Climate policy, steel decarbonisation, and trade fragmentation: a coupled energy-macroeconomic analysis for Europe

Alice Di Bella[a,b,c,*], Paola Rocchi[b,c]

[a] *Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milan, Italy*
[b] *CMCC Foundation - Euro-Mediterranean Center on Climate Change, Milan, Italy*
[c] *RFF-CMCC European Institute on Economics and the Environment, Italy*

Abstract

This paper examines the interaction between European Union climate ambition and recent trade policies affecting energy-intensive industries, with a particular focus on steel. It assesses the extent to which EU climate policy outcomes are influenced by current trade restrictions. By coupling a high-resolution European energy system model with a global computable general equilibrium framework, the analysis captures both technological feasibility and economy-wide adjustment mechanisms along the transition pathway. Two main results emerge. First, the paper quantifies economy-wide feedbacks associated with steel decarbonisation under EU climate policy. EU steel production declines by around 10% on average by 2040, with pronounced regional heterogeneity, while aggregate macroeconomic impacts remain limited, with EU-wide GDP losses below 0.5%. Second, trade fragmentation plays a secondary role relative to domestic climate policy. EU decarbonisation targets

*corresponding author
Email address: alice.dibella@polimi.it (Alice Di Bella)

remain technically achievable, while USA steel tariffs have only marginal additional effects on production, trade, and GDP, reflecting the limited exposure of EU steel-intensive sectors to the USA market. Overall, internal climate policy design is the primary driver of economic and industrial outcomes during the transition, reflecting the difference in scale between a comprehensive structural transformation package and relatively limited protectionist measures. Even in steel trade, competitiveness dynamics are shaped mainly by climate policy stringency. Although macroeconomic effects are modest, impacts are more visible in exposed sectors and vary across EU macroregions. Climate ambition should therefore be accompanied by targeted industrial and regional support. Where trade measures are unilateral and limited, assessing effective domestic exposure should precede any retaliatory action.
Keywords: Climate policy, trade balance, energy system model, general equilibrium model, model coupling, Fit-for-55

1. Introduction

The European Union (EU) has established itself as a forerunner in the fight against climate change with the implementation in 2020 of the European Green Deal (1), aiming to transform the EU economy for sustainability and prosperity. The path from European Green Deal's objectives to practical realization has been marked by two significant developments. The first is the European Climate Law (2), which legally binds EU Member States to achieve climate neutrality by 2050. The second is the Fit-For-55 (FF55) package (3), that combines revisions to existing legislation with the introduction of new policy instruments, with the aim to reduce EU's greenhouse gas emissions by 55% by 2030. Key policies within the package include amendments to directives governing the EU Emissions Trading System (EU ETS), targets for renewable energy deployment, energy efficiency standards, and CO_2 emissions regulations for vehicles. In addition to these changes, the FF55 package introduces novel mechanisms such as the Carbon Border Adjustment Mechanism (CBAM) and the Social Climate Fund.

Over the past decade, global economic governance has shown a tendency to move away from the liberalisation paradigm. Governments are adopting interventionist measures, such as subsidies and selective tariffs, to strengthen domestic competitiveness and strategic autonomy, a trend partially driven by rising geopolitical instability. In the United States, policies like the Inflation Reduction Act (4), together with renewed tariffs and trade renegotiations, aim to re-shore clean-tech production and reduce import dependence. The European Union has also implemented trade and industrial instruments such as the CBAM, targeted trade defences, and subsidy schemes to sustain low-carbon manufacturing. Emerging economies, including China and India, have likewise expanded domestic production mandates in key low-carbon sectors (5; 6). These developments redefine the context for Europe's decarbonisation efforts, reshaping the global conditions under which energy and industrial transitions unfold.

Given this framework, the scope of the paper is to situate European climate policies within an evolving landscape of economic and geopolitical uncertainty, and to assess how they interact. Through this lens, we evaluate their combined implications for both the energy system and the wider economy. In particular, we focus on the energy system and steel industry.

Decarbonising energy-intensive industries hinges on the availability and cost of low-carbon electricity, hydrogen, and other clean energy carriers. Focusing on the energy system thus allows us to capture how European climate policies, by altering the energy mix and carbon prices, reshape production costs, while trade shocks feed back into energy demand. We dedicate particular attention to the steel industry, a hard-to-abate sector that sits at the intersection of decarbonisation challenges and trade policy tensions. Steel production's energy-intensive nature and its strategic economic importance make it a critical lens through which to examine how trade policies affect industrial decarbonisation pathways. We use the 2025 USA tariffs on European steel as a case study to investigate to what extent trade barriers in this sector can affect production systems and influence Europe's industrial decarbonisation strategy.

Classical analyses of trade-environment linkages emphasise the roles of scale, composition, and technique effects in shaping environmental outcomes (7; 8). More recent work extends this perspective by showing that trade regimes and policy architectures themselves can embed environmental distortions, for example by shifting emissions across borders, altering relative competitiveness, or weakening incentives for low-carbon investment under asymmetric regulation (9; 10). Empirical evidence on pollution-haven and carbon-leakage dynamics remains mixed (11; 12; 13), yet it underscores the sensitivity of energy-intensive sectors to asymmetric regulation and trade costs. A growing literature has assessed policy instruments that seek to align trade with climate objectives, most notably carbon border adjustment mechanisms and climate clubs (14; 15; 16; 17). At the same time, heterogeneousfirm and innovation-focused analyses reveal that protectionist measures can dampen productivity and slow clean-technology diffusion (18), while open, rule-based regimes tend to favour innovation spillovers (19). Recent modelling work further explores how trade measures influence decarbonisation pathways in transport and industry (20; 21). Overall, these studies suggest that the climate impact of protectionism is context-dependent, varying with sectoral structure, technology availability, and policy design, making integrated assessments that capture energy-industry-trade interactions increasingly necessary.

Previous research has explored potential decarbonization pathways for the European economy, with a substantial body of literature utilizing Energy System Models (ESMs) to evaluate climate policy targets (22; 23; 24). Mikropoulos et al. (25) conduct a comprehensive multi-model comparison of integrated assessment and energy system models to assess EU climate policy pathways to 2050, finding broad consensus on reduced energy demand driven by electrification, increased renewables, and divergent technology choices that underscore the value of model diversity for robust policy insights under climate-neutral scenarios. Fragkos et al. (26) evaluated on the previous EU's target of reducing GHG emissions by 40% through simulations using the PRIMES energy-system model. Beyond the energy modelling perspective, economics research has addressed the economic, social and distributional impacts of energy policies (27; 28; 29; 30). One of the most relevant studies is the European Commission's Impact Assessment, which shows that achieving the EU's Fit-for-55 climate targets would strengthen energy security, reduce dependence on imported fossil fuels, and create jobs by redirecting investments from fossil fuels to clean energy technologies (31). Another crucial analysis in the economic assessment literature is Weitzel et al. (32), which employ the JRC-GEM-E3 Computable General Equilibrium (CGE) model, with inputs from energy system models, to assess policy scenarios combining regulations and carbon pricing, downscaling results to analyse household-level distributional and labour market impacts.

ESMs provide rigorous analytical frameworks to explore transition pathways, technological investments, and the feasibility of alternative energy strategies (33). CGE models offer a comprehensive tool to assess climate change mitigation policies by capturing multi-sectoral interactions, economic agents' behaviour, and international trade dynamics (34; 35). Energy models typically fail to account for the economic implications of changes in the energy system, such as variations in energy demand, with outcomes often influenced by externally defined assumptions about load levels (36; 37). In contrast, CGE models do not typically capture the detailed representation of supply technologies and technical constraints that ESMs offer as an advantage. Integrating different model types can expand the scope of analysis and enable a more nuanced examination of individual sectors (38).

Building on previous research advocating the integration of CGE and ESM frameworks, this study develops a coupled modelling approach linking an energy system model and a CGE to coherently assess the combined impacts of energy and trade policies. We develop an integrated framework that couples the ESM PyPSA-Eur (with industrial extensions) and the CGE model FIDELIO through a two-way soft link. This enables us to assess policy-driven decarbonisation pathways from technical feasibility to macroeconomic feedbacks, and analyse the implications of trade policies, specifically, steel tariffs, on Europe's energy and industrial transitions.

According to the literature, models can be linked through either hard or soft coupling. Hard coupling fully integrates models and typically involves joint solution of a simplified hybrid system, while soft coupling keeps models separate, using the output of one as input to the other. When information flows in both directions, the approach is referred to as two-way soft coupling; otherwise, it is one-way coupling.

Recent studies have advanced the integration of economic models with energy system models to better assess climate and energy policies. Gong et al. (39) develop a bidirectional soft-coupling between the integrated assessment model REMIND and the hourly power sector model DIETER to jointly solve for investments and operational details, improving representation of variable renewables and price signals in decarbonisation pathways for Germany. Fattahi et al. (40) illustrate a soft-linking approach between the CGE model ThreeME and the detailed energy system model IESA-Opt for the Netherlands, showing how linking models that represent macroeconomic feedbacks and energy technology detail can alter projections of energy demand and GDP under climate policy scenarios. Odenweller et al. (41) integrate REMIND with the European energy system model PyPSA-Eur through iterative, price-based soft coupling, enabling the combined evaluation of long-term investment decisions for Germany to assess technically feasible, economically viable pathways to climate neutrality and the role of demand-side flexibility. Collectively, these studies demonstrate how model coupling can provide detailed, policy-relevant insights by integrating macroeconomic and energy system dynamics, allowing evaluation of technology, market, and carbon pricing interventions under realistic system constraints.

The present study enriches the literature in different directions:

1. We assess how steel industries respond to economy-wide decarbonisation dynamics, addressing a gap highlighted by Gillingham et al. (42).
2. We evaluate the influence of recent trade policies on European climate policy outcomes, a timely and understudied topic.
3. We implement a soft coupling between a global CGE and a detailed European energy system model, applied at the EU level, a methodological advance, as previous soft-linking studies focused only on individual EU countries.

The paper is organized as follows. Section 2 describes the methodological framework, summarising the model coupling approach, expanded in Appendix A, and detailing the policy modelling strategy adopted in this study. Section 3 describes the main results. Finally, Section 4 discusses the outcomes and Section 5 draws some policy implications and conclusions.

2. Methods

To describe the methodology implemented, this Section provides first an overview of the two models employed (Subsection 2.1) and the methods used to couple them (Subsection 2.2). Second, we describe the policy context, looking at both the EU climate targets and then the USA tariffs on imported steel (Subsection 2.3). Finally, Subsection 2.4 details how these policies are implemented within the modelling framework, while Subsection 2.5 presents the scenario design used to address the research questions.

2.1. Models description

This analysis soft-couples a detailed energy system model, PyPSA-Eur with a macroeconomic CGE model, FIDELIO, to capture both economy-wide adjustments and technology-specific decarbonisation pathways.

PyPSA-Eur is an open-source techno-economic optimisation model of the European energy system that determines cost-minimising investment and dispatch decisions subject to technical, spatial and policy constraints. For a detailed description of the model, the reader is referred to Brown et al. (43). The model endogenously determines technology mix, energy prices, and investment requirements consistent with emissions constraints, minimizing system costs. PyPSA-Eur represents electricity generation, heat production, industry, transport, and transmission networks at high spatial and temporal resolution. For this study, it has been extended to include energy-intensive industrial processes, particularly steel production, following Di Bella et al. (44). In this paper industrial production is assumed to remain geographically fixed, relying on the existing stock of industrial plants. No relocation of production capacity across regions is permitted within the modelling framework.

The model is run in myopic mode for 2030, 2040, and 2050 at three-hourly resolution, with 31 country-level nodes covering the EU27 (excluding Cyprus and Malta) and the United Kingdom. Throughout this paper, the geographical aggregation for Europe derived from PyPSA-Eur is referred to as "EU26+UK". A brownfield setup is used, with endogenous expansion of renewables, storage, and selected technologies. Climate impacts on renewable generation are represented using climate-adjusted ERA5 and EURO-CORDEX projections under RCP 4.5. Electricity and methane networks are based on existing infrastructure with limited grid expansion allowed, while technology costs follow PyPSA Technology-Data assumptions (45). Biomass and CO_2 removal options are constrained in line with EU long-term strategies. Current power grid is included and the expansion of transmission lines is constrained to a maximum of 20% of existing installed capacity, weighted by individual line lengths.

FIDELIO is a recursive-dynamic, multi-region, multi-sector CGE model built on global multi-regional input-output data; a detailed documentation is provided in Rocchi et al. (46). It represents international trade through bilateral flows and Armington differentiation, and captures interactions between production, consumption, investment, government behaviour and foreign trade across countries and sectors. A key feature of FIDELIO is the explicit modelling of short-term rigidities and adjustment frictions, which allow transitional dynamics and policy-induced adjustment costs to be analysed rather than assuming instantaneous long-run equilibrium outcomes. The model solves sequentially over time, with each period depending on the previous one, making it suitable for analysing medium-term transition pathways under climate and trade policies.

The choice of these models reflects the need to jointly capture detailed energy system transformation within Europe and economy-wide trade and macroeconomic interactions at the global level. PyPSA-Eur offers a high-resolution, open-source representation of the European energy system, with detailed spatial and temporal resolution, a well-maintained and transparent database, and an extended formulation that endogenises steelmaking technologies through vintage plant modelling (44). Complementing this, FI-

DELIO provides a global, multi-regional macroeconomic framework with detailed sectoral and bilateral trade representations, allowing the analysis of demand responses, trade reallocation, and adjustment frictions across regions. Its structure is especially suited to evaluating trade-related policy shocks and their economy-wide spillovers, which are central to understanding the interaction between climate ambition and trade fragmentation. The integrated modelling framework combines PyPSA-Eur and FIDELIO through a two-way soft coupling. The full implementation is available in an open-source repository (https://github.com/cerealice/pypsa-fidelio), which provides the shell framework coordinating data exchange, iteration control, and convergence between the two models.

2.2. Models coupling

The two models are linked through a two-way, iterative soft-coupling framework designed to combine their respective strengths while preserving their internal consistency. Information is exchanged iteratively between them until convergence is achieved for a predefined set of variables. This approach allows each model to operate within its structure while capturing feedbacks between the energy system and the broader economy. The coupling follows a sequential logic, illustrated in Figure 1.

For each scenario, PyPSA-Eur is solved first to determine the energy-system and industrial transformation implied by the climate policy, including power-sector deployment, electricity and energy prices, steel production costs, investment levels, household electrification rates, and carbon price signals. This sequencing reflects the fact that several of these variables are endogenously determined within the energy system model and are not avail-

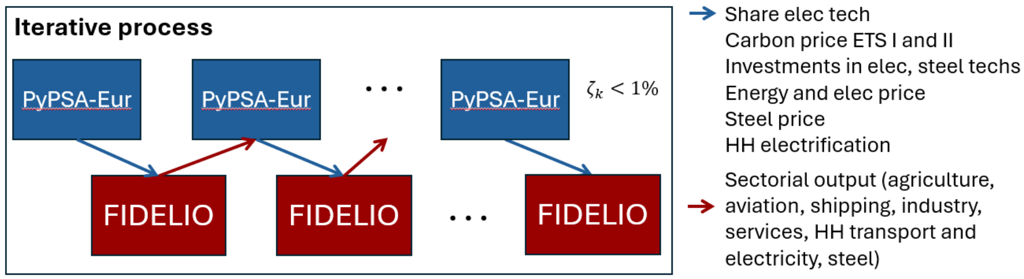

Figure 1: Iterative framework scheme. ζ_k denotes the convergence indicator; convergence is assumed when ζ_k falls below 1%.

able or cannot be resolved with sufficient technological detail in FIDELIO. These outputs are then translated into a set of harmonised shocks and parameters that are passed to FIDELIO. In FIDELIO, these inputs affect production costs, final demand, investment behaviour and trade flows, generating economy-wide adjustments in sectoral output and household demand. The CGE returns updated demand trajectories to PyPSA-Eur, meaning aggregate and sector-specific activity levels, as well as demand shifts for energy-intensive products and transport and energy services. PyPSA-Eur then re-optimises the energy system under these updated demand conditions. This exchange is repeated iteratively, until changes in the exchanged variables fall below a predefined convergence threshold.

Since the two models differ in temporal and spatial resolution, the coupling involves a number of harmonisation steps. PyPSA-Eur outputs, which are generated at high temporal resolution and for discrete milestone years, are aggregated and interpolated to match the annual time structure of FIDELIO. Conversely, economy-wide demand changes computed by FIDELIO are mapped onto the sectoral and service categories required by PyPSA-Eur.

Detailed documentation of the data mappings, convergence metrics, and implementation of the coupling is provided in Appendix A.

2.3. Climate and trade policy framework

The analysis considers the interaction between European climate policy and evolving international trade conditions. More in detail, this Section provides a description of the two specific policy tools assessed: (i) the implementation of the European Union's climate policy architecture under the Fit-for-55 package, and (ii) recent USA steel tariffs on imports.

The Fit-for-55 package constitutes the core instrument through which the European Union operationalises the objectives of the European Green Deal and the European Climate Law, namely a reduction of greenhouse gas emissions by at least 55% by 2030 relative to 1990 levels and the achievement of climate neutrality by 2050. FF55 is a comprehensive and integrated framework combining market-based instruments, regulatory standards, and supporting measures across energy, industry, transport, and households. At the centre of the package is the reform of the EU Emissions Trading System, which introduces a tighter emissions cap, a higher linear reduction factor, and a gradual phase-out of free allowances for energy-intensive sectors. The scope of emissions trading is expanded to maritime transport, while a new ETS (ETS2) applies to emissions from buildings and road transport. Complementary regulatory instruments include revised targets under the Renewable Energy Directive (RED) and the Energy Efficiency Directive, stricter CO_2 performance standards for road transport, and fuel-specific regulations for aviation and maritime transport. Additional provisions address hydrogen and gas markets, infrastructure deployment, and social compensation mechanisms, notably through the Social Climate Fund. Taken together, these measures influence technology choices, investment patterns, and energy-system configuration, while also generating economy-wide adjustment pressures. A distinctive element of the FF55 architecture is the Carbon Border Adjustment Mechanism, which links climate policy directly to international trade. CBAM aims to reduce carbon leakage risks by aligning the carbon cost of selected imports with that faced by EU producers under the ETS, and is closely connected to the progressive removal of free allowances in covered sectors, including steel.

Alongside climate policy, the analysis explicitly considers trade policy shocks reflecting a renewed use of tariffs and trade restrictions. The applied analysis focuses on recent USA tariffs on steel imports as a case study of trade measures affecting key hard-to-abate sectors. In early 2025, the USA administration announced a 50% tariff on steel imports, prompting the European Commission to impose retaliatory duties worth 26 bnEUR (47; 48). These tariffs alter relative prices, competitiveness, and trade flows independently of climate policy objectives, yet interact strongly with decarbonisation efforts by reshaping market conditions for energy-intensive industries.

For context, we report descriptive trade statistics from the 2015 benchmark underlying the FIDELIO model. While not intended to represent current trade patterns, these figures characterise the initial trade structure from which the policy simulations depart. As shown in Table 1, the United States absorbs around 11% of total EU exports in steel-related value-chain sectors, suggesting a meaningful but not dominant exposure of European producers to USA steel tariffs.

Table 1: EU26+UK (EU27 excluding Cyprus and Malta, plus UK) exports of steel value-chain sectors by top 10 destinations in 2015.

Destination	Share (%)
China	17.9
USA	11.4
Russia	6.3
Switzerland	6.1
Turkiye	6.0
Norway	3.2
Saudi Arabia	3.1
Mexico	3.0
South Korea	2.6
Australia	2.4

2.4. Policies implementation

Climate and trade policies are implemented within the coupled PyPSA-Eur-FIDELIO framework according to the scope and modelling strengths of each model. Policies that directly affect the energy system, technology choices, and emissions constraints are primarily represented in PyPSA-Eur, while policies that operate through trade costs, income redistribution, and macroeconomic channels are implemented in FIDELIO. Through the two-way coupling, the effects of these policies propagate across both models.

The Fit-for-55 climate policy package is implemented as a coherent set of constraints consistent with the EU's emissions reduction objectives for 2030, 2040, and 2050. In PyPSA-Eur, these objectives are operationalised through sector-specific greenhouse-gas emission caps, technology and fuel-mix requirements, and performance standards that guide investment and dispatch decisions in the power system, transport, and selected industrial sectors. An overarching emissions trajectory ensures a 55% reduction by 2030, a 90% reduction by 2040, and Net-Zero emissions by 2050 at the EU level. Instruments such as the Carbon Border Adjustment Mechanism and the recycling of climate-policy revenues are implemented directly in the macroeconomic model. Trade policy shocks are implemented in FIDELIO as changes in bilateral trade costs affecting energy-intensive sectors, with a particular focus on steel.

A detailed overview of the individual policy instruments and their specific representation within each model is provided in Table 2.

Table 2: Overview of Fit-for-55 policy measures and their implementation in the modelling framework.

Measure	**Details**	**Model implementation**
Revision of EU ETS	Power, energy-intensive industry, and aviation (+maritime): -63% GHG emissions in 2030 relative to 2005.	PyPSA-Eur, imposing a cap on GHG emissions from the respective sectors.
ETS2	Buildings (commercial and residential) and road transport: -43% GHG emissions in 2030 relative to 2005.	*PyPSA-Eur*, imposing a cap on GHG emissions from the relative sectors.

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Table 2 – *Continued from previous page*

Measure	**Details**	**Model implementation**
CBAM	Industrial products from countries without ETS pay CBAM certificates.	FIDELIO: CBAM is modelled as an additional import tariff on EU imports of CBAM-covered goods, calculated as the EU ETS carbon price multiplied by the embedded CO_2 intensity of exporter production (sector-weighted and time-updated) and adjusted for the progressive phase-out of free allowances. The mechanism is applied to all CBAM-covered industrial sectors, while electricity imports are excluded, reflecting their physical transmission constraints.
Revision of ESR	National emission reduction targets for buildings, road transport, agriculture, waste, and small industries to achieve -40% GHG emissions in 2030 relative to 2005.	PyPSA-Eur, imposing a cap on GHG emissions from non-ETS sectors.
Performance standards for Internal Combustion Engine (ICE)	Ban on internal combustion engine sales after 2035	PyPSA-Eur, adjusting Electric Vehicles (EVs) shares to meet performance targets, detailed in Appendix B.1.
FuelEU Maritime	Annual carbon intensity reduction with respect to 2020: -6% (2030), -38% (2040), -80% (2050) [CO_2/t-mile]. Reference value: 91.16 gCO_2e/MJ.	PyPSA-Eur, adjusting maritime fuel mix to meet carbon intensity targets, detailed in Appendix B.2.
Refuel EU Aviation	SAF (Sustainable Aviation Fuels) shares: 6% (2030), 34% (2040), 70% (2050); e-fuels: 1.2% (2030), 15% (2040), 35% (2050).	PyPSA-Eur, adjusting aviation fuel mix to meet SAF and e-fuel targets, detailed in Appendix B.3.

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Table 2 – *Continued from previous page*

Measure	**Details**	**Model implementation**
Social Climate Fund	ETS revenues earmarked for vulnerable households, microenterprises, and transport users.	FIDELIO: ETS revenues are recycled through the Social Climate Fund by reallocating 50% of carbon tax revenues to public consumption, representing transfers and support measures for households and vulnerable users, while the remaining 50% is redistributed through other government channels.
Gas markets	Development of a hydrogen backbone network.	PyPSA-Eur, enabling hydrogen grid expansion and utilisation.
Revision of Energy Efficiency Directive	-39% primary and -36% final EU energy consumption by 2030 (this translated in no more than 1023 Mtoe for primary, 787 for final (49)).	PyPSA-Eur, validated ex-post through resulting primary energy consumption in Appendix C.1.
Revision of Energy Performance of Buildings	-16% average primary energy in residential buildings by 2030, -20% by 2035; phase-out of fossil boilers by 2040.	PyPSA-Eur, oil boilers are not included, energy performance is validated ex-post through resulting building energy demand in Appendix C.1.
REPowerEU (Revision RED)	Renewable energy share target: 42.5-45% in final energy.	PyPSA-Eur, validated ex-post through resulting RES shares in Appendix C.1.
Regulation on methane	Common standards for methane emissions; mandatory leak detection and repair; ban on venting/flaring.	Not implemented (methane leaks not represented in models).
Alternative Fuels Infrastructure Regulation	EV recharge stations every 60 km by 2026; H_2 refuelling every 100 km by 2028.	Not implemented (specific infrastructures not included).
New LULUCF rules	-310 MtCO_2 target in 2030.	Sector not adequately represented in either model.
Market Stability Reserve (ETS)	Adjustment of allowance supply in EU ETS.	Not explicitly modelled.
Revision of Energy Taxation Directive	Restructuring of energy taxation based on carbon content and energy efficiency.	Not explicitly modelled.

The EU ETS2 and the ESR partially overlap in buildings and road transport, combining national emission targets with a market-based carbon price. From 2027, both apply simultaneously, requiring coordination to ensure policy coherence, while the ESR remains relevant for uncovered sectors such as agriculture and waste. ETS2 also includes a price stabilization mechanism, with allowance releases if prices exceed EUR 45/tCO_2 before 2029; accordingly, this price cap is imposed until 2030 (30). For transport sectors, policies usually refer to emission or performance standards. Designing those in PyPSA-Eur requires some calculations, that are shown in Appendix B.

2.5. Scenarios design

Three scenarios are analysed to disentangle the effects of climate policies and trade tariffs. The *Baseline* scenario represents a counterfactual pathway without climate policy, providing the reference trajectory against which all policy impacts are evaluated. The *EU ClimPol* scenario implements the full Fit-for-55 policy package and the European Climate Law objectives. The *EU ClimPol + Tariffs* scenario builds on the climate-policy scenario by introducing trade policies in the form of the 50% tariffs on steel imports in the US. This scenario allows the assessment of how rising protectionism and geopolitical fragmentation interact with climate policy, particularly in hard-to-abate sectors. Across all scenarios, policies are applied consistently over time, and results are reported for the milestone years 2030, 2040, and 2050. By comparing outcomes across scenarios, the analysis isolates the macroeconomic, trade, and energy-system effects of climate policy alone and in combination with trade shocks.

3. Results

Results are presented as energy-system outcomes generated by PyPSA-Eur (Subsections 3.1 and 3.2) and then macroeconomic outcomes produced by FIDELIO (Subsections 3.3 and 3.4). To facilitate interpretation, EU countries are grouped into three macro-regions: Southern Europe (SEU), comprising Spain, Greece, Italy, and Portugal; Eastern Europe (EEU), including Bulgaria, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Poland, Romania, Slovenia, and Slovakia; and Northwestern Europe (NWEU), covering Austria, Belgium, Germany, Denmark, Finland, France, the United Kingdom, Ireland, Luxembourg, the Netherlands, and Sweden.

3.1. Electricity production

Figure 2 shows electricity production and consumption per capita by macro-region and total electricity generation and demand at the EU26+UK level across the three scenarios. Relative to the *Baseline*, both climate-policy scenarios (*EU ClimPol* and *EU ClimPol + Tariffs*) exhibit a pronounced increase in electricity demand over time, reaching the total value of around 8200 TWh in 2050. This reflects the central role of electrification in decarbonization, as power increasingly substitutes for fossil fuels across industry, transport, and other end-use sectors. The PyPSA-Eur-FIDELIO coupling allows electricity demand to respond endogenously to structural economic changes, providing additional flexibility and robustness to the results. In comparison, the uncoupled PyPSA-Eur model yields electricity demand that is, on average, 12.3 TWh higher, corresponding to less than 0.2% of total demand in 2050. This limited divergence suggests that, for this vari-

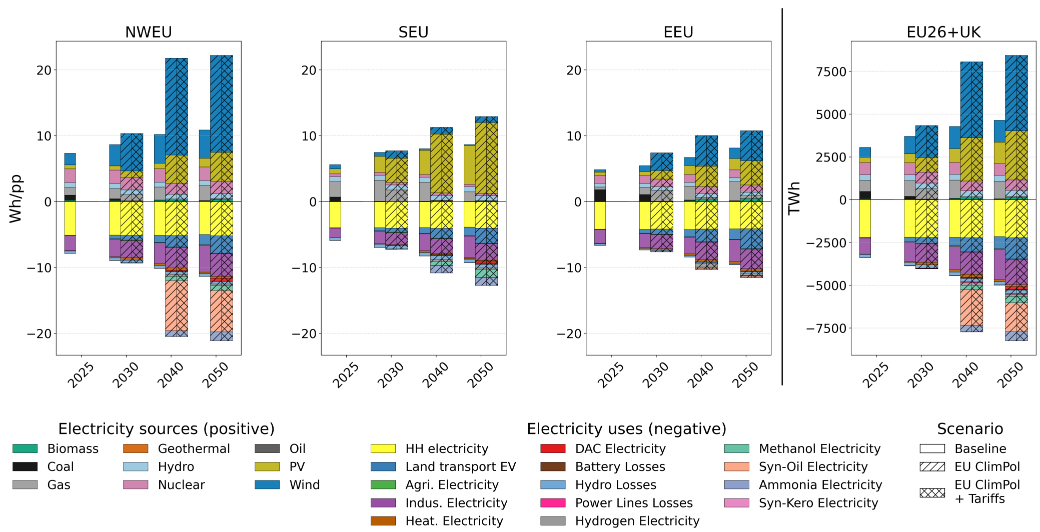

Figure 2: Electricity production and demand per capita by macro-region (left panels) and total electricity production and demand at the EU26+UK level (right panel) under the *Baseline*, *EU ClimPol*, and *EU ClimPol + Tariffs* scenarios. Positive values represent power generation for different technologies, while negative values show how this electricity is consumed by end-use sector. Results are shown for 2030, 2040, and 2050.

able, long-term electricity demand trajectories are only weakly affected by economy-wide feedbacks, and appear largely driven by the structural features and constraints of the electricity system representation.

The expansion of power demand is broadly consistent with findings from other European decarbonisation assessments, including recent analyses by the Joint Research Centre (50). While their standard projections estimate EU gross electricity will range between 3850 and 6400 TWh by 2050, the Low-Carbon Energy Observatory outlines a significantly higher scenario reaching 10548 TWh, driven by the energy intensity of hydrogen and e-fuel production.

NWEU displays the highest per-capita electricity production, due to extensive wind deployment, SEU relies more strongly on solar generation, while EEU shows a more balanced renewable mix. In addition to the existing European power grid, transmission expansion is limited to a maximum increase of 20% of existing capacity, reflecting a conservative assumption on cross-border coordination. This allows for moderate EU power market integration, while potentially understating the benefits of deeper grid expansion. The power generation mix remain similar across the two climate-policy scenarios, indicating that trade measures have limited influence on the electricity system compared to the scale of electrification and decarbonization. A major driver of electricity demand growth in the climate-policy scenarios is the production of electro-based fuels, in particular synthetic oil, via Fischer-Tropsch processes. These fuels contribute significantly to total electricity consumption, accounting for 26.7% of all power use in 2040 across climate policy scenarios. This reflects the central role of syn-fuels in decarbonising hard-to-electrify sectors such as aviation and maritime transport. The magnitude of this effect is also influenced by modelling assumptions in PyPSA-Eur, where all synthetic fuels are produced domestically; allowing for imports could alleviate pressure on the electricity system and potentially reduce overall costs.

3.2. Steel production

Figure 3 illustrates the evolution of steel production and prices across EU macro-regions under climate and trade policy scenarios. In the *Baseline* scenario, steel production follows historical spatial patterns, with output concentrated in NWEU (71.2 Mt/yr) and lower production levels in SEU (39.9 Mt/yr) and EEU (15.0 Mt/yr).

In 2030, climate policy has little impact on steel output, as the transi-

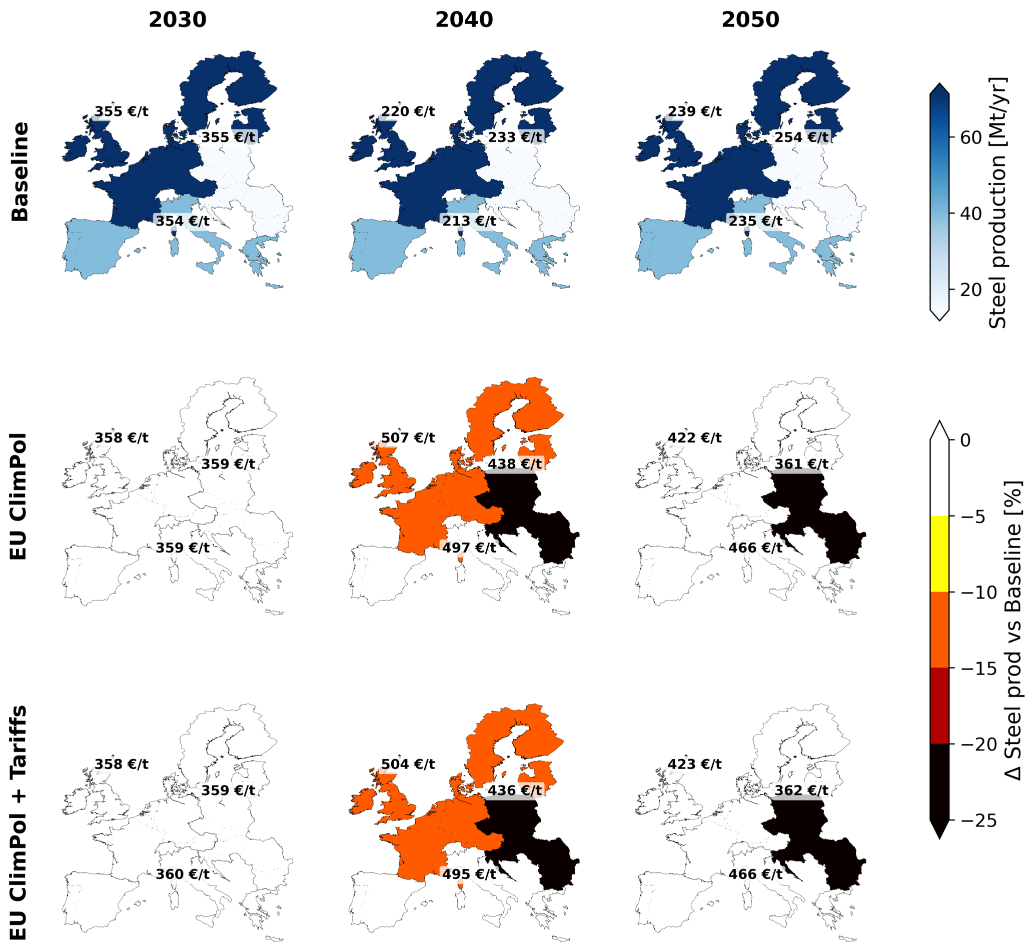

Figure 3: Spatial distribution of steel production and production-weighted steel prices across EU macro-regions in 2030, 2040, and 2050 under the *Baseline*, *EU ClimPol*, and *EU ClimPol + Tariffs* scenarios. The top row shows absolute steel production levels (Mt/yr) in the *Baseline*. The middle and bottom rows report percentage deviations in steel production relative to the *Baseline* under climate policy alone and with additional trade tariffs, respectively. Annotated values indicate average production-weighted steel prices [EUR/t] by macro-region.

tion is still in its early stages and production structures remain largely unchanged, while 2040 represents the most disruptive phase, marked by deep emissions reductions and peak investment and restructuring in the steel sector. EU26+UK steel production declines sharply in 2040, by 11.7% under *EU ClimPol* and 12.3% under *EU ClimPol + Tariffs*, before recovering by 2050, when output is 0.2% and 0.3% below the *Baseline*, respectively.

Eastern European countries experience the largest relative reductions in steel output, reaching around 25% by 2040. However, EU steel production is largely concentrated in NWEU and SEU, where relative declines are more limited, so we observe a smaller contribution to aggregate EU output changes. This reflects the assumption that industrial production capacity is geographically fixed, thus changes in steel output occur within the countries where production is historically located and cannot be offset through spatial reallocation.

Steel prices increase substantially under climate policy scenarios, most notably in 2040, reflecting higher production costs associated with low-carbon technology investments, before stabilising by 2050 as major capital adjustments are completed. By comparison, the uncoupled PyPSA-Eur model yields a production-weighted average steel price of about 526 EUR/t for EU26+UK in 2050. When the macroeconomic feedbacks captured by FIDELIO are taken into account, EU26+UK steel prices are around 9.1% lower (478 EUR/t), indicating that price formation is substantially influenced by the coupling.

3.3. Macroeconomic results

Figure 4 shows GDP deviations relative to the *Baseline* for EU macro-regions under the *EU ClimPol* and *EU ClimPol + Tariffs* scenarios, computed as five-year averages for 2030, 2040, and 2050.

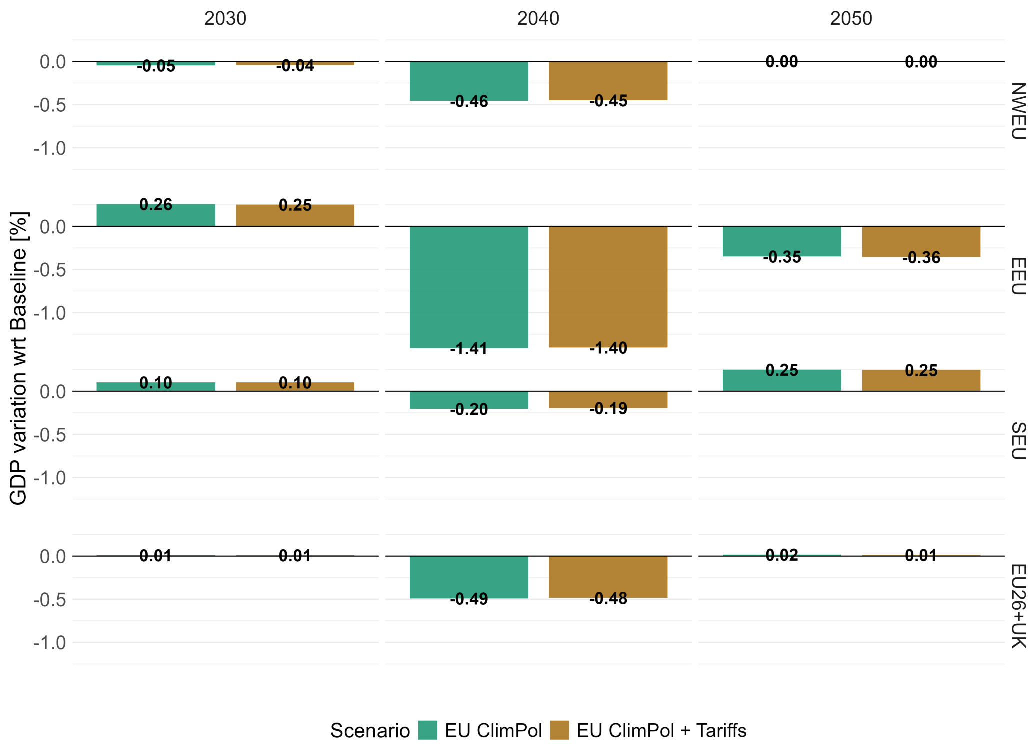

Figure 4: Variation in GDP relative to the *Baseline* scenario, expressed in percentage points, for NWEU, EEU, SEU, and the EU26+UK aggregate. Results are shown for the *EU ClimPol* and *EU ClimPol + Tariffs* scenarios and for the milestone years 2030, 2040, and 2050, averaging for 5 years around the corresponding one.

Overall, aggregate GDP impacts for the EU26+UK remain limited, indicating moderate system-wide transition costs, as higher production costs are partly offset by increased low-carbon investment. GDP effects are slightly positive in 2030, reflecting the early transition phase with moderate investment needs and less stringent emissions constraints. By 2040, GDP impacts turn negative with respect to the *Baseline* values, coinciding with the most demanding phase of the transition, marked by deep emissions reductions (-90%) and peak investment and restructuring requirements. In 2050, GDP deviations partially recover as major transition investments have largely been completed and the system enters a more stable phase. Impacts are uneven across regions: EEU experiences the largest GDP losses, reaching up to -1.4%, while NWEU and SEU are less affected, reflecting differences in industrial structure and renewable resource availability, with more limited renewable potential in the EEU compared to strong wind resources in the NWEU and solar potential in the SEU. Finally, the introduction of USA steel tariffs does not significantly alter the GDP trajectory relative to the climate policy scenario alone. This limited effect is primarily attributable to two factors: steel production represents only 1.3% of EU GDP (51), and steel-intensive products exported to the USA account for less than 2% of total EU production in these sectors[1] (52).

3.4. Trade implications

Figure 5 reports the variation in export volumes, excluding intra-EU trade, by macro-region and year (2030, 2040, and 2050) for the aggregated steel-intensive sectors, as percentage deviations relative to the *Baseline*. We

[1] According to the FIGARO input-output database (2015), around 11% of EU exports of steel-intensive products are destined to the USA, and extra-EU exports represent approximately 17% of total EU production of these goods. Combining these shares implies that US-bound exports correspond to roughly 2% of overall EU steel-intensive production.

focus on these sectors because the analysis aims to provide a closer assessment of industries that are particularly exposed both to decarbonisation policies and to trade restrictions, given their energy intensity and trade openness. Appendix Appendix C.3, with Figures C.14 and C.15, reports the corresponding results for total trade flows. While the qualitative patterns are similar, the magnitude of changes is substantially smaller when considering aggregate trade, reflecting the more limited exposure of the overall economy compared to steel-intensive sectors.

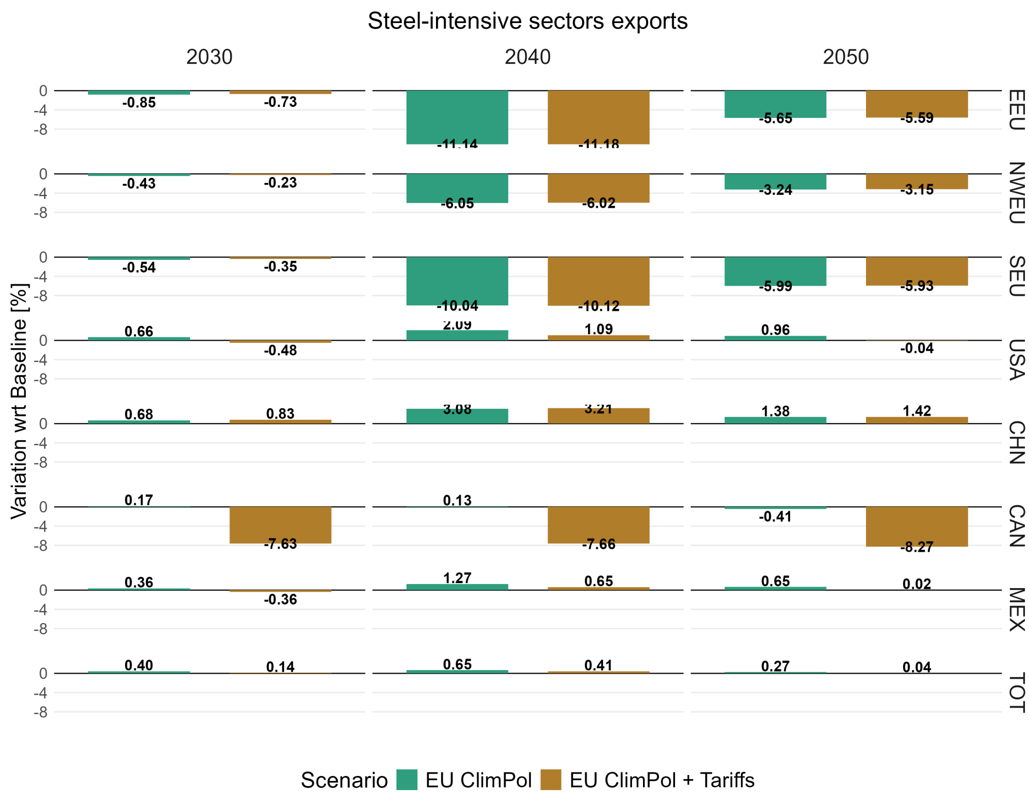

Figure 5: Variation in exports of steel-intensive sectors by macro-region relative to the *Baseline*, for *EU ClimPol* and *EU ClimPol + Tariffs*. Values are computed as 5-year averages and exclude intra-EU macro-regional trade flows. The steel-intensive sectors sectors includes primary steel production, fabricated metal products, machinery and equipment, and motor vehicles and transport equipment.

All values represent five-year averages before the target years, smoothing short-term fluctuations. The steel-intensive sectors encompass primary steel production (Classification of Products by Activity code CPA_C24_S) as well as downstream steel-intensive manufacturing sectors: fabricated metal products (CPA_C25), machinery and equipment (CPA_C28), motor vehicles, trailers and semi-trailers (CPA_C29), and other transport equipment

(CPA_C30). This classification is adopted to capture not only direct trade effects in raw steel but also indirect adjustments transmitted through vertically integrated industrial activities. Regional aggregation distinguishes the three chosen European macro-regions and selected non-EU economies that play a central role in global steel trade.

Across all European macro-regions, climate policy implementation leads to a reduction in exports from 2040, reflecting a broadly homogeneous response across Eastern, Southern, and Northwestern Europe. Export reduction for EU regions is lower when intra-European trade is included, as shown in Appendix C.2 (e.g., in Figure C.10 for 2040, *EU ClimPol*: EEU -8.21%, NWEU -4.34%, SEU -6.53%). This reflects the fact that intra-EU trade is less affected by transition-related price increases and constitutes a substantial share of total EU trade (around 70% (52)). The introduction of USA tariffs has a negligible additional effect on EU exports, indicating that the dominant driver of the export contraction is domestic decarbonisation rather than external trade measures. Figures C.18 further reports the evolution of trade dependency indicators, measured as the ratio of exports to sectoral output. While non-zero, changes in export intensity remain modest across regions and years. In particular, decarbonisation induces only limited increases in the export/output ratio, suggesting that climate policy affects trade volumes without generating a structural shift in the trade orientation of steel-intensive sectors. In contrast, USA experiences an increase in exports under *EU ClimPol* scenario, up to 2.09% in 2040, consistent with a competitiveness-driven reallocation of steel and steel-intensive production towards regions facing weaker climate constraints. This export expansion is reduced when tariffs are introduced, highlighting the role of trade tariffs in dampening competitiveness gains associated with asymmetric climate ambition. China exhibits a larger increase in export with respect to USA, within the *EU ClimPol* up to 3.08%, slightly more when tariffs are applied. Finally, Canada shows a pronounced sensitivity to USA trade measures: while EU climate policy alone has a limited effect on Canadian exports, the introduction of tariffs leads to a marked reduction, reflecting Canada's strong trade integration with the US.

Figure 6 presents the variation in import volumes, excluding the intra-EU trade, by macro-region and year (2030, 2040, and 2050), measured as percentage deviations from the *Baseline* for the aggregated steel-intensive sectors.

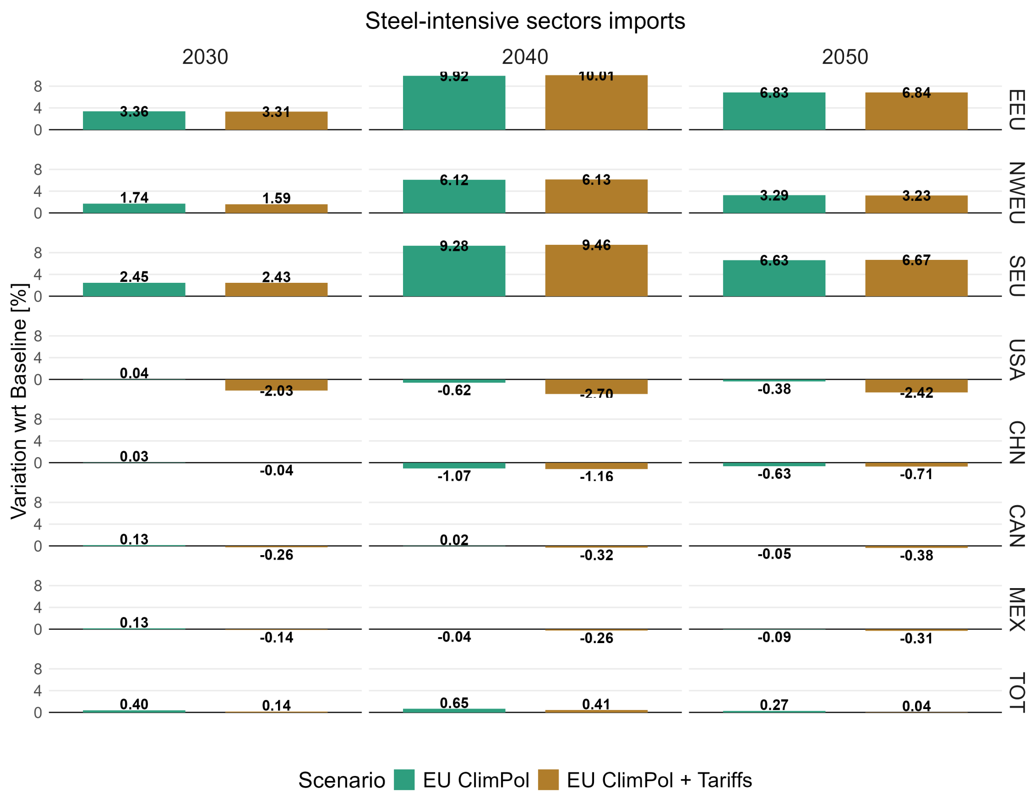

Figure 6: Variation in total imports of steel-intensive sectors by macro-region relative to the *Baseline*, for *EU ClimPol* and *EU ClimPol + Tariffs*. Values are computed as 5-year averages and exclude intra-EU macro-regional trade flows. The steel-intensive sectors sectors includes primary steel production, fabricated metal products, machinery and equipment, and motor vehicles and transport equipment.

Import increase in all EU26+UK regions with respect to the *Baseline*, particularly in 2040. The introduction of USA tariffs leads to only marginal additional changes, confirming that EU import dynamics are primarily shaped by internal climate policy rather than external trade measures. As for exports, Figure C.19 shows the evolution of import dependency, measured as the ratio of imports to sectoral output. While climate policy induces increases in import shares in some regions, these remain limited in absolute terms, indicating a marginal rise in trade relevance rather than a structural change in external dependence. The United States experiences a moderate reduction in imports, which becomes more pronounced when tariffs are introduced (-2.70% in 2040). China shows a decline in imports under the *EU ClimPol* scenario, while USA tariffs further amplify this contraction. For both countries, the observed reduction in imports is predominantly attributable to decreased procurement from EU member states, partially offset by the substitution of products sourced from other countries and the expansion of domestic manufacturing within steel-intensive sectors (as in Figure C.16 (2040): *EU ClimPol* yields +0.75% USA and +1.18% China; *EU ClimPol + Tariffs* yields +0.68% and +1.24% respectively). Canada and Mexico, by comparison, exhibit minor change in import volumes under *EU ClimPol* alone, and both nations record slightly stronger reductions of imports once USA tariffs are applied.

4. Discussion

This study integrates a high-resolution European energy system model with a global macroeconomic trade model to assess how climate ambition and trade fragmentation jointly shape energy, industrial, and economic outcomes. By soft coupling PyPSA-Eur and FIDELIO in a two-way iterative framework, the analysis captures feedbacks between technology deployment, energy prices, industrial costs, trade flows, and aggregate economic activity that are typically examined in isolation. In line with other similar studies (53; 54), the two-way coupling highlights an important asymmetry in cross-model feedbacks. On the energy-system side, electricity demand levels adjust endogenously to macroeconomic changes, but these variations do not substantially alter the optimal technology mix or the spatial structure of generation, which remains primarily driven by resource availability and system constraints. By contrast, price signals transmitted from the energy system to the macroeconomic model play a much stronger role. In particular, changes in energy and steel prices generated by PyPSA-Eur significantly affect production costs, trade flows, and demand responses in FIDELIO. Steel prices are especially sensitive to the coupling, as endogenous demand adjustments and economy-wide feedbacks lead to systematically lower prices than in the uncoupled energy-system representation. Overall, these results suggest that coupling is most critical for capturing price- and demand-mediated adjustment mechanisms, while the core technological configuration of the energy system remains relatively robust to macroeconomic feedbacks.

Across all scenarios, changes in production, trade, and economic outcomes for EU26+UK are shaped predominantly by EU climate policy itself, while trade tariffs on steel play a secondary role. Trade disruptions do not materially alter the direction or timing of the decarbonisation pathway, reflecting the difference in scale between a comprehensive structural transformation package and relatively limited protectionist measures. .

Looking at specific industries, in line with other recent studies (55; 56), the electricity system emerges as the backbone of the transition, with rapid electrification and the expansion of renewable generation underpinning emissions reductions across sectors. Synthetic fuel production for aviation and maritime transport substantially amplifies electricity demand (57). This central role of electricity also highlights the importance of examining potential frictions that could hinder such expansion, including political and strategic constraints that lie outside the scope of the present modelling framework.

The reduction in steel output peaks around 2040, when emissions targets tighten sharply and a large share of existing steelmaking capacity must be replaced or retrofitted with low carbon technologies, increasing adjustment costs and output price, and temporarily reducing production. Even in the steel sector, where trade measures might be expected to play a more prominent role, production adjustments remain primarily driven by the stringency of climate policy. The steel sector's adjustment dynamics highlight not only the relevance of climate ambition in driving production changes but also the potential role of complementary industrial support. This is in line with recent proposals envisaging the re-purposing of free allocation and the alignment of ETS revenues with broader industrial decarbonisation objectives that aim to direct additional resources toward the deployment and scaling of low-carbon technologies, thereby potentially mitigating adjustment costs and reinforcing competitiveness in emissions-intensive sectors (58).

The primary driver of adjustment in steel-intensive trade flows for EU is domestic climate policy rather than external trade measures. EU decarbonisation leads to higher production costs and prices in steel and downstream sectors, reducing export competitiveness and increasing reliance on imports. This finding is consistent with the risk of carbon leakage in emissions-intensive industries under asymmetric climate ambition. Existing literature suggests that instruments such as carbon border adjustments or targeted industry support may mitigate these competitiveness effects by narrowing cost differentials across regions, although their effectiveness depends on design and coverage (59; 60; 15). By contrast, the introduction of USA steel tariffs generates only marginal additional effects on EU trade flows, reflecting both the limited exposure of EU steel-intensive production to the USA market and the dominance of internal policy-driven cost pressures. Outside the EU, asymmetric climate ambition creates temporary competitiveness gains for regions with weaker climate constraints, notably the United States and China, while tariffs primarily reallocate trade away from closely integrated partners such as Canada rather than delivering sustained export gains for the tariff-imposing country.

At the macroeconomic level, GDP impacts remain moderate for overall EU26+UK but are unevenly distributed across regions, with Eastern Europe experiencing the largest relative losses due to differences in industrial structure and more limited renewable resource availability. These regions often have economies reliant on fossil-fuel industries or energy-intensive manufacturing and show "low adaptability" to the clean energy shift (61). This result is in line with literature (61; 62) and highlights the importance of accompanying climate policy with targeted support measures, such as enhanced investment subsidies, expanded use of the Social Climate Fund, and region-specific industrial transition assistance.

Consistently, analyses of recent trade tensions show that the macroeconomic impact of tariffs on Europe is minor. For example, an EU-USA "trade war" scenario was estimated to trim EU GDP by only ~0.2-0.5%. Moreover, only about 3% of EU GDP is tied to exports potentially affected by USA steel tariffs, "constraining the potential for significant direct economic damage" (63). Within the scenarios considered in this paper, moderate tariffs do not materially influence the direction or timing of the transition, implying that escalation through retaliatory trade measures is unlikely to deliver meaningful economic or climate gains.

5. Conclusions

This paper set out to examine two closely related questions: whether recent USA trade measures materially affect European climate policy outcomes, and how steel decarbonisation interacts with broader economic and trade dynamics. The results show clearly that, for EU26+UK, the trajectory of decarbonisation is determined primarily by internal climate ambition rather than by external trade policies. Recent steel tariffs, while relevant for specific bilateral trade relations, do not significantly alter the timing, direction, or feasibility of the EU's transition pathway, nor do they materially affect aggregate economic outcomes. Their effects are concentrated largely outside the EU, generating distortions for closely integrated trading partners with USA, without delivering sustained competitiveness gains for the tariff-imposing country.

More broadly, the analysis demonstrates that steel decarbonisation in the EU is shaped by economy-wide adjustment processes rather than by sector-specific technological constraints. Production, prices, and trade flows in the steel sector respond to the interaction between climate policy stringency and endogenous demand adjustments captured in the coupled PyPSA-Eur-FIDELIO framework. The pronounced contraction of EU steel production observed around 2040 reflects the alignment of tightening emissions targets with peak investment and restructuring needs, while the partial recovery by

2050 indicates that adjustment pressures ease once major capital turnover has occurred. Persistent regional heterogeneity, particularly the larger relative output losses in Eastern Europe, underscores the importance of analysing industrial decarbonisation within an integrated macroeconomic context.

Taken together, these findings suggest that safeguarding EU industrial competitiveness is less a matter of defensive trade measures and more a question of aligning climate ambition with targeted industrial support, coordinated climate–trade instruments, and region-specific transition policies. Delivering an economically resilient and politically sustainable decarbonisation pathway therefore requires coherent integration of climate, industrial, and social policy frameworks.

From a modelling perspective, the study highlights the added value of integrated energy–economy frameworks for analysing industrial decarbonisation. While high-resolution energy-system models capture technological feasibility and system-level constraints, coupling with a macroeconomic trade model is essential to represent endogenous price formation, demand responses, and trade adjustments that materially affect sectoral and aggregate economic outcomes. The results indicate that such coupling is particularly important when research questions concern global trade dynamics, competitiveness, and economy-wide adjustment mechanisms. By contrast, for analyses focused primarily on power-system technologies or operational optimisation, the incremental benefits of full energy–economy integration are more limited relative to the additional complexity and computational cost.

Limitations and future research

Several simplifying assumptions point to promising avenues for future research. In the macroeconomic model, investments related to steel are aggregated within the broader "Manufacture of Basic Metals" sector (C24 in CPA codes), encompassing iron and steel, ferro-alloys, and non-ferrous basic metals. This aggregation may obscure upstream and downstream value-chain interactions that could influence adjustment dynamics. In addition, trade measures are assumed to persist over the full projection horizon, climate policy is implemented only within the European Union, and synthetic fuel demand is fully satisfied by domestic production. Relaxing these assumptions would allow future analyses to better capture evolving trade regimes, international fuel supply chains, and the global diffusion of climate ambition.

A further limitation is the exclusion of tariffs on steel-intensive downstream products. For example, the United States has imposed tariffs on car imports, set at 25% for most trading partners, with differentiated rates of 15% for EU27 countries and 0% for Canada and Mexico under existing trade agreements (64). Such measures may indirectly affect steel demand by dampening production in one of its largest end-use sectors. Extending the modelling framework to incorporate downstream tariff measures would enable a more comprehensive assessment of how trade policy propagates through value chains and ultimately shapes steel consumption and industrial decarbonisation trajectories.

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Data availability

The code to reproduce the experiments is available at https://github.com/cerealice/pypsa-fidelio and is stored in a Zenodo repository.

CRediT authorship contribution statement

A. Di Bella: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing.

P. Rocchi: Data curation, Formal analysis, Software, Writing - review & editing, Conceptualization, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the language of this paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Appendix A. Methodology for models' coupling

Appendix A.1. Qualitative description of the coupling

The coupling between PyPSA-Eur and FIDELIO requires the definition of a *Baseline* scenario, as several variables are introduced as shocks relative to baseline values and a counterfactual is needed for comparative analysis. Accordingly, the first stage of the coupling consists of iteratively running the two models until convergence is achieved in the *Baseline* scenario.

PyPSA-Eur is executed first, as FIDELIO relies on a number of exogenous inputs derived from the energy system model and does not explicitly represent electricity and energy system dynamics. Prior to this step, FIDELIO is run in a *Pre-Baseline* configuration that excludes inputs from PyPSA-Eur. This preliminary simulation is necessary because baseline variables in FIDELIO are defined as deviations relative to the *Pre-Baseline* scenario.

The variables transferred from PyPSA-Eur to FIDELIO include:

- Shares of electricity generation technologies in the electricity mix;
- Average electricity and energy prices (PyPSA-Eur operates at hourly resolution; averages are computed using hourly consumption as weights);
- Average steel and aluminium production costs (PyPSA-Eur operates at hourly resolution; averages are computed using hourly consumption as weights);
- Investments in electricity generation technologies;
- Investments in steel and aluminium production technologies;

- Household-level electricity and non-electricity consumption shares, particularly for passenger transport and residential heating (which are not endogenously modelled in FIDELIO);

- Carbon prices at the European level for ETS1 and ETS2.

A series of Python and R scripts is used to process and transform the outputs of PyPSA-Eur into the input format required by FIDELIO. FIDELIO is then executed with the corresponding input interface activated and the relevant scenario specification selected.

Following the FIDELIO simulations, the outputs are processed into a format compatible with PyPSA-Eur to initiate the first iteration of the coupled modelling framework. The corresponding script computes shock values capturing changes in key economic indicators under the *EU ClimPol* and *EU ClimPol + Tariffs* scenarios relative to the *Baseline*, as well as changes in the *Baseline* relative to the *Pre-Baseline* scenario. The variables transferred from FIDELIO to PyPSA-Eur consist of variations in:

- Industrial production;

- Agricultural output;

- Service-sector activity;

- Household consumption of electricity and heat;

- Household demand for land-based transport;

- Demand for maritime transport services;

- Demand for aviation services;

- Steel and aluminium production levels.

Once these shock values are prepared, PyPSA-Eur is rerun to complete Iteration 1, now incorporating the economic feedbacks derived from FIDELIO. This iterative process is repeated until a predefined convergence threshold is reached, at which point the final simulations of each model are taken as the converged results of the coupled framework.

The two models differ along multiple dimensions, necessitating harmonization of variables to ensure consistent interactions. First, regarding temporal resolution, PyPSA-Eur operates with a three-hourly time step for a single year in 2020, 2030, 2040, and 2050, whereas FIDELIO has annual resolution and runs continuously from 2015 to 2050. To transfer variables from PyPSA-Eur to FIDELIO, values for non-simulated years are obtained through linear interpolation, while historical values for 2015 are derived from FIDELIO's source data. Conversely, when transferring variables from FIDELIO to PyPSA-Eur, only values corresponding to years simulated in PyPSA-Eur (2030, 2040, 2050) are used, as 2020 is treated as historical and fixed. Second, with respect to spatial resolution, PyPSA-Eur represents most countries at a single-node country level, with additional nodes for geographically complex countries (e.g., Italy: one node for the peninsula and Sicily, one node for Sardinia). FIDELIO provides country-level values for the EU, as well as for selected non-EU countries (e.g., USA, China, India) and a "Rest of the World" category. For countries outside the EU, model inputs are held constant during the coupling, though FIDELIO's internal trade mechanisms allow them to interact with EU economies. A core assumption of the coupled framework is that non-EU countries do not implement climate policies, consistent with the study's focus on the European Union.

Appendix A.2. Variables exchanged from PyPSA-Eur to FIDELIO

A python script converts PyPSA-Eur variables into a standardized nomenclature, then an R-based data processing workflow harmonizes PyPSA-Eur outputs for FIDELIO. The script standardizes regional identifiers, filters relevant countries and technologies, and maps PyPSA technology codes to a consistent nomenclature. FIDELIO adopts 2015 as its baseline year, whereas PyPSA-Eur simulations begin in 2020. However, as the analysis focuses on future developments rather than historical dynamics, values for years prior to 2020 are assumed to remain constant and identical across both models to ensure consistency in the coupling framework. The variables exchanged and details about the processes are described below. For the *Baseline* scenario, only electricity generation shares and carbon price are exchanged. All other variables are expressed as deviations from the corresponding PyPSA-Eur values in the policy scenarios, relative to the *Baseline*.

Appendix A.2.1. Electricity generation shares

PyPSA-Eur electricity generation results are post-processed through a dedicated data harmonisation pipeline, spatially aggregated at the country level and mapped to FIDELIO's electricity subsectors of the NACE D35 code which is "Electricity, gas, steam and air conditioning supply". For each scenario, country, and model year, electricity production is converted into technology-specific shares. To align the differing temporal resolutions of the models, PyPSA-Eur outputs available for the years 2020, 2030, 2040, and 2050 are interpolated to annual values over the 2015-2050 horizon, using linear or exponential interpolation where required to ensure numerical stability and convergence of the coupled framework. To ensure compatibility with the FIDELIO base-year calibration, electricity technology shares are rebased on observed 2015 input-output production structures from the FIDELIO database. Specifically, PyPSA-Eur derived shares are scaled such that total electricity output by country and year matches the corresponding D35 aggregate, while preserving the relative technology composition implied by the energy system optimisation. This ensures that D35 continues to represent the same share of output in monetary terms in the economy. The rebasing is performed according to Eq. A.1.

$$s_{c,t,y}^{\mathrm{FID}} = \frac{s_{c,t,y}^{\mathrm{PyPSA}}}{\sum_t s_{c,t,y}^{\mathrm{PyPSA}}} \cdot S_{c,y}^{\mathrm{D35}}, \tag{A.1}$$

where $s_{c,t,y}^{\mathrm{PyPSA}}$ denotes the PyPSA-Eur electricity share of technology t in country c and year y, and $S_{c,y}^{\mathrm{D35}}$ is total electricity production in the FIDELIO input-output database.

Finally, the processed variables are exported as exogenous shares of electricity production as variation with respect to values in 2015.

Appendix A.2.2. Carbon price trajectories for ETS1 and ETS2

CO_2 price trajectories produced by PyPSA-Eur correspond to the shadow prices of the CO_2 emissions constraints applied to the sectors covered by ETS1 and ETS2, respectively. In the *Baseline* scenario, these prices are zero, reflecting the absence of binding emissions constraints. PyPSA outputs are available only at milestone years (2020, 2030, 2040, and 2050); therefore, the time series are harmonized by introducing a zero-price reference in 2015 and constructing annual values through piecewise linear interpolation. For the *Baseline* scenario, ETS1 prices are entirely replaced by an exogenous projection based on IEA assumptions (56), ensuring consistency with the reference pathway adopted in FIDELIO. ETS2 prices are set to zero prior to the system's introduction and capped at an upper bound of 45 EUR/tCO_2 in 2030 to prevent unrealistically steep short-term price increases (65). Finally, ETS1 prices over the initial period (2015-2020) are harmonized across scenarios in order to isolate policy-induced price differentials in subsequent years.

Appendix A.2.3. Average electricity and energy prices

Electricity and energy price signals from PyPSA-Eur are transferred to FIDELIO in the form of country-level relative price variations with respect to PyPSA-Eur *Baseline*. PyPSA-Eur provides electricity prices as shadow prices of the electricity balance constraint, and aggregate energy prices as shadow prices of the secondary energy balance constraint, both reported at optimized years (2030, 2040, and 2050). Prices are defined on each timestep and are therefore calculated as weighted averages, with weights corresponding to electricity generation and energy production, respectively. Changes in prices induced in the Climate Policy scenarios are expressed as proportional deviations from the corresponding *Baseline* values at the country-year level. For each price type $x \in \{\text{elec}, \text{ener}\}$, the price shock applied in FIDELIO is computed as Eq. A.2

$$\Delta p^x_{c,t} = \frac{p^{x,\text{policy}}_{c,t} - p^{x,\text{baseline}}_{c,t}}{p^{x,\text{baseline}}_{c,t}} \tag{A.2}$$

where $p_{c,t}^{x,\text{policy}}$ and $p_{c,t}^{x,\text{baseline}}$ denote, respectively, electricity or aggregate energy prices in country c and year t under the policy and *Baseline* scenarios. To ensure consistency with FIDELIO's annual temporal resolution, the resulting relative price shocks are extended over the period 2015-2050 using piecewise linear interpolation between milestone years, with a zero-deviation reference imposed in 2015. The final country-specific electricity and energy price deviation profiles are implemented as exogenous price shifters of the endogenous prices of the macroeconomic model.

Soft-linking detailed energy system models (e.g., TIMES, PRIMES, PyPSA) with CGE models can generate unrealistically large macroeconomic impacts when high ESM-derived energy price increases are passed directly to the CGE. European studies show that strong decarbonization or supply shocks often produce price spikes that translate into implausible GDP losses (e.g., -5.5% for the Netherlands in Fattahi et al. (40)), partly due to inconsistencies between base-year CGE prices and future marginal prices in ESMs (54). To avoid this, researchers commonly apply price-dampening methods, such as numerical scaling, elasticity adjustments, or iterative smoothing, to ensure that the transmitted price signals yield credible macroeconomic outcomes. The scaling is necessary because electricity prices in the two models reflect different underlying mechanisms: in PyPSA-Eur, prices are marginal-cost indicators shaped by network constraints, hourly dispatch, and the shadow value of carbon or system-integration requirements, whereas in FIDELIO they summarise average production costs within a CES-based, annually-aggregated equilibrium. Passing the full PyPSA-Eur price change into FIDELIO would therefore overstate the effective cost shock perceived at the macroeconomic level, conflating marginal scarcity signals with structural production costs. In this case we apply a price dampening coefficient of 50%. An additional methodological clarification is required regarding the interpretation of energy prices. In our modelling framework, electricity and energy prices are obtained as the dual variables of the respective demand-balance constraints. They therefore represent marginal system costs, that is, wholesale prices reflecting the short-run marginal cost of supplying an incremental unit of energy. As a consequence, these prices do not incorporate the recovery of capital expenditures made in previous optimisation periods, even though capacity built in earlier years is carried forward in the pathway simulations. In real-world energy systems, such costs are typically recouped through system charges or regulated tariffs. To ensure that the price signals passed from PyPSA-Eur to FIDELIO fully reflect the investment requirements of the system, we assume a uniform investment repayment period of ten years. Given that our pathway simulations advance in ten-year increments, this implies that all investments made in a given optimisation year are fully amortised by the time the next iteration is computed. Importantly, the technical lifetimes of assets remain unchanged and follow the values specified in the technology dataset. This approach guarantees that the investment costs associated with electricity supply technologies are consistently accounted for and ultimately embedded within the electricity prices faced by end-users in FIDELIO.

In coupled energy-economy frameworks, electricity price changes induced by climate policy reflect multiple underlying mechanisms. Decarbonisation policies simultaneously increase the capital intensity of electricity supply, through a shift toward low-carbon generation technologies, and raise the cost of residual fossil-based generation through carbon pricing and associated operating cost changes. When transmitting these effects from a detailed energy-system model to a macroeconomic model with distinct price channels for current production and investment, it is therefore necessary to distinguish between price changes linked to capital deepening in the power sector and price changes arising from carbon pricing and operational costs borne by non-decarbonised generation. Representing the electricity price shock as a composite of an investment price effect and an electricity output price effect provides a pragmatic way to preserve this distinction within a general equilibrium framework, while remaining consistent with the structure of both modelling approaches. We operationalise this decomposition by using the change in the low-carbon "green" electricity share as a proxy for the capital-intensity component of the electricity price shock. Specifically, we define the investment-driven share of the electricity price change as Eq. A.3.

$$from\_inv_{s,n,t} = \frac{green\_share_{s,n,t} - green\_share_{Baseline,n,t}}{1 - green\_share_{Baseline,n,t}} \tag{A.3}$$

where s indexes policy scenarios, n denotes countries, and t denotes model periods. This expression measures the scenario-induced increase in green generation relative to the maximum feasible increase from the baseline (i.e., up to a fully green electricity mix), yielding a normalised share in $[0, 1]$ under typical conditions. We allocate the fraction $from\_inv_{s,n,t}$ of the electricity price shock to the investment price channel, capturing the higher capital intensity associated with the shift toward low-carbon generation, and the remaining fraction $1 - from\_inv_{s,n,t}$ to the electricity output price channel, capturing price effects arising from carbon pricing on residual fossil-based generation as well as other short-run operating cost changes. This mapping allows the coupled framework to represent electricity-sector decarbonisation as both a contemporaneous cost shock faced by electricity users and a capital-deepening process with broader macroeconomic implications, while remaining consistent with system constraints embedded in the energy-system scenarios. Because this decomposition relies on a proxy rather than an accounting identity, it should be interpreted as a modelling assumption; future work could refine the split using explicit system cost decompositions (e.g., separating CAPEX, fixed O&M, fuel, and carbon components) directly from the energy-system results.

Appendix A.2.4. Average steel and aluminium prices

Steel and aluminium prices are treated analogously to electricity and energy prices. In PyPSA-Eur, price signals are obtained as shadow prices of the corresponding industrial production constraints. Annual country-level prices are computed as weighted averages over timestep, with weights given by steel and aluminium production, respectively. Policy-induced effects are expressed as proportional deviations from the *Baseline* scenario at the country-year level and are available for 2030, 2040, and 2050. These deviations are extended to annual trajectories over 2015-2050 via piecewise linear interpolation, imposing a zero-deviation reference in 2015-2020. The resulting country-specific price shock profiles are introduced in FIDELIO as exogenous shifters of endogenous industrial production costs. For the same reasons as the electricity and energy price a dampening coefficient is imposed to smooth the effect of these price shocks on the CGE structure.

Appendix A.2.5. Investments in power generation technologies

Electricity sector investment signals are extracted from PyPSA-Eur at the country- and technology-specific level and harmonized with FIDELIO's baseline investments. In PyPSA-Eur, investments are reported on an annual basis for each power generation technology and are annualized taking into account the assets lifetimes and a discount rate. Reported investments include not only new capacity additions for the given year but also ongoing expenditures from previous years that have not yet reached the end of their economic lifetime (e.g., investments recorded in 2040 also account for unexpired investments made in 2030). Policy-induced investment effects are expressed as proportional deviations from the *Baseline* scenario following Eq. A.4.

$$\Delta I_{c,t}^{tech} = \frac{I_{c,t}^{\text{policy}} - I_{c,t}^{\text{base}}}{I_{c,t}^{\text{base}}} \tag{A.4}$$

where $I_{c,t}^{\text{policy}}$ and $I_{c,t}^{\text{base}}$ are the PyPSA-Eur investment values for country c, technology $tech$, and year t under the policy and Baseline scenarios, respectively. In cases where both *Baseline* and policy investments are zero, deviations are set to zero. If the policy scenario shows zero investment while a baseline investment exists, the deviation is set to -1 with a small offset to prevent negative scaling issues. Conversely, if the *Baseline* is zero but policy investments are positive, the deviation is computed relative to the mean baseline investment of the country to ensure consistency with national investment levels. These deviations are then applied to FIDELIO's baseline investments anchored in 2015. The resulting trajectories are extended to a full yearly time series over 2015-2050 using piecewise linear interpolation and capped to avoid negative or implausibly large values. Finally, the processed country- and technology-specific investment paths are implemented in FIDELIO as exogenous shocks, driving the evolution of power system capacity.

Appendix A.2.6. Investments in steel and aluminium production technologies

Investments in industrial assets are calculated following the same methodology as for the electricity sector, at the country- and technology-specific level. Annual investment values are computed from PyPSA-Eur outputs and reflect annualized capital costs, including investments from previous optimization years that have not yet been fully amortized. Policy-induced effects are expressed as proportional deviations from the *Baseline* scenario. Cases where both *Baseline* and policy investments are zero are set to zero; if only the policy scenario is zero, the deviation is slightly adjusted to avoid negative scaling; if only the *Baseline* is zero, deviations are calculated relative to the country's mean baseline investment. These deviations are applied to FIDELIO's 2015 baseline investments, extended over 2015-2050 using linear interpolation, and capped to avoid negative or implausibly large values. The resulting country- and industry-specific investment trajectories are incorporated into FIDELIO as exogenous shocks driving industrial capacity evolution.

Appendix A.2.7. Electrification shares across households

For each scenario, annual sectoral shares of electricity required to satisfy energy service demand in the passenger transport and household sectors are extracted and normalized, checking that the upper bound is 100%. Values for intermediate years are determined via linear interpolation between the available data points, ensuring a temporally smooth trajectory. The relative change of electrification under policy scenarios compared to the *Baseline* is computed for each country n, sector s, and year t as Eq. A.5.

$$\text{pct\_diff}_{n,s,t} = \frac{\text{share}^{\text{policy}}_{n,s,t} - \text{share}^{\text{baseline}}_{n,s,t}}{\text{share}^{\text{baseline}}_{n,s,t}} \tag{A.5}$$

where $\text{share}^{\text{policy}}_{n,s,t}$ is the electrification share under the policy scenario, $\text{share}^{\text{baseline}}_{n,s,t}$ is the electrification share under the baseline scenario, and $\text{pct\_diff}_{n,s,t}$ represents the relative difference in electrification share between the policy and baseline scenarios. Missing or negative values set to zero for consistency.

Appendix A.3. Variables from FIDELIO to PyPSA-Eur

Economic feedbacks generated by the CGE model FIDELIO are transferred to PyPSA-Eur through a systematic comparison of policy and *Baseline* simulation outputs. The analysis focuses on sectoral output and household consumption variables evaluated at the optimized years in PyPSA-Eur, which are 2030, 2040, and 2050. At the sectoral level, production quantities are aggregated across detailed sectors belonging to a given macro-sector (industry, agriculture, shipping, aviation, and services) for each country n and year t. For a generic sector s, the relative policy-induced variation with respect to the baseline is computed as in Eq. A.6.

$$\Delta_{n,s,t} = \frac{Q^{\text{Policy}}_{n,s,t} - Q^{\text{Baseline}}_{n,s,t}}{Q^{\text{Baseline}}_{n,s,t}} \tag{A.6}$$

where $Q^{\text{Baseline}}_{n,s,t}$ and $Q^{\text{Policy}}_{n,s,t}$ denote total sectoral output in the *Baseline* and policy scenarios, respectively. Relative changes below a small threshold are set to zero to avoid the propagation of numerical noise. Household consumption effects are derived using a two-step procedure based on COICOP categories. First, total household consumption expenditure is reconstructed for each country and year by combining household purchasing power, an exogenous consumption bridge, and endogenous consumption shares. Household consumption in COICOP category c is computed in Eq. A.7.

$$H_{n,c,t} = B_{n,t} \cdot PP_{n,t} \cdot \sigma_{n,c,t} \tag{A.7}$$

where $PP_{n,t}$ denotes household purchasing power, $B_{n,t}$ is an exogenous scaling bridge, and $\sigma_{n,c,t}$ is the consumption share associated with COICOP category c. Policy-induced variations in household consumption are then computed analogously to the sectoral case. In addition to individual COICOP categories, transport-related consumption effects are obtained by aggregating COICOP categories associated with passenger transport services prior to computing relative changes. The resulting country- and year-specific relative change signals are exported as exogenous shocks and fed back into PyPSA-Eur, where they modify sectoral demand levels and household consumption patterns in subsequent energy system optimization runs.

Appendix A.4. Convergence algorithm

In each scenario, the modelling framework follows an iterative coupling between PyPSA-Eur and FIDELIO, as displayed in Figure 1, in order to ensure that the results of the two models are aligned.

Before initiating the integrated modelling process, FIDELIO is first executed independently (without inputs from PyPSA-Eur) to generate a set of parameters required for the *Baseline* scenario. These include electricity demand shares prior to the PyPSA-Eur optimisation, steel production levels, and historical input-output values for the year 2015, which serve as reference points for subsequent analyses. In the first step, PyPSA-Eur is run to produce detailed representations of the energy system, which then serve as inputs to FIDELIO. FIDELIO subsequently simulates the macroeconomic adjustments and generates updated demand for selected service sectors, which are fed back into PyPSA-Eur as shocks to corresponding energy services. This iterative exchange continues until both models converge on a consistent solution. This method is applied for all the three scenarios evaluated.

To evaluate if the coupled models reach a stable equilibrium, convergence between consecutive iterations is assessed using a Gauss-Seidel method, as commonly applied in similar soft-coupling frameworks (66). At iteration k, the convergence criterion ζ_k quantifies the relative variation in the exchanged demand vectors between two successive iterations, aggregated over all years $y \in (2030, 2040, 2050)$.

Each demand vector $D_{y,i}$ represents the European-level aggregation of variables exchanged from FIDELIO to PyPSA-Eur (industry, steel, agriculture, water transport, air transport, and services output, and household consumption data for *COICOP4* and *COICOP8-10*), for a given year $y \in (2030, 2040, 2050)$.

The adjusted demand vector $D'_{y,k}$ is computed as a weighted sum of all previous demand vectors $D_{y,i}$ up to iteration k, following the recursive formulation in Eq. A.8:

$$D'_{y,k} = \frac{2}{(k+2)(k+3)} \cdot \sum_{i=0}^{k} (i+1) \cdot D_{y,i} \tag{A.8}$$

where i denotes the iteration index. This weighting scheme progressively smooths the convergence trajectory by assigning greater weight to more recent iterations. This process is repeated also to get $D'_{y,k-1}$, stopping at the previous iteration $k-1$

The convergence criterion ζ_k quantifies the relative change between consecutive iterations of the coupled model. It is defined as the ratio of the Euclidean distance between the two most recent adjusted demand vectors, $D'_{y,k}$ and $D'_{y,k-1}$, to the Euclidean norm of the latest demand vector $D'_{y,k}$, as in Eq. A.9

$$\zeta_k = \frac{\sqrt{\sum_y \left(D'_{y,k} - D'_{y,k-1}\right)^2}}{\sqrt{\sum_y \left(D'_{y,k}\right)^2}} \tag{A.9}$$

A small value of ζ_k indicates limited variation between iterations, suggesting that the coupled system has approached a steady-state equilibrium (we assume 1% as the threshold to be reached).

Appendix B. Modelling emission/performance standards from European policies

Appendix B.1. Passenger cars and vans

PyPSA-Eur requires, as an input, the distribution of Electric Vehicles (EVs), fuel cell electric vehicles (FCEVs), and internal combustion engine (ICE) cars within the total vehicle fleet for each investment year. In this study, we determine the share of EVs based on observed technological trends and current policy provisions, assuming no deployment of FCEVs for land-based passenger transport. Fuel cell vehicles are excluded due to their limited cost-competitiveness and low energy conversion efficiencies, which result in a financially unsustainable total cost of ownership (67). EU Commission sets target for new registered cars, thus we need to translate these into fleet-wide average emission factors and subsequently into the projected EV share. As of 2021, the average emission factor of the EU vehicle fleet was 173.95 gCO_2/km, based on calculation from JRC-IDEES data (68). The European car market replaces approximately 11.37 million vehicles per year out of a total fleet of 291 million (2019) (69), corresponding to an annual turnover of 4%. Starting from a 2021 baseline emission factor for newly sold cars of $EF_{\text{newcars,2021}} = 95$ gCO_2/km (49), the emission factor of new cars in each subsequent year y is calculated as Eq. B.1.

$$EF_{\text{newcars},y} = EF_{\text{newcars,2021}} \cdot (1 - r)^{(y-2021)} \tag{B.1}$$

where r represents the annual reduction rate. In the *Baseline* scenario, the annual emission factor reduction rate r is set to 1.6%, corresponding to the historical average for light-duty vehicles (70). Under the FF55 policy framework, the EU targets emission factors of 49.5 g CO_2/km for new passenger cars and 90.6 g CO_2/km for new vans by 2030, the latter accounting for approximately 11% of the light-duty vehicle (LDV) fleet (71). From 2035 onward, new internal combustion engine (ICE) vehicle sales are to be fully phased out, with a target of 0 g CO_2/km for new vehicles (72). The average emission factor of the entire fleet in a given year Y_{end} is then obtained recursively as Eq. B.2.

$$EF_{\text{allcars},Y_{\text{end}}} = \sum_{y=Y_{\text{start}}}^{Y_{\text{end}}} [s_{\text{new}} \cdot EF_{\text{newcars},y}] + (1 - s_{\text{new}})^{(Y_{\text{end}} - Y_{\text{start}})} \cdot EF_{\text{allcars},Y_{\text{start}}} \tag{B.2}$$

where $s_{\text{new}} = 11.37/291 = 4\%$ denotes the annual share of newly sold vehicles. In this analysis, EF_{allcars} is computed for 2030, 2040, and 2050, using $Y_{\text{start}} = 2021$ and the corresponding Y_{end}.

The share of FCEVs is assumed to remain at 0%, as hydrogen-powered cars and vans are generally more expensive than EVs for passenger applications, and the development of hydrogen refueling infrastructure continues to lag behind that of electric charging networks (73; 74). The share of EVs in the total fleet is derived from the resulting fleet emission factor, assuming that EVs emit 0 gCO_2/km and that the initial share of EVs in 2021 was negligible (approximating 100% ICE LDV), as Eq. B.3:

$$EV_{\text{share}} \cdot 0 + (1 - EV_{\text{share}}) \cdot EF_{\text{allcars},2021} = EF_{\text{allcars},Y_{\text{end}}} \tag{B.3}$$

Solving for EV_{share} yields the implied share of electric vehicles consistent with the FF55 performance standards. The shares are depicted in panel a and b of Figure B.7. Currently, PyPSA-Eur represents only passenger land transport within its framework. To enhance the scope of the analysis, future extensions will incorporate additional transport sectors, such as maritime and aviation, to provide a more comprehensive assessment of the decarbonization pathways in the European mobility system.

Appendix B.2. Shipping sector

The FuelEU Maritime Regulation, part of the Fit-for-55 package, establishes a progressive reduction in the GHG intensity of fuels used in maritime transport, aiming for a 6% decrease by 2030, 38% by 2040, and 80% by 2050, relative to the 2020 fleet-wide average GHG intensity of 91.16 gCO_2eq/MJ (**?**). To achieve these targets, alternative fuels such as ammonia and methanol, both included in PyPSA-Eur, are expected to play a crucial role in decarbonising the maritime sector. Ammonia is a hydrogen-based fuel with a zero direct emission factor (0 gCO_2eq/MJ), whereas methanol has an emission intensity of 68.9 gCO_2eq/MJ). Given the lower thermal efficiency of methanol in internal combustion engines compared to oil, an efficiency value of 36% is assumed (75). In the absence of policy intervention, the maritime sector is assumed to remain fully reliant on oil-based fuels. Under the FuelEU Maritime regulatory framework, however, the model must identify the optimal fuel mix among ammonia, methanol, and oil that satisfies the required GHG intensity constraints.

For 2030, this regulation overlaps with the International Maritime Organization (IMO) strategy on reducing GHG emissions from ships, which mandates that at least 5% of the energy used in international shipping come from zero-emission fuels (76). Accordingly, we assume that 5% of the maritime energy demand in the EU is supplied by ammonia. The remaining shares of methanol and oil are computed using Eq. B.4.

$$MeOH_{share} \cdot GHG_{MeOH} + NH_3share \cdot GHG_{NH_3} + (1 - NH_3share - MeOH_{share}) \cdot GHG_{Oil} = GHG_{target} \tag{B.4}$$

where GHG_{MeOH}=68.9 gCO_2eq/MJ, GHG_{NH_3}=0 gCO_2eq/MJ, GHG_{Oil}=91.16 gCO_2eq/MJ, $GHG_{target,2030}$=85.69 gCO_2eq/MJ and NH_3share=5%. Solving Equation B.4 yields a methanol share of 4.14% for 2030. By 2050, oil is assumed to be completely phased out from maritime fuel use, requiring an average GHG intensity of 18.23 gCO_2eq/MJ. Solving the same balance equation without the oil component results in a composition of 73.5% ammonia and 26.5% methanol. For 2040, we assume a linear increase in the methanol share of approximately 1.1% per year, leading to a 15.3% methanol share. To meet the 2040 target intensity of 56.5 gCO_2eq/MJ, the corresponding share of ammonia is 34.3%, with the remainder supplied by oil. Extending the same linear trend to 2050 implies a 26.3% methanol share; assuming conservatively that 25% of demand is still met by oil in 2050, the remaining 48.7% is supplied by ammonia. Results in terms of energy are shown in Figure B.7, panel c.

Appendix B.3. Aviation sector

PyPSA-Eur receives as input the shares of various fuels in a sector's energy consumption, enabling a straightforward application of policy measures. The model incorporates the use of synthetic fuels (synfuels) produced from CO_2 and hydrogen, initially synthesizing methanol and subsequently converting it into kerosene. Additionally, for Sustainable Aviation Fuels (SAF), PyPSA-Eur considers biofuels derived from sustainably sourced biomass. Under the ReFuel Aviation policy (77), a specific proportion of the SAF share is mandated to come from synfuels, while the remainder consists of biofuels. The model assumes that the efficiency of a turbofan engine powered by synfuels is equivalent to that of a kerosene-based engine, given that the chemical composition remains unchanged. In contrast, for biomass-fuelled engines, Akdeniz et al. (78) estimate an 18.18% increase in thermal efficiency compared to the conventional thermal efficiency of 50.084% (79). The projected shares are depicted in Figure B.7, panel d.

Appendix C. Additional results

Appendix C.1. Consistency of model outcomes with Fit-for-55 directives

This section presents an assessment of model outcomes for the *EU ClimPol* scenario against EU 2030 energy policy targets that could not be directly implemented as model constraints. These include the revised Energy Efficiency Directive, the revised Energy Performance of Buildings Directive, and the revised Renewable Energy Directive. Since PyPSA-Eur treats energy service demands as exogenous inputs, simply reducing demand levels would not reveal the system-level challenges associated with achieving these targets. Similarly, for renewable energy shares, imposing them as constraints would not capture the difficulty or trade-offs the system faces in meeting such objectives.

First, total EU final energy consumption in 2030 reaches approximately 13000 TWh, corresponding to about 1116 Mtoe, which is around 9% above the reference value associated with the revised Energy Efficiency Directive

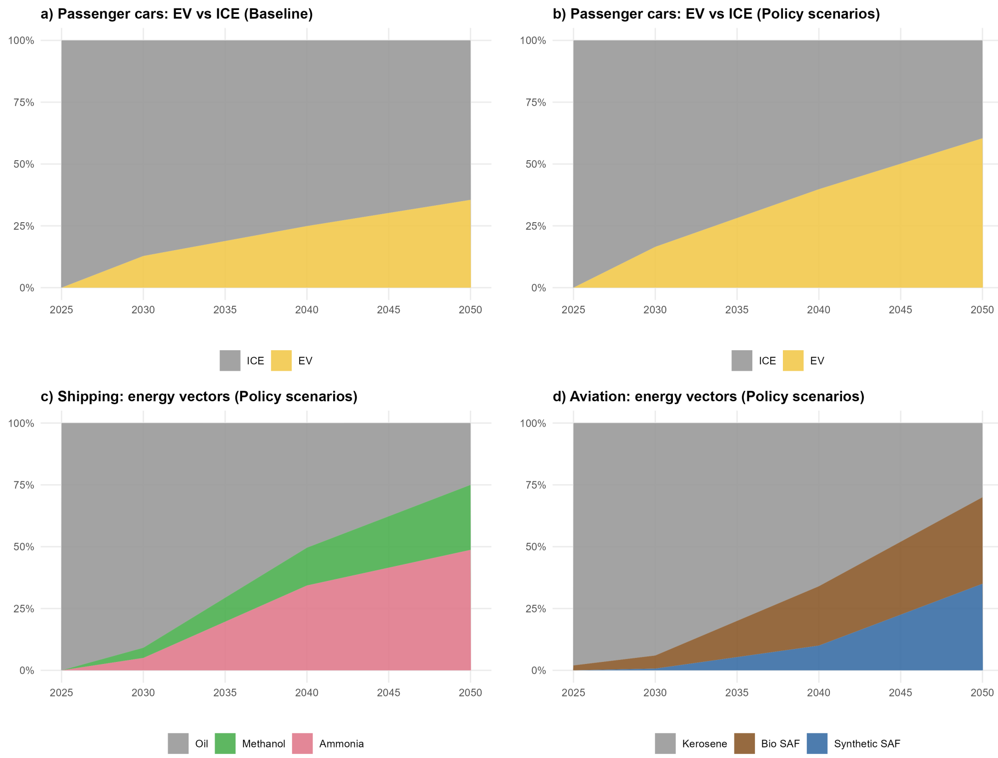

Figure B.7: Assumed evolution of transport technology and energy carrier shares under *Baseline* and policy scenarios. (a) Passenger car drivetrain shares in the *Baseline* scenario. (b) Passenger car drivetrain shares under policy scenarios. (c) Shipping energy carrier shares under policy scenarios. (d) Aviation energy carrier shares under policy scenarios.

target (1023 Mtoe). This indicates that, while the transition substantially reshapes the energy system, the simulated pathways do not fully achieve the required reduction in aggregate final energy consumption by 2030, suggesting either remaining demand rigidities or conservative assumptions on efficiency improvements in end-use sectors.

Second, the results show a markedly stronger performance for the buildings sector. Final energy use in residential and services buildings decreases by more than 23% relative to the 2020 reference level set by the directive, exceeding the revised Energy Performance of Buildings Directive target of a 16% reduction by 2030. This outcome reflects the strong penetration of electrification in buildings heating and indicates that the modelled transition is consistent with near-term policy ambitions in this sector.

Third, renewable electricity generation amounts to roughly 4160 TWh in 2030, corresponding to only about 32% of total final energy consumption, well below the RED target range of 42.5-45%. Even under a sensitivity case in which nuclear electricity is counted as renewable, the share rises only to around 37%, still short of the target. This gap is noteworthy when placed in context: in 2024, renewables accounted for approximately 25.4% of total final energy consumption (80), implying that while the modelled scenarios deliver a substantial increase relative to current levels, they fall short of the acceleration required to meet the revised RED targets by 2030. Importantly, nuclear energy is not considered renewable under EU legislation, and its inclusion here serves only as an illustrative upper bound, reinforcing the conclusion that achieving the 2030 renewable share target would require faster deployment of renewables beyond the power sector. Overall, these results suggest that the modelled transition is broadly aligned with sector-specific efficiency objectives, particularly in buildings, but that additional policy effort or more ambitious assumptions would be required to simultaneously meet economy-wide energy efficiency and renewable share targets by 2030.

Appendix C.2. Bilateral trade results

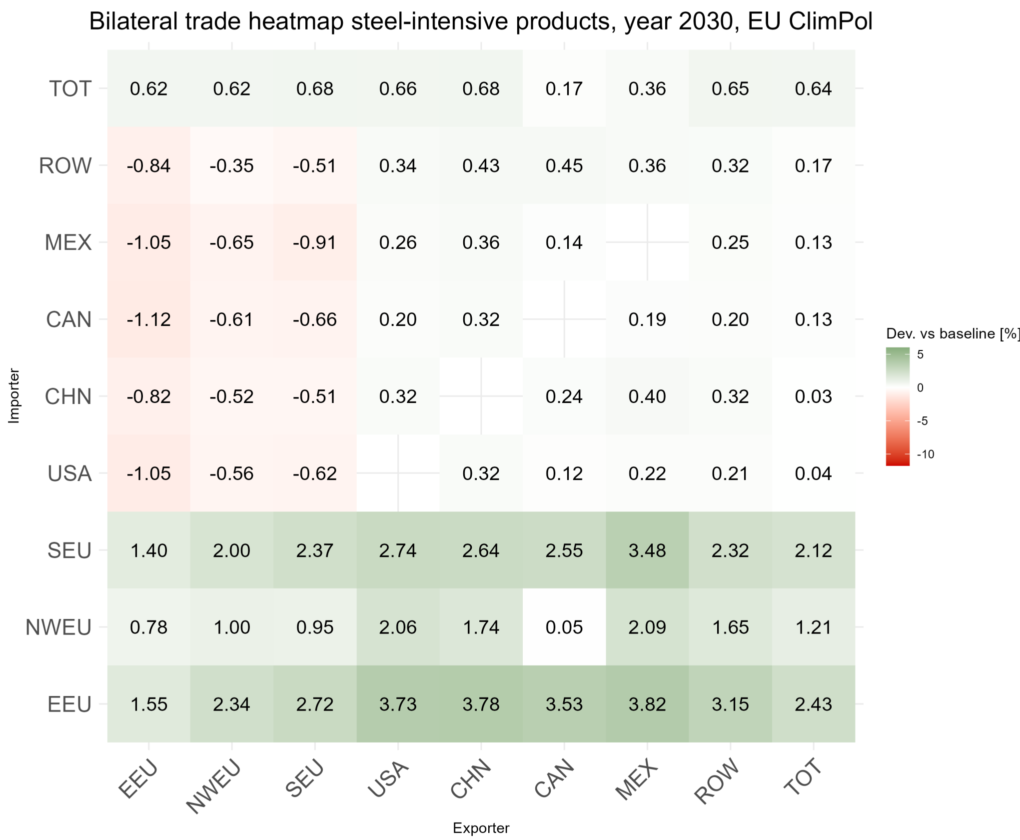

Figure C.8: Bilateral trade deviations for steel-intensive products under EU climate policy (*EU ClimPol*), for year 2030, averaged over 2026-2030. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

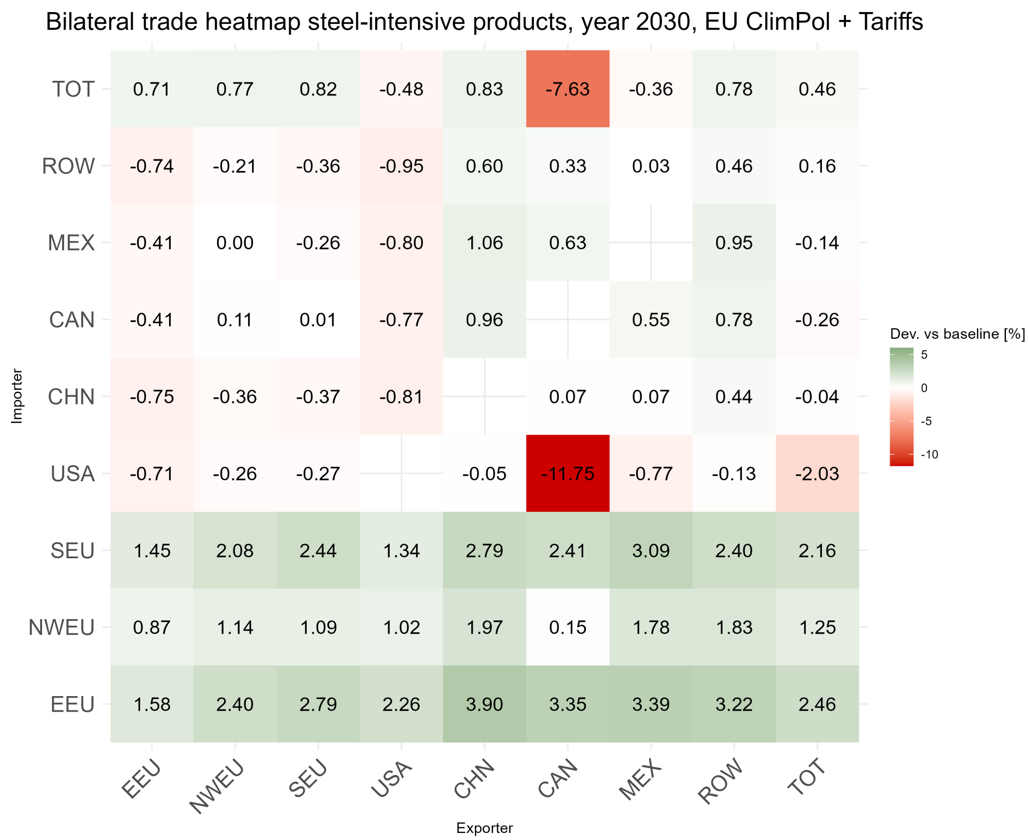

Figure C.9: Bilateral trade deviations for steel-intensive products under EU climate policy and USA tariffs on steel implementation (*EU ClimPol + Tariffs*), for year 2030, averaged over 2026-2030. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

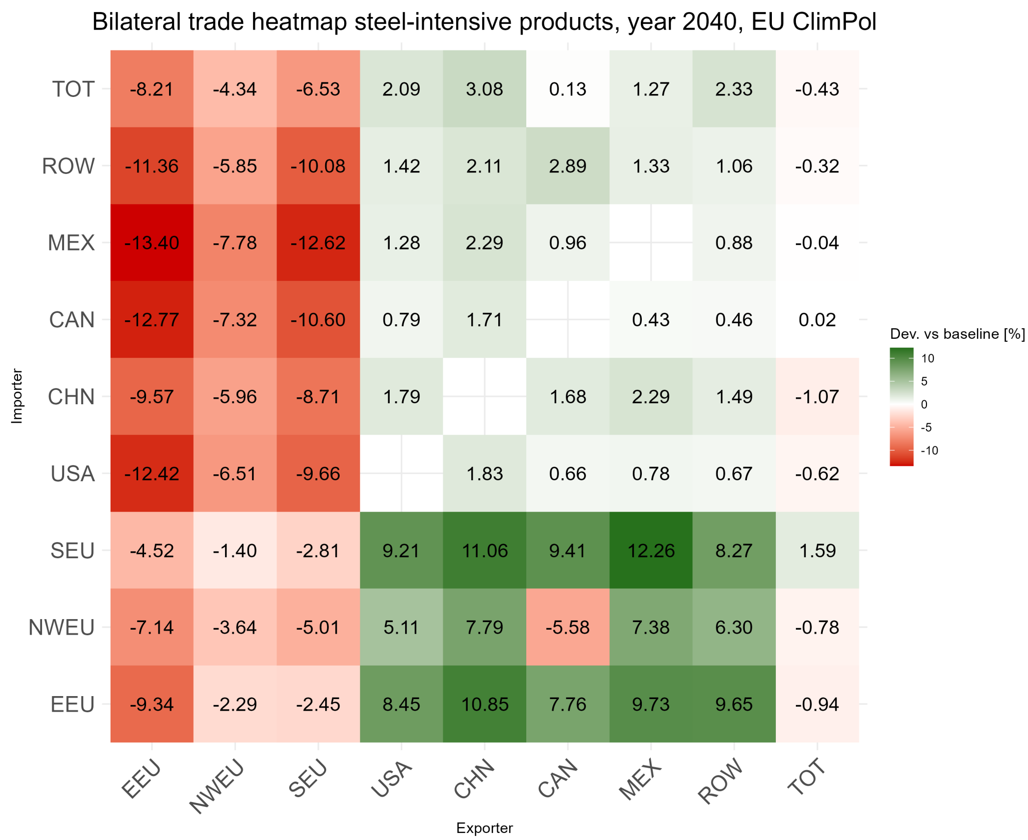

Figure C.10: Bilateral trade deviations for steel-intensive products under EU climate policy (*EU ClimPol*), for year 2040, averaged over 2036-2040. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

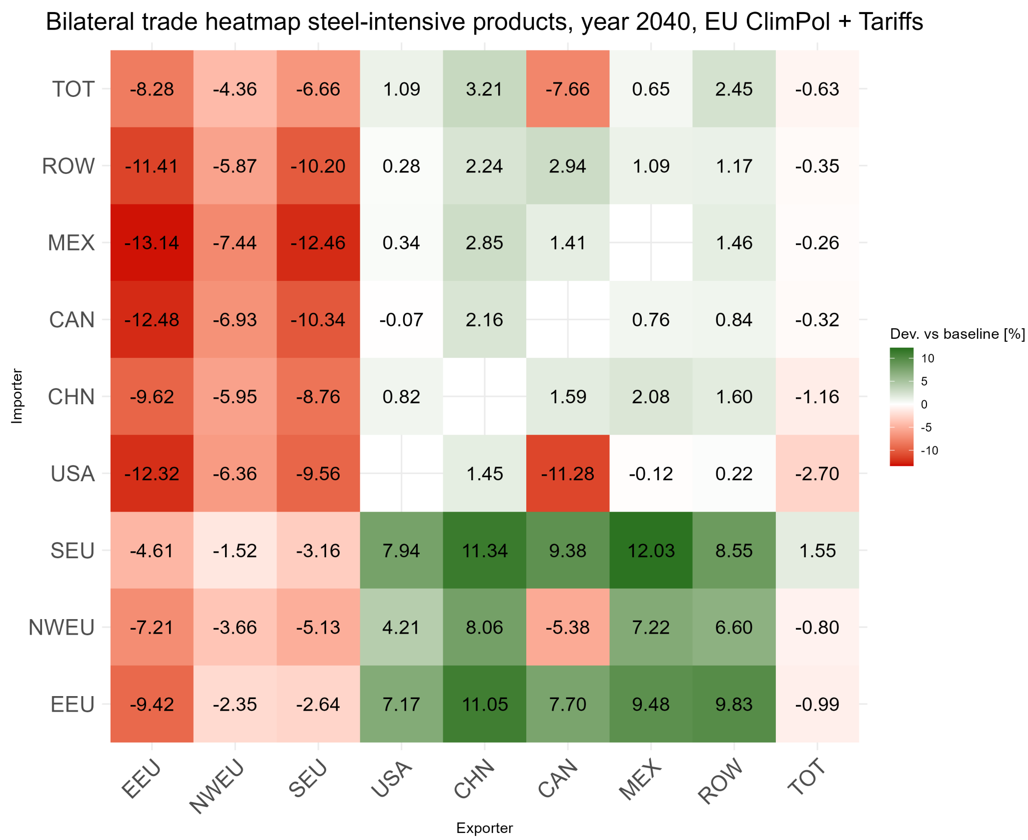

Figure C.11: Bilateral trade deviations for steel-intensive products under EU climate policy and USA tariffs on steel implementation (*EU ClimPol + Tariffs*), for year 2040, averaged over 2036-2040. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

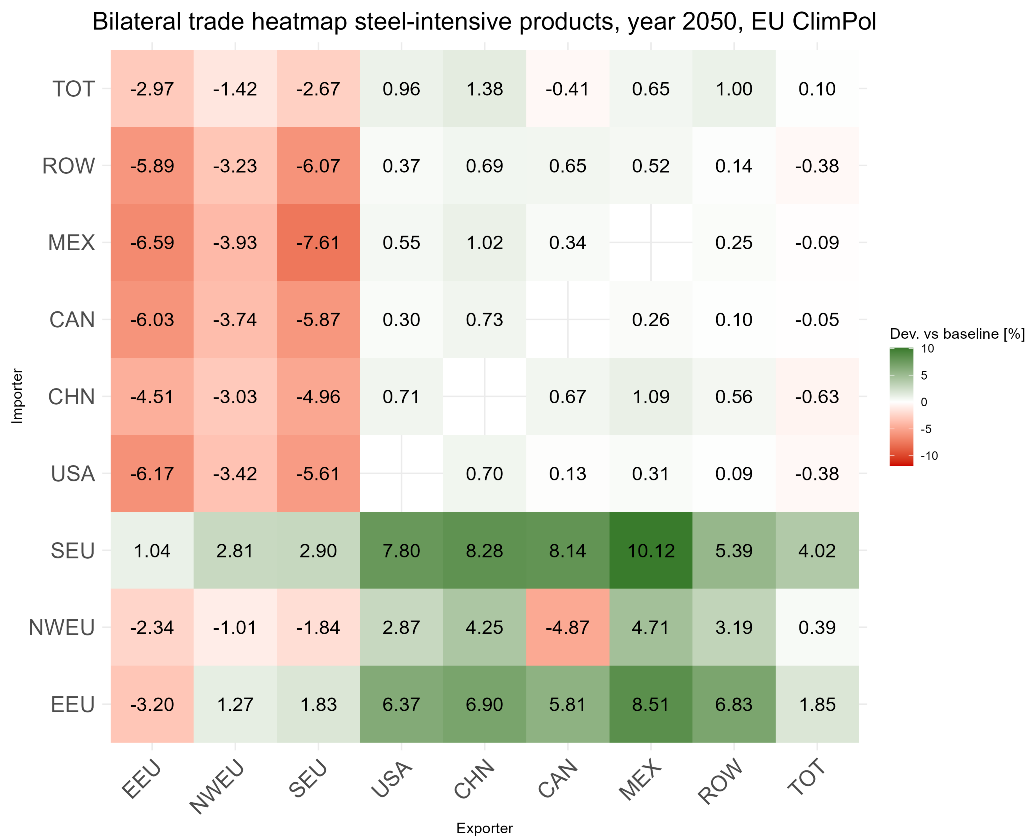

Figure C.12: Bilateral trade deviations for steel-intensive products under EU climate policy (*EU ClimPol*), for year 2050, averaged over 2046-2050. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

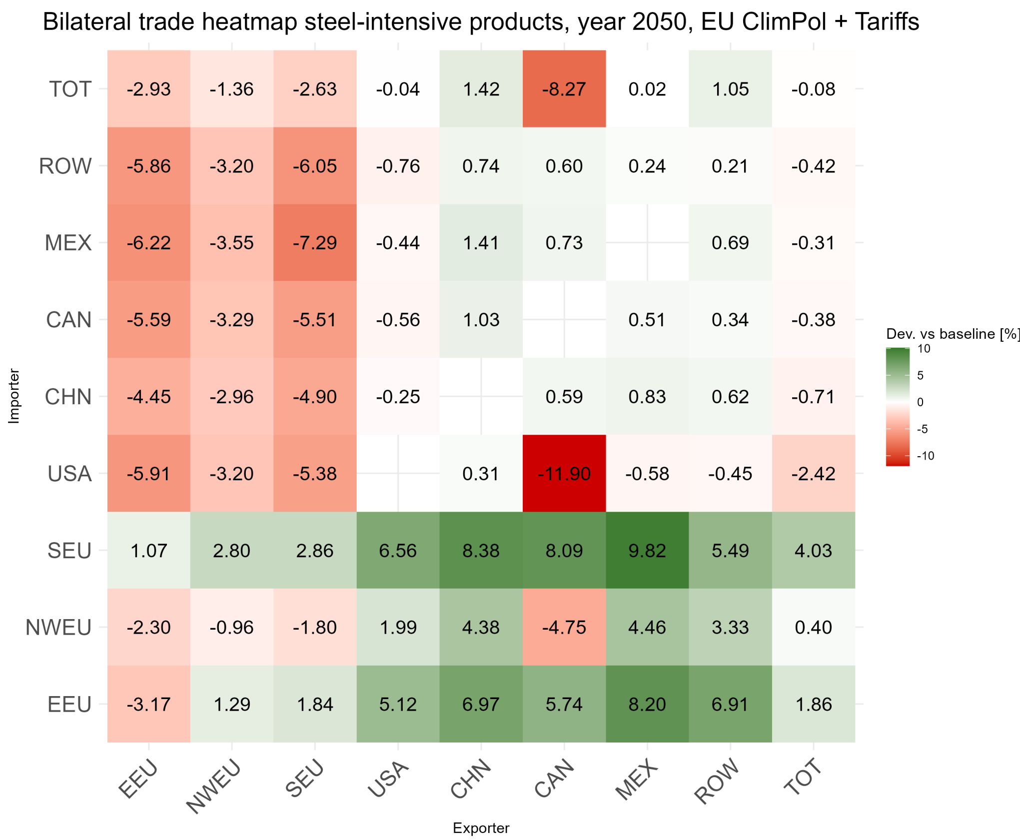

Figure C.13: Bilateral trade deviations for steel-intensive products under EU climate policy and USA tariffs on steel implementation (*EU ClimPol + Tariffs*), for year 2050, averaged over 2046-2050. The heatmap reports percentage deviations in bilateral trade flows relative to the *Baseline* for aggregated regions (EEU, NWEU, SEU, USA, CHN, CAN, MEX, ROW), including intra-EU macro-regional trade. Rows indicate importers and columns exporters; the final row and column ("TOT") show total imports and exports by region.

Appendix C.3. Further trade results

Figure C.14: Variation in total exports of products from all sectors by macro-region relative to the *Baseline*, for *EU ClimPol* and *EU ClimPol + Tariffs*. Values are computed as 5-year averages and exclude intra-EU macro-regional trade flows. The steel-intensive sectors sectors includes primary steel production, fabricated metal products, machinery and equipment, electrical equipment), and motor vehicles and transport equipment

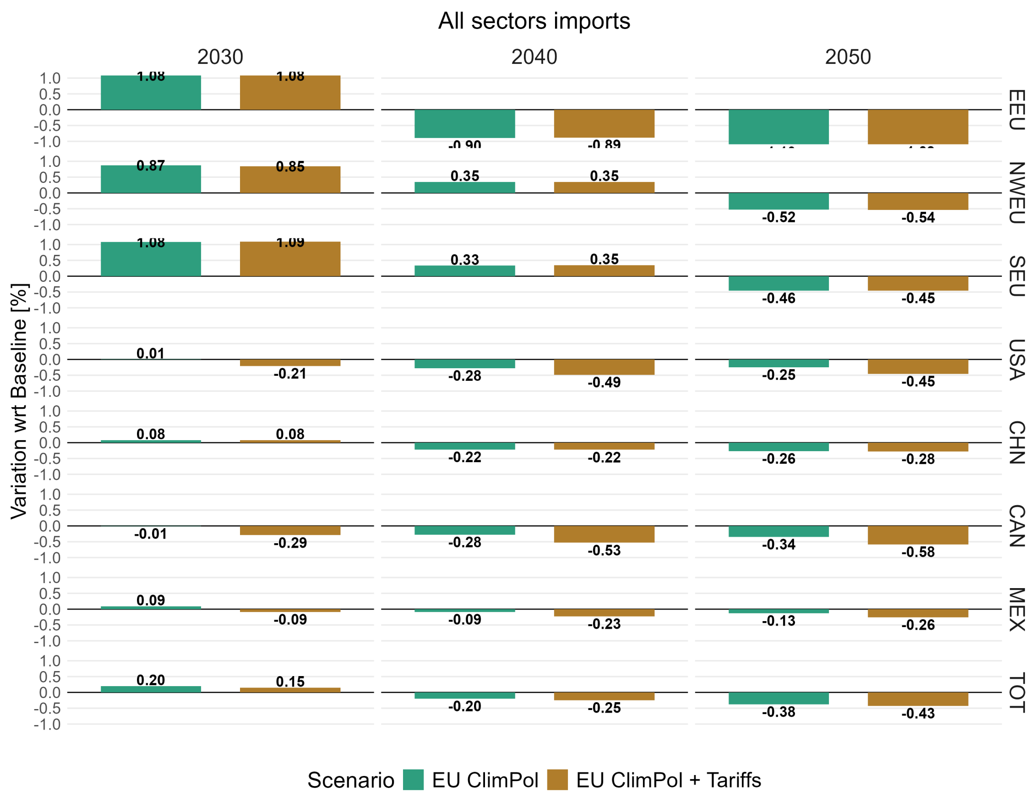

Figure C.15: Variation in total imports of products from all sectors by macro-region relative to the *Baseline*, for *EU ClimPol* and *EU ClimPol + Tariffs*. Values are computed as 5-year averages and exclude intra-EU macro-regional trade flows. The steel-intensive sectors sectors includes primary steel production, fabricated metal products, machinery and equipment, electrical equipment), and motor vehicles and transport equipment

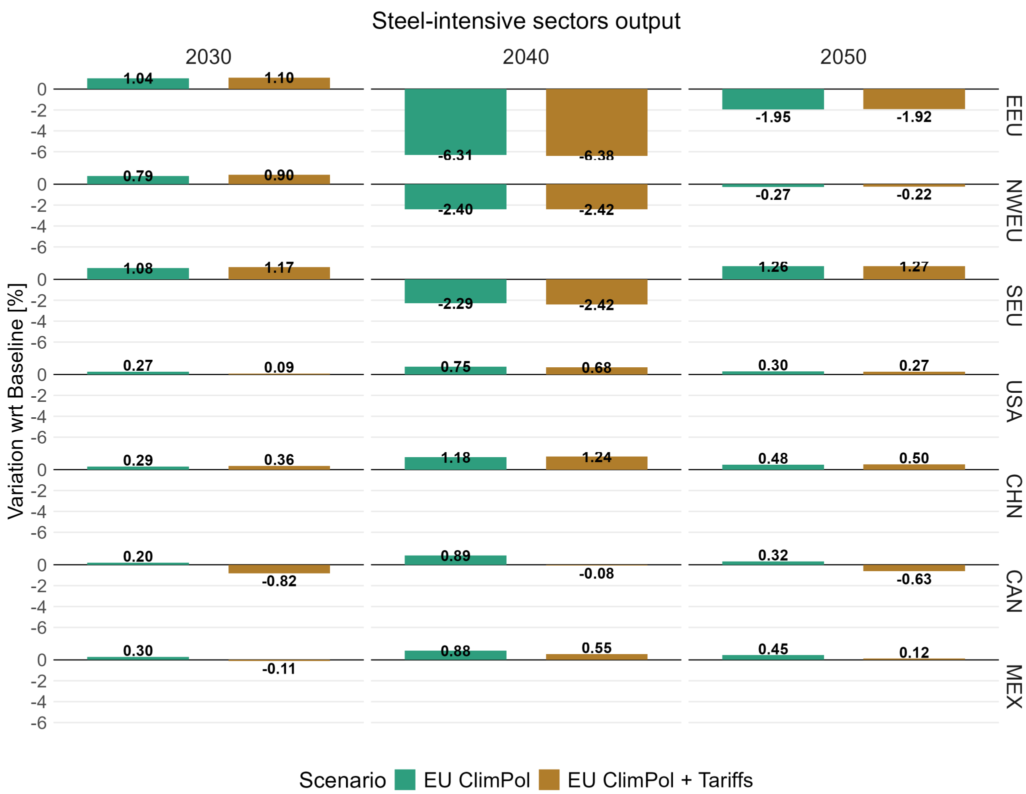

Figure C.16: Percentage deviations in output of steel-intensive products relative to the *Baseline* under the *EU ClimPol + Tariffs* scenario in 2050 (five-year average over 2046-2050).

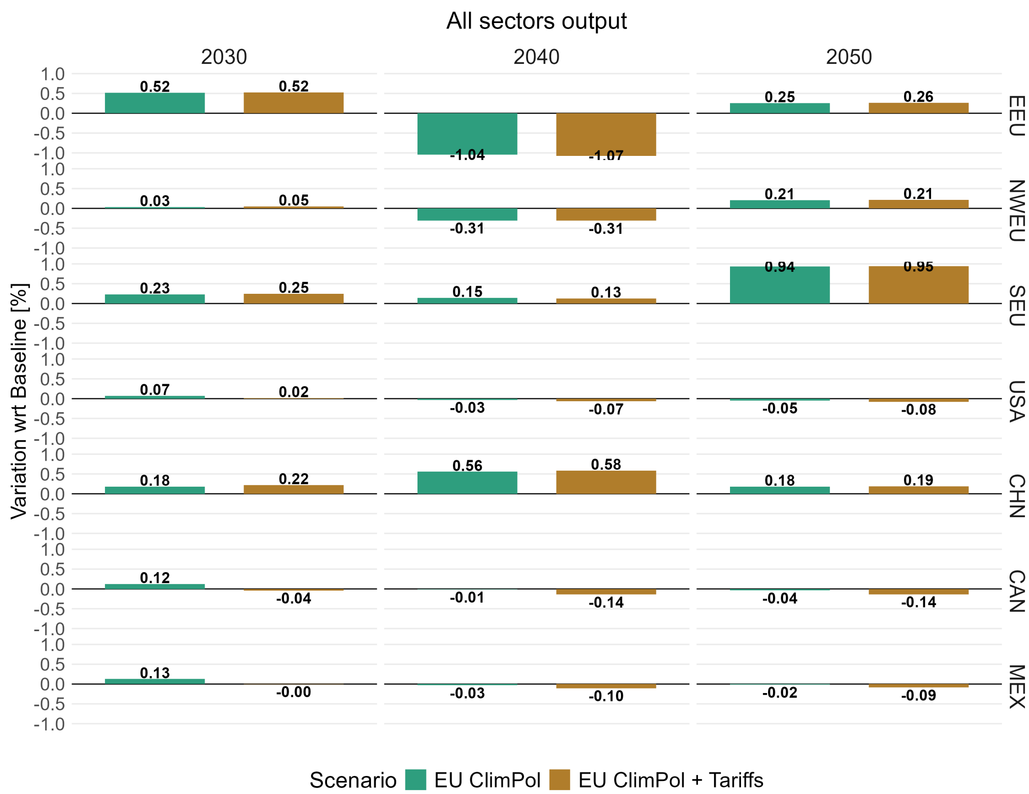

Figure C.17: Percentage deviations in total output of all products relative to the *Baseline* under the *EU ClimPol + Tariffs* scenario in 2050 (five-year average over 2046-2050).

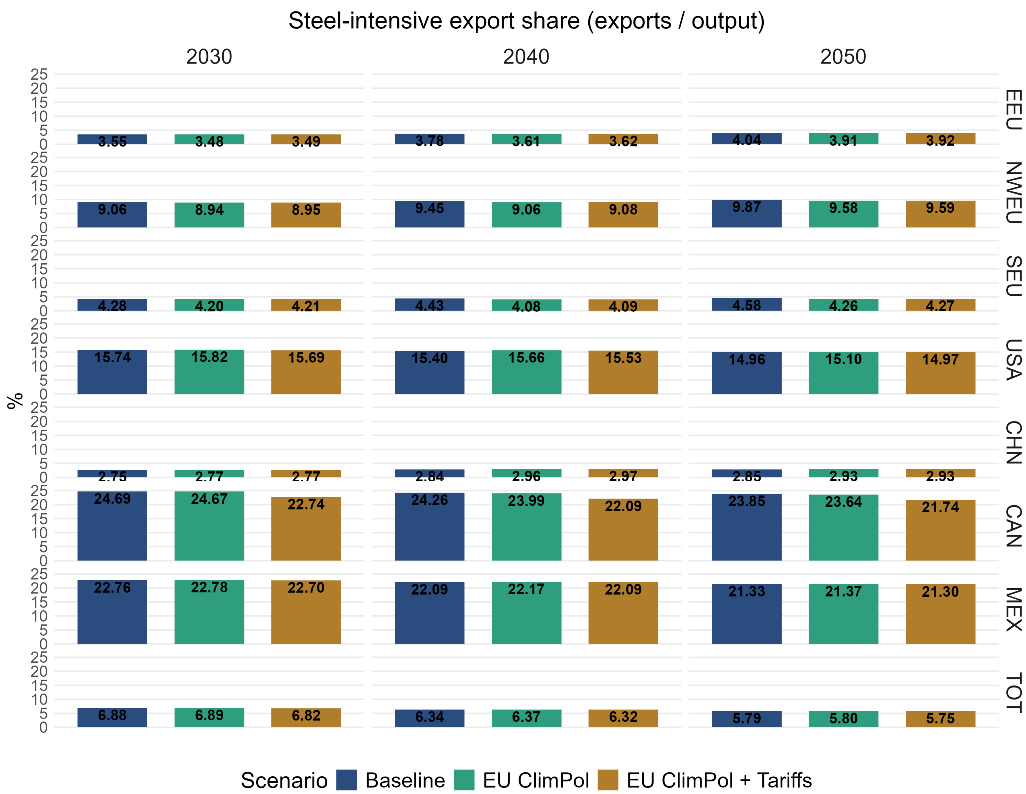

Figure C.18: Share of steel-intensive exports in total steel-intensive industry output, indicating export dependency by macroregion. Results are shown for the *Baseline*, *EU ClimPol*, and *EU ClimPol + Tariffs* scenarios for 2030, 2040, and 2050 (five-year averages).

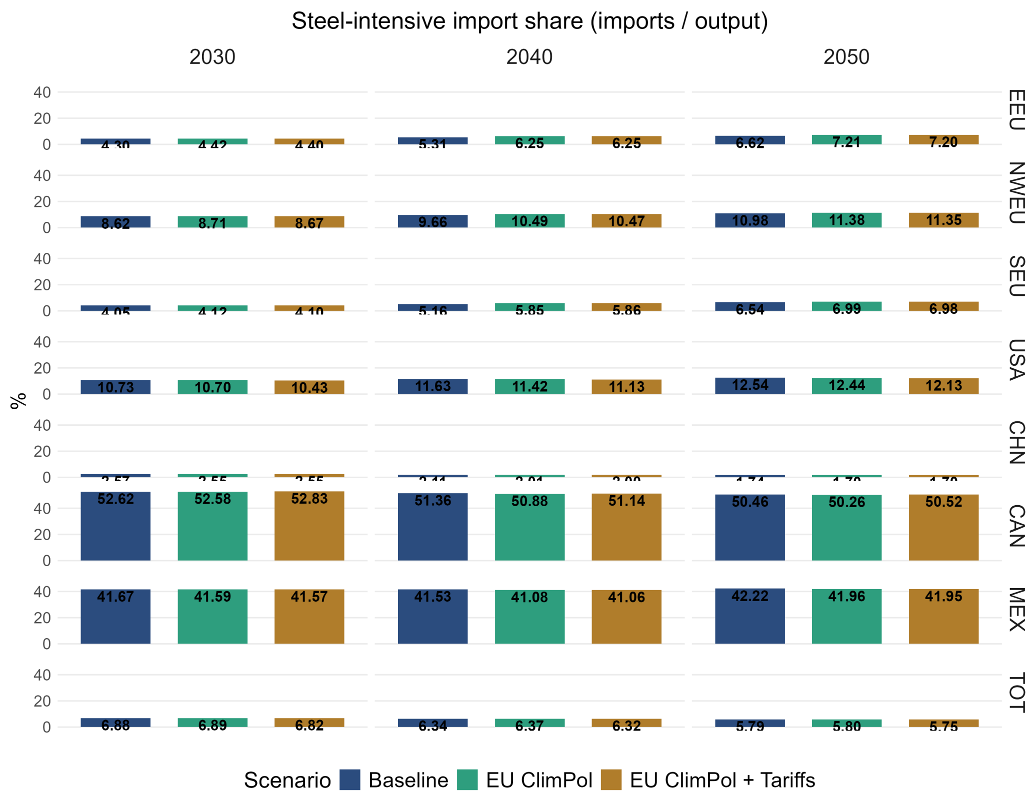

Figure C.19: Share of steel-intensive imports in total steel-intensive industry output, indicating import dependency by macroregion. Results are shown for the *Baseline*, *EU ClimPol*, and *EU ClimPol + Tariffs* scenarios for 2030, 2040, and 2050 (five-year averages).