. Regions with abundant, inexpensive renewable energy can produce hydrogen competitively compared to blue hydrogen (IEA 2021a), leading to potential cost competition and making hydrogen a globally traded commodity in the future. Improvements in energy security, falling renewable energy costs, and advancements in electrolysis technologies have made green hydrogen an appealing low-carbon alternative for the future.

Renewable energy resources for hydrogen production are far more geographically diverse than fossil fuels, which are limited to specific regions. This diversity allows hydrogen to fundamentally transform the global energy trade and establish a powerful new class of energy exporters. As a result, countries with high renewable energy potential can benefit economically from the clean energy transition. It is cost effective to transport hydrogen in high volumes over very long distances via ship compared to building high voltage transmission lines. Additionally, it can also be stored for the future, either as fuel or as a potential energy source to generate electricity, providing a long-term, large-scale energy storage solution that improves the resiliency of power grids.
International hydrogen trade is set to significantly influence future markets by connecting regions rich in renewable energy with those that have high demand for hydrogen. Countries that can produce low-cost renewable electricity are likely to become major exporters. The International Renewable Energy Agency (IRENA) forecasts that by 2050 (IRENA 2022a), about 25% of green hydrogen production will be traded internationally, while the International Energy Agency (IEA) estimates that hydrogen trade will account for 20% of global demand (IEA 2021b). Many countries have begun negotiating bilateral trade agreements for low-cost renewable hydrogen, with around 90 agreements signed so far (IRENA 2022b). Active importers include Germany, Japan, and the Netherlands, while various nations are positioning themselves as exporters through national hydrogen strategies. By 2030, significant import volumes are anticipated in Europe and Asia, especially in Germany, the Netherlands, Japan, and South Korea due to planned hydrogen import infrastructure and supply partnerships (IEA 2022). Planned hydrogen export projects are diverse, with Latin America leading in project volume, followed by Australia, Europe, Africa, and the Middle East. This trend highlights a growing momentum toward the development of international hydrogen markets. However, competitive production costs play a critical role in shaping international trade flows between nations. High project financing costs, which are a significant factor in renewable energy projects, can restrict the economic viability of these projects and hinder developing countries from fully realising their renewable energy potential.

Low-carbon technologies necessitate substantial upfront investments, a stark contrast to fossil fuel technologies, which primarily incur costs related to fuel throughout their lifecycle. For assessing the investment choices among different alternatives, the cost of capital is used in calculating investment appraisal metrics like levelised cost of

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hydrogen (LCOH) or levelised cost of electricity (LCOE). The LCOH can increase by 2.3 times as the weighted average cost of capital (WACC) rises from 0% to 12%. Given the capital-intensive nature of low-carbon technologies, they are highly sensitive to changes in cost of capital rates, making it imperative to consider this factor when assessing their viability. In advanced economies, capital costs like land and equipment make up the majority of clean energy project expenses, whereas in developing economies, financing costs are more significant. The financing disparity arises from exaggerated perceptions of macroeconomic risk in less integrated markets, resulting in interest rates 2-3 times higher in emerging economies compared to advanced ones (Goyal et al., 2019; IMF, 2025). Despite decreasing clean energy technology costs, developing economies face challenges in securing financing due to political, regulatory, and macroeconomic risks. High financing costs that developing countries face limit their ability to produce hydrogen competitively. Therefore, it is essential to understand how financing costs affect hydrogen production costs and shape the future hydrogen trade market.

Numerous studies have examined various aspects of renewable hydrogen supply chains, including different green hydrogen production processes from renewable resources, potential demand, and the infrastructure necessary for regional supply chains (Dawood et al., 2020; Tarvydas, 2022; Riera, 2023). A particular emphasis has been placed on hydrogen's role in transitioning to a low-carbon energy system and the implications of international hydrogen trade, encompassing technical readiness and geopolitical factors. Fakhreddine et al. conducted a systematic review to understand the advancements and challenges in modelling global hydrogen trade pathways (Fakhreddine et al., 2025). Other research has explored the economic aspects of hydrogen trade, such as the costs associated with producing and transporting hydrogen globally. These studies indicate that regions with abundant solar energy, like Africa and the Middle East, possess significant production potential. Transportation costs are crucial, as future hydrogen demand will require interregional transportation. Rezaei et al. examined the cost competitiveness of green hydrogen and its sensitivity to financial and technical factors (Rezaei et al., 2022). In this study they found that levelised cost of hydrogen is more sensitive to the financial environment compared to technical factors in Australia and economic instrument like green subsidy can help to offset the high financing cost related to green hydrogen projects. However, this study did not address how these financial factors influence global hydrogen trade dynamics and the trade relationships between different regions.
To address this research gap, we assess the impact of financing costs on the future international trade of renewable hydrogen in this study. While current research primarily evaluates hydrogen trade potential based on uniform financing costs, this study examines how cross-country and technology-specific variations in the cost of capital could influence trade competitiveness. By incorporating these variations into a quantitative framework, this research offers new insights into how differentiated financing conditions can shape the future outlook for international hydrogen trade.

4.2 Methods

We developed a global framework to simulate the development of renewable hydrogen markets and international trade by 2050. The framework integrates country-specific renewable hydrogen supply curves, regional demand curves, global supply chains, and a market equilibrium model designed to match supply with demand under the 1.5°C climate scenario. The model is formulated as a mixed-integer linear program (MILP) with the objective of maximising social welfare. Details about the framework is mentioned in Alanazi et al (2025). The renewable hydrogen supply curves are derived from each country's solar, onshore wind, and offshore wind resource potential. We calculate the levelised cost of electricity (LCOE) and levelised cost of hydrogen (LCOH) for each technology and country. A key techno-economic parameter used in this analysis is WACC, which reflects the cost of financing from debt and from equity investors (weighted by share of financing). WACC values vary drastically across countries, with macroeconomic and political factors being a principal driver. Although country-specific WACC data has traditionally been limited due to the confidential nature of empirical data on financing terms, recent IRENA analysis has provided expert-survey data on WACC values for solar and wind energy projects globally (IRENA, 2023, Hatton et al. (2024)). We utilise this data for our analysis and perform sensitivity analysis for electrolyser technologies, incorporating assumptions regarding long-term learning curves and investment risks for individual countries.

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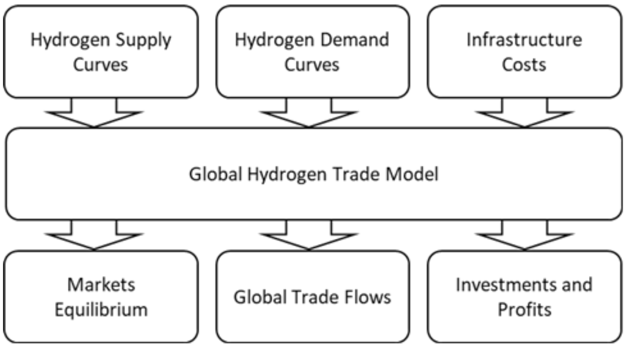

Figure 4-1: Hydrogen trade modelling framework

Global hydrogen trade model: The global hydrogen trade model that simulates market equilibrium in demand regions. The model matches supply and demand taking into account viable supply chains options and transport cost parameters. This study examines hydrogen transport through pipelines and ships. For pipelines, a greenfield investment approach is used for distances up to 5000 km, with costs covering initial investments and operation, including compression and storage. For shipping, three carriers are analysed: liquefied hydrogen, ammonia, and liquid organic hydrogen carriers (LOHC). Gaseous hydrogen is converted to a carrier in the export country, shipped to import countries, and then reconverted back to gas at import terminals. Unit transport costs for each carrier are calculated throughout the value chain, including conversion, shipping, and reconversion. In this approach, hydrogen trade model is formulated as a mixed-integer linear programming (MILP) that aims to maximise the sum of producers and consumers surplus, which is effectively the area circumscribed by the supply and demand curves.

The objective function maximises the total surplus which is defined as the sum of revenues from hydrogen sales minus the sum of production and transportation costs.

$$\text{Max total surplus} \sum_{imp \in IMP} \text{Revenue}_{imp} - \sum_{exp \in EXP} \text{ProdCost}_{exp} - \sum_{\substack{exp \in EXP \\ imp \in IMP}} \text{TranCost}_{exp,\, imp}$$

The trade model formulation assumes a benevolent social planner that seeks optimal hydrogen resource allocation under perfect competition assumption. The model considers producers supply curves and consumers demand curves as discretised production and consumption levels. Supply and demand nodes are mapped through possible supply chain options. Taking into account potential production and consumption levels of producers and consumers, the model simulates the optimal market equilibrium with supply and demand curves calculated endogenously.

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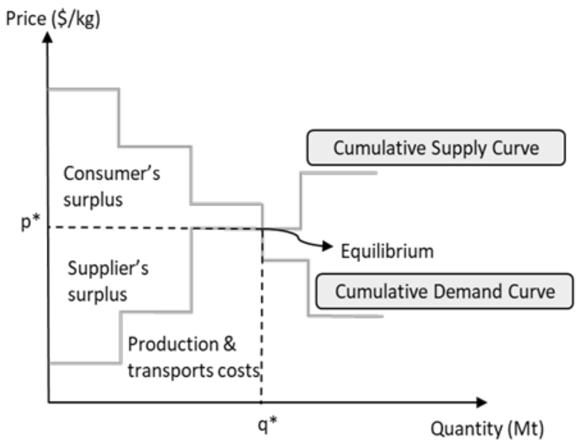

Figure 4-2: Supply – demand curve endogenously generated by the trade model

Scenarios: We have developed six scenarios to assess the impact of financing costs on the future trade outlook of renewable hydrogen, providing valuable insights to inform policy and investment decisions (see below).

- *Uniform WACC without import diversification*In this scenario, a uniform weighted average cost of capital (WACC) of 8% is assumed for all nations and technologies, which include solar, onshore wind, offshore wind, and electrolyzers, without any differentiation. Additionally, in this scenario, nations are not exploring the option of diversifying their trading partners to mitigate supply-related risks.
- *Convergence WACC without import diversification:* In this scenario, we consider that the weighted average cost of capital (WACC) values differ by technology—specifically solar, onshore wind, offshore wind, and electrolyzers. However, the WACC values in developing countries will converge to those in developed countries, where they are lower. Like above scenario, nations are overlooking the critical need to diversify their trading partners
- *Differentiated WACC without import diversification:* In this scenario, we have considered that the weighted average cost of capital (WACC) values varies by country and technology, including solar, onshore wind, offshore wind, and electrolysers without considering the strategy to diversify their trading partners
- *Uniform WACC with import diversification:* The WACC assumptions are the same as in the first scenario but in this scenario, nations are exploring strategies to diversify their trading partners to reduce their vulnerabilities to supply-side shocks and to build resilience within the system.
- *Convergence WACC with import diversification:* The WACC assumptions remain the same in the second scenario, but nations are seeking to diversify their trading partners to reduce vulnerabilities to supply-side shocks and enhance system resilience.
- *Differentiated WACC with import diversification:* The WACC assumptions remain the same in the third scenario, but nations are considering import diversification to enhance supply side resilience.

By analysing these scenarios, we quantify the impact of country- and technology-specific financing costs on future hydrogen trade including potential exporting and importing countries, hydrogen prices, demand, and required investments.

4.3 Results

4.3.1 Global Hydrogen Trade flow by 2050

The results show that global hydrogen trade is expected to account for about a quarter of global demand by 2050. This proportion remains largely stable despite variations in financing costs across different scenarios.

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However, significant differences arise in hydrogen trade flows, as country-specific financing costs shape the global outlook for major exporting and importing nations (see Figure 4-3). In the Uniform WACC without import diversification scenario, pipelines emerge as the primary mode for hydrogen trade, comprising 62% of the total. In contrast, this share drops to 50% in a differentiated WACC scenario and to 47% in a convergence scenario. Major producing countries, including China, the USA, and India, primarily rely on pipelines for hydrogen transportation. In the uniform WACC scenario with import diversification, the share of transportation via liquid hydrogen increases from 17% to 20%. To enhance their energy security, Japan and South Korea reduce their reliance on Chile for green hydrogen imports in the Uniform WACC with import diversification scenario. Additionally, both countries also import green hydrogen from Argentina and Morocco to diversify their trading partners in this scenario.

Our analysis reveals that there is a major shift in the key players in the convergence WACC scenario compared to differentiated WACC and uniform WACC scenarios The Latin American countries, particularly Argentina, Chile, and Peru, dominates international trade flows in the convergence WACC scenario. These countries primarily export hydrogen using ammonia as a carrier to major markets such as Japan, South Korea, and other developing Asian nations. Following Latin America, North African countries like Morocco, Egypt, and Algeria also play a significant role, exporting hydrogen via pipelines and liquefied hydrogen to Europe and the Middle East.

The South American nations, particularly Argentina and Chile, are positioned as leading hydrogen exporters in the convergence scenarios, as their WACC is lower compared to the other scenarios. This advantage is attributed to their abundant solar energy resources and available land. Ammonia is primarily preferred for longer-distance routes, linking South American exporters—Chile and Argentina—to Asian markets resulting in the higher share of ammonia in convergence scenario compared to the uniform and differentiated WACC scenarios.

In the "Differentiated WACC" scenario, countries with lower financing costs become key hydrogen exporters. For instance, Australia takes on a prominent role in supplying Japan and South Korea with liquefied hydrogen, replacing imports from Latin America, particularly from Argentina and Peru, where higher financing costs limit competitiveness. In Western Europe, access to low-cost finance allows the region to reduce its reliance on international markets, with countries such as the United Kingdom, France, and Denmark emerging as significant hydrogen producers within the region.

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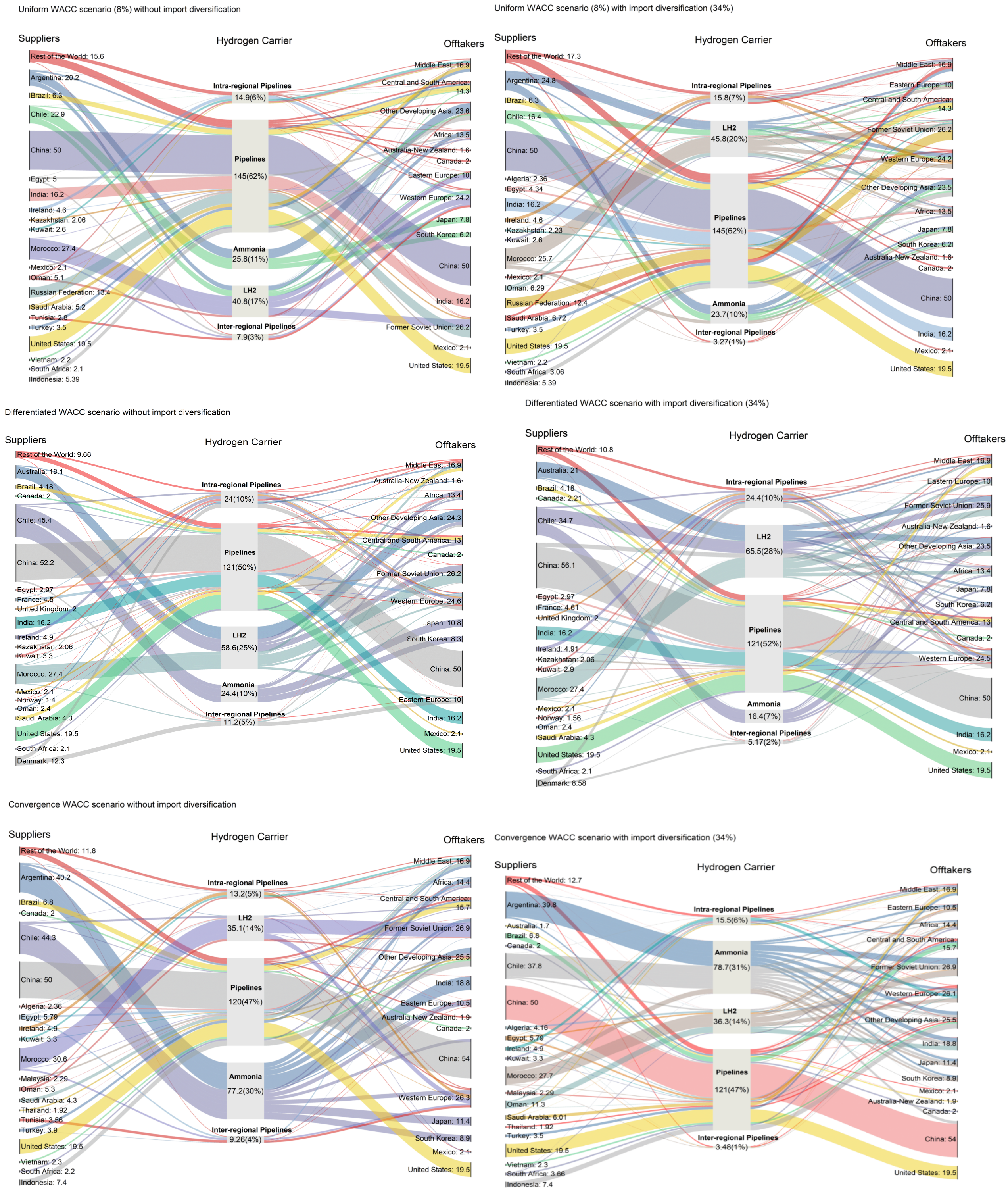

Figure 4-3: Hydrogen regional trade flow by 2050 via different transportation modes in six scenarios

The overall trade volume also increases by 9% in convergence WACC scenario compared to uniform WACC scenario without diversification due to reduction in the WACC values (see Figure 4-4).

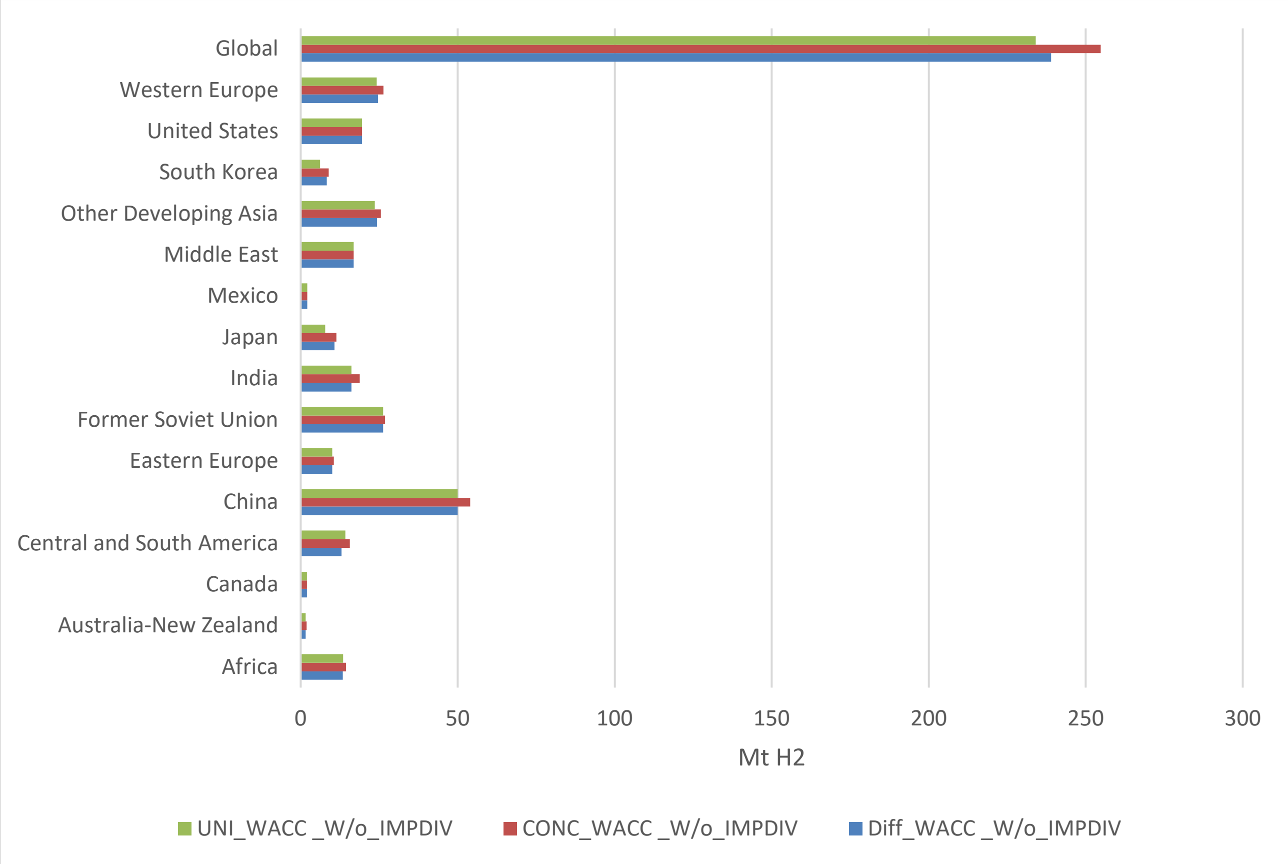

Figure 4-4: Regional equilibrium demand data in different scenarios

4.3.2 Hydrogen Investment

The cumulative investment required in the differentiated scenario is higher than in the other two scenarios (Figure 4-5). The total investment needed for hydrogen in the differentiated WACC scenario is $8 trillion, compared to $6.8 trillion in the uniform scenario and $7.3 trillion in the convergence scenario. Investment in shipping increases significantly in the differentiated WACC scenario due to a shift in funding from Latin America to Australia and Western Europe. Hydrogen pipelines require considerably less investment than shipping, which is why the investment is lower in scenarios where the pipeline is a more preferred method for transporting hydrogen. The investment in convergence scenario is higher than uniform due to higher trade flow and high share of ammonia as preferred model of H_2 transport compared to uniform WACC scenario resulting in higher investment in conversion and reconversion and shipping.

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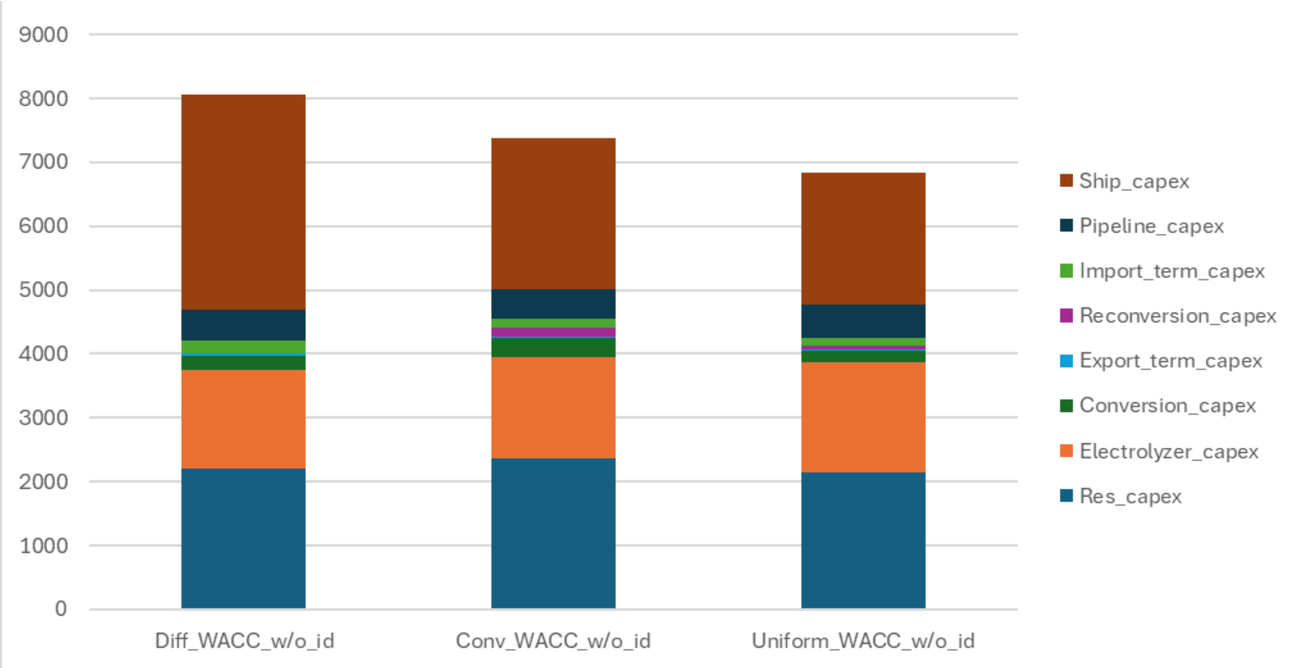

Figure 4-5: Cumulative investment required in different scenarios (Billion $)

4.4 Conclusion

International trade could play a key role in meeting future renewable hydrogen demand within a decarbonised global energy system. Many countries have announced ambitious plans to become major hydrogen exporters in the coming years. However, given the capital-intensive nature of renewable hydrogen projects, financing costs are a key determinant of the cost competitiveness of individual countries. This research sheds light on the role of financing costs in shaping the global outlook for renewable hydrogen trade. We provide quantitative insights into how financing costs influence potential exporting and importing regions, as well as key market indicators such as demand and pricing. Our results indicate that developing countries, particularly in Latin America and North Africa, possess significant potential to become major hydrogen exporters due to their abundant, high-quality renewable resources. However, high financing costs hinder their competitiveness, allowing countries with lower financing costs—such as China, Australia, and those in Europe (notably the United Kingdom, France, and Denmark)—to emerge as leading hydrogen producers and exporters. Ultimately, this research suggests that developing countries could greatly benefit from policies aimed at de-risking energy investments and lowering financing costs, fostering a more cost-effective supply of renewable hydrogen within the global energy system.

ANNEX

Stakeholder questions on Study 4

- *2.1 Member State Analysis: How could spatial relocation of the steel industry occur within the EU based on the use of different policy instruments/subsidies in support of green steel?*
- *2.2 Intermediate Product Imports: What are the potential imports of intermediate products and their impact on steel transformation within the EU? - E.g., quantities of green hydrogen or direct reduced iron.*
- *2.3 How much steel production should we have in Europe for security vs. competitiveness vs. cost reasons? - How much steel production relocation makes sense from an economic efficiency standpoint (both within and outside the EU)?*
- *2.4 What are the effects of explicit support for low-carbon steel compared to even subsidies for European steel?*
- *2.5 How does the import of cheaper produced intermediaries affect the European green steel value chain?*
- *2.6 How does steel sector decarbonisation differ by EU countries, depending on the factors above?*
- *2.7 What are the potential benefits of more circular solutions in green steel production?*
- 2.8 What are the energy demands of a decarbonised industrial sector in Europe?
- 2.9 What are the best instruments for driving innovation in the steel sector in Europe?
- *Make explicit what ramping limits on certain technologies are in place, such as how fast hydrogen can be scaled up based on labour and capital availability*
- *3.3 How realistic are the Net Zero Industry Act targets for European manufacturing?*

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