IAM COMPACT

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

D4.6 – National, regional, global mitigation pathways – Update

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

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Responsible Author	Alaa Al Khourdajie	**Email**	a.alkhourdajie@imperial.ac.uk		
	Imperial	**Phone**	N/A		
Contributors	Adam Hawkes [Imperial]; Shivika Mittal [CICERO]; Alexandros Nikas, Natasha Frilingou [NTUA]; Russell Horowitz, Dirk-Jan Van de Ven [BC3]; Ryna Yiyun Cui, Alicia Zhao [UMD]; Amit Garg, Jyoti R. Maheshwari, Saritha Sudharmma Vishwanathan [IIMA]; Yu Wang, Tianpeng Wang [THU]; Panagiotis Fragkos, Eleftheria Zisarou [E3M]				
Reviewer(s)	Francesco Gardumi [KTH], Ioannis Tsipouridis [TUM], Shivika Mittal [CICERO]				
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EC Summary Requirements

1. Changes with respect to the DoA

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

2. Dissemination and uptake

This report is being used internally by all consortium partners as a benchmark for outstanding mitigation modelling work in the project. It develops a set of stakeholder-driven global, regional, and national mitigation pathways and updates the implementation of IAM COMPACT's "Broad Scenario Logic", as described in detail in Deliverable D4.4. The report will be shared with stakeholders outside the consortium in the form of policy briefs, planned for dissemination in June 2025, to discuss how the credibility of results can be improved. It will also be presented during our final event, which will take place at the end of the project in Athens, Greece.

3. Short summary of results (<250 words)

This report is an update to Deliverable D4.6, building upon earlier work to address the new stakeholder-driven research questions that emerged during the co-creation process of the 2nd cycle of the Policy Response Mechanism (PRM2). Specifically, we introduce Study 8, which examines how global trade dynamics (in particular, for clean energy technologies) and policy frameworks may impact the EU's decarbonisation efforts and green technology transition in a world of increasing trade and economic tensions. Using a combination of materials modelling (MARIO) and integrated assessment models (GCAM, TIAM, PROMETHEUS), the study investigates the implications of restricted trade between major economies and explores alternative partnerships for green technology supply chains, with a focus on electric vehicles (EVs). We find that disruptions to EV supply chains significantly affect decarbonisation pathways. Results show that domestic battery production increases EV prices by 12.7% with emissions penalties of 4.5-10.9% by 2050, while alternative partnerships offer varying trade-offs, with Brazil emerging as most favourable with minimal price increases and substantial carbon reductions. All scenarios demonstrate decreased electrification, compensated differently across models: GCAM and PROMETHEUS project increased hydrogen use while TIAM shows greater reliance on conventional fuels. Despite methodological differences, all models consistently identify Brazil as the optimal alternative partner and EU domestic production as least favourable, highlighting how the EU's climate objectives are substantially influenced by global supply chain configurations and strategic trade partnerships.

In addition to Study 8, this deliverable continues to build on the extensive work conducted with stakeholders in the USA, India, and China.

4. Evidence of accomplishment

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Preface

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

NTUA – National Technical University of Athens	EL
Aalto – Aalto Korkeakoulusaatio SR	FI
AAU – Aalborg Universitet	DK
BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES
Bruegel – Bruegel AISBL	BE
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CICERO – Cicero Senter for Klimaforskning Stiftelse	NO
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KTH – Kungliga Tekniska Hoegskolan	SE
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TUM – Technical University of Mombasa	KE
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Executive Summary

The previous version of this deliverable established the IAM COMPACT model ensemble's flexibility in addressing urgent policy needs, including quick insights into Europe's energy supply crisis. It outlined the project's multi-step policy response mechanism (PRM) that co-defines relevant policy questions with EC and national policymakers, groups these questions into Studies, co-designs scenario frameworks, and conducts modelling analyses. The first cycle of this mechanism (PRM1) documented a baseline considering current mitigation efforts, updated policies, NDCs for 2030, and new long-term strategies. It also included mitigation scenarios for major emitting nations (India, China, USA), which were co-created with stakeholders.

This update (PRM2) builds upon the previous work by addressing new stakeholder-driven research questions that emerged during the co-creation process. Specifically, we introduce Study 8, which examines how global trade dynamics (in particular for clean energy technologies) and policy frameworks impact the EU's decarbonisation efforts and green technology transition in a scenario of increased trade and economic tensions. Using a combination of materials modelling (MARIO) and integrated assessment models (GCAM, TIAM, PROMETHEUS), this study investigates the implications of restricted trade between major economies and explores alternative partnerships for green technology supply chains, with a focus on electric vehicles (EVs). The study shows that disruptions to EV supply chains significantly affect decarbonisation pathways. Findings show that domestic battery production increases EV prices by 12.7% with emissions penalties of 4.5-10.9% by 2050, while alternative partnerships offer varying trade-offs, with Brazil emerging as most favourable with minimal price increases and substantial carbon reductions. All scenarios demonstrate decreased electrification, compensated differently across models: GCAM and PROMETHEUS project increased hydrogen use while TIAM shows greater reliance on conventional fuels. Despite methodological differences, all models consistently identify Brazil as the optimal alternative partner and EU domestic production as least favourable, highlighting how the EU's climate objectives are substantially influenced by global supply chain configurations and strategic trade partnerships.

In addition to Study 8, this deliverable continues to build on the extensive work conducted with stakeholders in major emitting nations. Updates on mitigation pathways and policy frameworks include the following:

In the case of the US, the contribution presents comprehensive modelling of US emission pathways through 2050 using the state-disaggregated GCAM-USA-CGS integrated assessment model. The study explores four distinct policy scenarios, finding that Current Policies would achieve 48% emissions reductions by 2035 (relative to 2005), whilst an Enhanced Ambition scenario could achieve 65% reductions instead, while reaching net zero by 2050. The electricity and transport sectors contribute 41% and 27% of emissions reductions respectively, with additional significant contributions from methane mitigation (10%), buildings (7%), and industry (8%). Through extensive stakeholder engagement with over 214 participants representing 140 organisations, the analysis also evaluates the potential impacts of federal policy reversals and demonstrates how non-federal leadership could maintain momentum towards climate goals, with state-level ambition categorised into three tiers of policy implementation.

In the case of India, the contribution focuses on decarbonising India's building sector as a critical component of achieving the country's Net Zero 2070 target. A stakeholder workshop convened 65 participants including building sector experts, financial managers, and academics, to identify challenges and opportunities. The analysis shows that buildings account for 33% of India's total final energy consumption with projected growth of 8% per annum, whilst building and construction sectors contribute approximately one-third of national GHG emissions. Two scenarios are developed, Business as Usual (BAU) and Net Zero Scenario (NZS), both projecting from 2018 to 2050, with the latter emphasising increased adoption of super-efficient appliances in the residential sector. The research identifies significant policy gaps at both design and implementation levels and highlights the need for enhanced cross-sector collaboration to address the sector's rising energy demands

Finally, in the case of China, the study presents a dynamic modelling framework that links a global multi-regional input-output GMRIO table with the TIMES model China-MORE 2.0, and the CGE model IMACLIM-CHN to quantify how the EU's Carbon Border Adjustment Mechanism (CBAM) will affect China's iron, steel, aluminium, and related

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product exports (ISAP), taking into account China's pledge under its 2035 NDC. In this approach, by 2034 direct emissions embedded in ISAP shipments to the EU total 5.4 Mt CO_2, resulting in CBAM costs of €1,157 million. When indirect electricity use is included, those emissions rise to 7.4 Mt CO_2 and the cost climbs to €1,572 million, while full supply-chain emissions push the total emissions to 15.8 Mt CO_2 and costs to €3,378 million. More than 65% of these costs are borne by five provinces—Hebei, Jiangsu, Shanxi, Liaoning, and Zhejiang. An ambitious mitigation strategy toward 2035, particularly speeding the adoption of electric arc furnaces, could offset roughly 45% of the additional abatement costs through avoided CBAM costs.

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1. Second Policy Response Mechanism: Study 8 (Trade dynamics)

The Policy Response Mechanism (PRM) lies at the heart of IAM COMPACT's stakeholder engagement strategy, providing a structured forum in which project partners and stakeholders jointly frame policy questions, share knowledge, and build mutual trust, as well as provide direct inputs to IAM COMPACT and co-create the research process, incorporating political and societal realities into our modelling. Through continuous dialogue—most recently in June and July 2024, as the first cycle wrapped up and the second began—policy steering groups reviewed initial cycle findings, assessed their ongoing relevance, suggested refinements, and identified new lines of inquiry aligned with the European Commission's emerging priorities. This process confirmed that the questions posed at the outset of cycle 1 remained pertinent 18 months on.

Study 8 is part of the *Global Effects* theme[1], which considers trade and macroeconomic issues and their effects on European decarbonisation. During the first cycle, the theme included Study 3 on geopolitical shocks and supply-chain constraints[2], and Study 6 on the impact of uneven interest rates worldwide[3]. Meetings with DG Trade, the European Central Bank, and the National Bank of Belgium revealed a desire to deepen these analyses by exploring alternative trade-partner scenarios—both among major powers and between Europe and prospective markets—giving rise to the following research question:

How would different global trading configurations—both between leading economies and between Europe and emerging partners—affect Europe's pathway to net-zero?

The research question was then discussed internally by project partners, with the aim of translating it to a model-ready study that capture the core policy priorities communicated by the stakeholders—also in consideration of actual modelling capacity. The study was further developed in a co-creative fashion with the Core Working Groups in the workshop "*EU Decarbonisation in the Global Economy*[4]", which was held in November 2024, and included discussions around scenario building and policy framing.

1.1 Introduction

As global economies navigate the complexities of decarbonisation and green technology transitions, trade relationships and economic tensions have emerged as critical factors that can either accelerate or hinder climate progress. This study addresses specific research questions that emerged from stakeholder consultations in the IAM-COMPACT project regarding the resilience of EU policy frameworks, potential partnerships for green technology supply, and the sectoral impacts of trade restrictions.

The following research questions were identified by stakeholders in our Policy Steering Groups as priorities for investigation:

Stakeholders' Research Questions for modelling:

- 2.11 What are the implications of a global scenario with high tariffs between China and the USA? Are EU policy frameworks (such as CBAM) resilient to such a scenario?
- 3.2 What other countries are best suited to partnering with the EU on green technology? In other words, who else is suitable for supplying key green technologies? Suggested countries to explore are Latin American countries, India, and Indonesia. Are countries that are closer geographically more suitable partners?
- 3.4 What are the effects on Europe's decarbonisation of increasing trade tariffs depending on the sector?

[1] https://iam-compact.eu/listening/second-prm
[2] DOI 10.5281/zenodo.13840865
[3] DOI 10.5281/zenodo.12751959
[4] https://iam-compact.eu/news-events/core-working-group-workshop-eu-decarbonisation-global-economy

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In other words, are solar panels, EVs, or green steel more important from an emissions standpoint?

Due to modelling capabilities and constraints, these questions have been reformulated to better align with available tools and methodologies. Specifically, while the stakeholder questions covered multiple green technologies, our modelling focus has been narrowed to electric vehicles exclusively. From the suggested countries, our study selected two countries with different carbon intensities and geographical proximities. Indonesia was chosen as an Indo-Pacific strategic region, which is rich in resources and production capability of nickel, but also of high spatial distance, which helps us explore whether proximity is a relevant parameter. To explore hydrogen trade, Brazil was chosen as a representative Latin America region, with a cleaner electricity mix thanks to high hydropower penetration.

Revised research questions based on consultation with stakeholders:

RQ1: What are the implications of *restricted trade* between China, the USA, and the EU on the EU's decarbonisation efforts, particularly in the EV sector?

- How important is China's role in enabling the transition in the EU and the USA?
- How resilient are EU policies (such as CBAM) under such restricted trade scenarios?

(Maps to stakeholder questions: 2.11 and 3.4)

RQ2: Which countries are suitable *alternative partners* for the EU in supplying key green technologies, considering geographic proximity and trade efficiency?

- Specifically, what is the potential of countries like Brazil, and Indonesia in supplying green technologies to the EU?
- What are the impacts of shifting imports from China to these alternative partners on the EU's decarbonisation efforts?

(Maps to stakeholder questions: 3.2 and 3.4)

In addition, stakeholders identified several policy-oriented research questions that, whilst not directly amenable to modelling within our current framework, merit thorough consideration through literature review and discussion:

- 3.5 What is the effect of heterogeneous carbon prices around the world on carbon leakage from Europe and on global decarbonisation efforts? (Note: a World Bank study found that there is no major effect)
- 3.6 What other tools (excluding CBAM) can be used to incentivise low-carbon production of important goods and technologies?
- 3.8 How would the completion of the capital union change the perception of risk and facilitate investments?

These additional questions are addressed in the literature review and discussion sections of this deliverable, drawing upon existing literature rather than direct modelling exercises.

1.2 Literature review

The literature review addresses stakeholder questions that could not be directly answered through modelling but remain crucial for understanding the broader context of global trade and decarbonisation efforts. This review touches upon various aspects.

Variations in carbon pricing across major economies create uneven cost pressures on industries, raising concerns about carbon leakage (the shift of emissions-intensive production to regions with laxer climate policies). In jurisdictions with high carbon prices (e.g. the EU's Emissions Trading System), domestic firms may face competitive disadvantages, potentially losing market share to foreign competitors from low-price regions commonly with less strict environmental regulation, potentially shifting emissions and production abroad (Arroyo-Currás et al., 2015). This leakage undermines the environmental benefit of the original policy and poses

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competitiveness challenges. However, ex-post empirical evidence finds that historical carbon pricing schemes have so far caused little to no leakage in practice. For example, analysis of the EU ETS shows no significant carbon leakage to date (Verde, 2020), likely because carbon prices were relatively low and industries received compensatory measures (like free allowances). These findings suggest that while policy asymmetry does pose a leakage risk, actual leakage has been limited under past conditions – though this could change as carbon prices rise sharply (Naegele and Zaklan, 2019).

To address leakage from carbon-price heterogeneity, policymakers have proposed border carbon adjustment (BCA) mechanisms. BCAs impose a carbon cost on imported goods (and sometimes rebate costs for exports) to level the playing field between domestic products (facing carbon costs) and imports from countries with weaker policies (Al Khourdajie and Finus, 2018). Economic modelling indicates that BCAs can significantly mitigate leakage. A meta-analysis of 25 studies finds that adding a BCA to unilateral climate policy typically reduces the carbon leakage rate by around 6 percentage points on average (Branger and Quirion, 2014). BCAs also help preserve domestic competitiveness – the same meta-analysis shows output losses in energy-intensive industries are very limited with a BCA. Empirical simulations thus support BCAs as an effective tool to curb leakage, although real-world evidence is limited since few BCAs have been implemented to date (Mehling et al., 2024). However, these benefits must be weighed against potential economic drawbacks, as BCAs would tend to increase domestic production costs with negative GDP effects. Firms facing higher input costs may see squeezed profit margins, cut back on investment or output, and pass through some of the burden to consumers in the form of higher prices, dampening aggregate demand. As a result, GDP can experience a modest but measurable decline: model-based assessments by the European Central Bank show that, although BCAs reduce carbon leakage, they slightly hurt GDP and inflation as the competitive gain is offset by the higher costs of imported intermediate inputs (Delgado-Téllez et al., 2025). For emissions-intensive, trade-exposed industries that both import a significant share of carbon-adjusted inputs and export much of their output, import adjustments alone can worsen—not alleviate—the adverse impacts of unilateral emissions pricing (Böhringer et al., 2022).

Carbon pricing and tariffs are not the only mechanisms to promote low-carbon production. In fact, a broad literature emphasises the need for policy mixes. "Comprehensive and consistent policy packages have been found to be more effective than single policies" in achieving deep decarbonisation (IPCC, 2023). Non-tariff instruments have proven effective in fostering low-carbon production and green technology innovation when deployed strategically. These policy tools encompass targeted subsidies and tax incentives—exemplified by feed-in tariff programmes that catalysed Germany's solar PV industry growth and China's renewable energy policies that enabled significant scale-up of manufacturing capacity (Hinrichs-Rahlwes, 2024; Mu et al., 2024). Additionally, public investments in research, development and demonstration address innovation market failures by accelerating technology advancement and cost reductions across sectors. Regulatory approaches, including performance standards for emissions and efficiency benchmarks, have successfully driven cleaner production methods in automotive and industrial sectors, whilst green public procurement leverages governmental purchasing power to create market demand for low-carbon products. Evidence suggests that such investments and instruments are most effective when implemented as complementary policy packages that simultaneously stimulate supply, demand and innovation (Suthakavatin et al., 2024; Eugster, 2021)

International cooperation offers promising pathways for reducing embodied emissions in trade through three primary mechanisms identified in recent literature. Technology transfer agreements facilitate the diffusion of climate-friendly production methods globally, enabling producers in emerging economies to adopt cleaner processes and directly lowering the carbon content of traded goods (Deane and Hurst, 2024). Sector-specific international agreements present a second approach, establishing common standards or targets for emissions within particular industries, thus addressing embedded carbon by ensuring producers worldwide adhere to specified performance levels—with initiatives already emerging in steel, cement and aluminium sectors (Unger, et al., 2024; Rossetto, 2023). The third approach involves 'climate clubs', wherein coalitions of countries agree to implement stronger climate action jointly whilst applying penalties to non-members, effectively reducing carbon leakage and trade friction by internalising these challenges within the club (Nordhaus, 2015). Evidence suggests these cooperative instruments can complement unilateral measures by addressing emissions at their source, with

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the G7 Climate Club and International Solar Alliance representing early examples of such multilateral efforts to harmonise decarbonisation strategies (Hermwille et al., 2022; Paroussos et al., 2019).

The integration of global capital markets plays a critical role in financing green technology deployment, with market fragmentation significantly impacting investment costs and flows. Capital market fragmentation, characterised by regulatory differences, currency risks, and information asymmetries, substantially increases risk premiums on green projects, particularly in emerging economies. Evidence demonstrates that identical renewable projects face dramatically different financing costs based solely on location; solar farms in South Africa incur much higher capital costs than equivalent installations in Germany despite similar technological risks (Sweerts et al., 2019). This financing disparity arises from exaggerated perceptions of macroeconomic risk in less integrated markets, resulting in interest rates 2-3 times higher in emerging economies compared to advanced ones (Goyal et al., 2019; IMF, 2025). Greater capital market integration facilitates more efficient green investment flows globally. Emerging and developing economies, representing two-thirds of the global population, require up to 6 time increase in current financial flows (Kreibiehl, 2022). Where stronger capital market links exist, through mechanisms like green bonds or foreign direct investment, greater green investment flows are observed. A more complete capital market, offering comprehensive instruments for hedging and risk-sharing, can significantly reduce perceived risk and capital costs through multiple mechanisms. Finally, standardised information frameworks and climate risk disclosure requirements reduce uncertainty premiums (Einfeld, 2024). Recent empirical work demonstrates that mechanisms like global green investment guarantee funds could substantially reduce interest rates for renewables in developing markets by effectively socialising risk (Matthäus and Mehling, 2020), highlighting how more complete financial markets can channel capital to socially efficient projects at lower costs.

1.3 Methods

Modelling Workflow

The modelling approach for Study 8 employs a sequential methodology where outputs from a materials and trade model feed into integrated assessment models to capture both supply chain dynamics and broader system-wide implications of trade and material flows.

First, MARIO (Multi-functional Analysis of Regions through Input-Output) model calculates the impacts of shifts in trade patterns on EV battery prices under different scenarios. These price impacts reflect changes in production costs due to trade restrictions, tariffs, and supply chain reconfiguration. The resulting EV price differentials are then fed into three IAMs (GCAM, TIAM, and PROMETHEUS) to assess broader system-level implications, including effects on EV adoption, energy system transformation, emissions trajectories, and economic impacts.

This linkage between models allows for capturing both the direct effects of trade policy on technology costs and the indirect effects on decarbonisation pathways through changes in technology deployment rates, energy demand, and emissions.

Scenario Design

Current EV Market (2023)

The baseline market conditions for vehicles in 2023, as calculated using MARIO, show a market price of 45,000 USD per car and carbon footprint of 15.0 tonnes CO2eq per car. These values serve as a reference point for evaluating scenarios.

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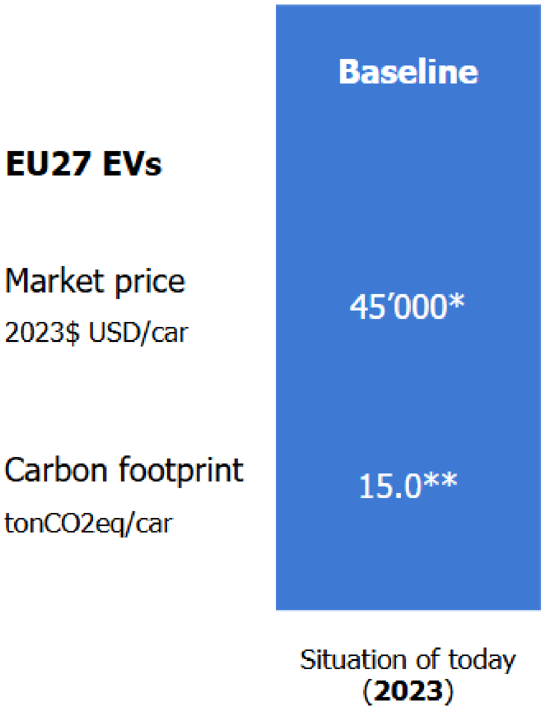

Figure 1: EU27 Electric Vehicle Market Characteristics (2023)

The figure presents baseline values for EU27 electric vehicles, showing current market price (45,000 USD per car) and carbon footprint (15.0 tonnes CO2eq per car). Emission footprint data is based on MARIO modelling. In subsequent analysis using IAMs (GCAM, TIAM, and PROMETHEUS), emission footprints will be determined by each model individually based on regional energy mixes, technology assumptions, and other model-specific parameters.

Restricted Trade Scenario

Description: This scenario simulates restricted trade conditions as follows: 'Restricted Trade EU Domestic Production' scenario: The EU switches to domestic manufacturing of the batteries needed for its domestic market (no imports), assuming the flow of required minerals continues to be secure.

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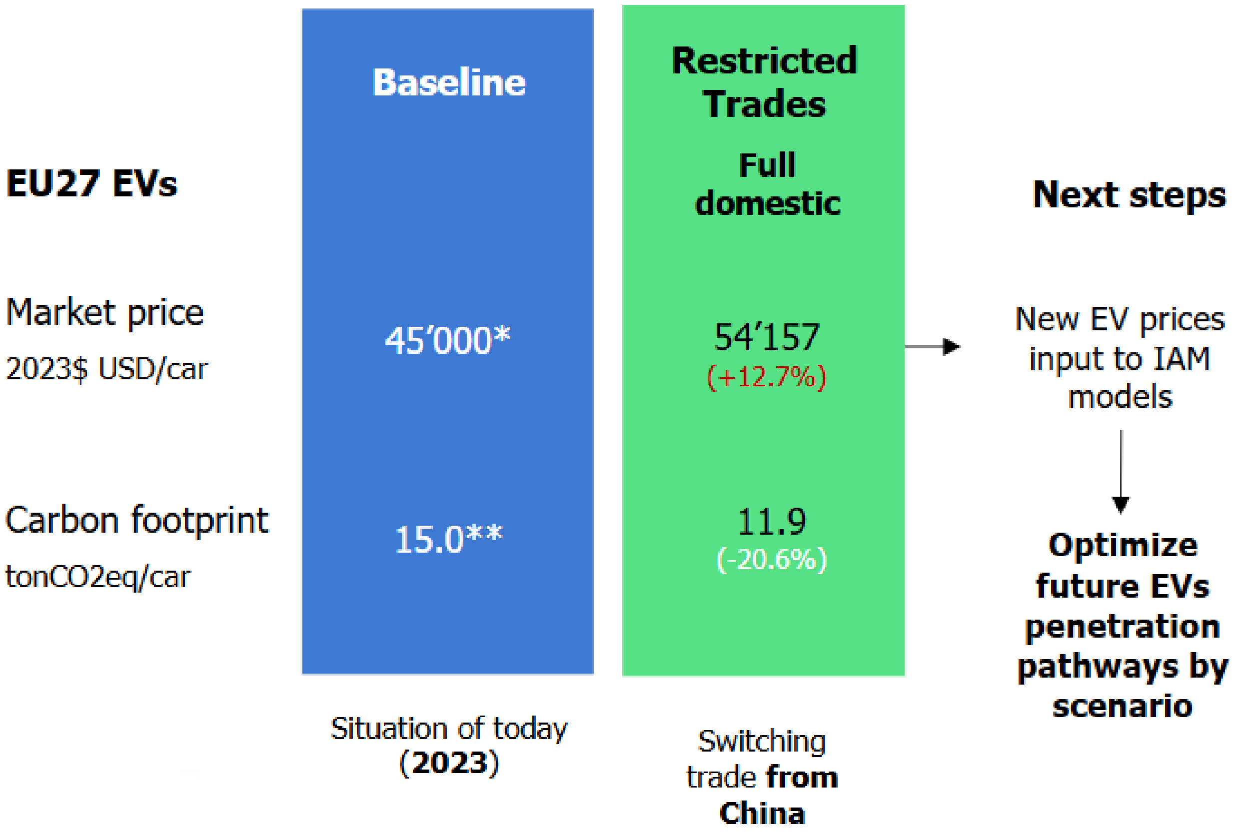

Figure 2: EU27 EV Market Changes Under Restricted Trade Scenario

MARIO modelling results show that shifting to full domestic battery production in the EU increases EV prices by 12.7% to 54,157 USD per car compared to the 2023 baseline. However, this shift reduces the carbon footprint by 20.6% to 11.9 tonnes CO2eq per car. These price and emission changes become inputs for IAM models to determine impacts on EV adoption pathways.

Alternative Partnership Scenarios (3 variants)

Description: These scenarios explore increased trade cooperation between the EU and alternative partners, focusing on specific countries and considering current trade patterns and geographic proximity. Three variants:

- Alternative Partnership Brazil scenario
- Alternative Partnership USA scenario
- Alternative Partnership Indonesia scenario

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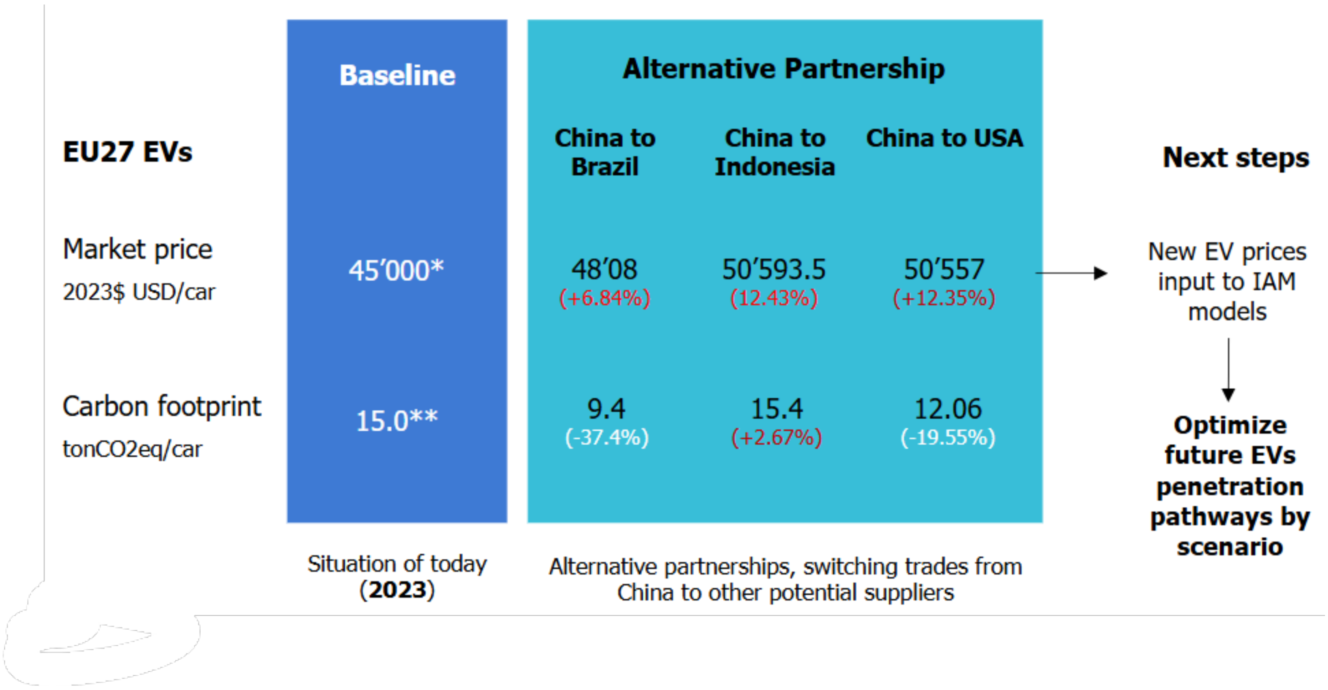

Figure 3: EU27 EV Market Changes Under Alternative Partnership Scenarios

MARIO modelling indicates varying impacts when shifting battery imports from China to alternative suppliers. Brazil offers the most favourable trade-off with only a 6.8% price increase (to 48,080 USD) while achieving a substantial 37.4% reduction in carbon footprint (to 9.4 tonnes CO2eq). Indonesia shows a 10.4% price increase (to 50,593.5 USD) with a slight 2.67% increase in emissions (to 15.4 tonnes CO2eq). The USA partnership results in a 12.35% price increase (to 50,557 USD) with 19.5% lower emissions (to 12.06 tonnes CO2eq). These differentials are fed into IAM models to optimise EV deployment pathways.

Approach:

- POLIMI conducting "what if" analyses using MARIO, imposing different import shares from various suppliers towards the EU.
- Analysis of the impact of importing from geographically closer countries
- Simulation of the impact of supply chain bottlenecks, including extraction, refining and assembly
- IAMs running scenarios based on numbers provided by MARIO
- Focus on cases from three continents

NDC_LTT Scenario

This baseline scenario reflects Long Term Targets with ambitious decarbonisation goals. The global modelling runs represent various post-COP26 ambition levels. The NDC-LTT (Long-term targets) scenario incorporates countries' stated climate mitigation ambitions that lack concrete policy agendas. These targets extend beyond 2030 NDC commitments, creating a more ambitious pathway. The scenario implements these commitments as linear trajectories from 2030 NDC targets (NDC_LTT). NDCs represent short-term ambitions codified in law or policy, though implementation remains vulnerable to political changes. In the context of our study, NDC_LTT serves as the reference against which other scenarios are compared.

Scenarios names

- LTT scenario (NDC_LTT)

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- NDC_LTT_RT_euDom
- NDC_LTT_AP_BRA
- NDC_LTT_AP_USA
- NDC_LTT_AP_IDN

1.3.1 GCAM Model Description

GCAM (Global Change Analysis Model) is a technology-rich, partial equilibrium IAM that represents the behaviour of, and interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate. The energy system is a detailed representation of the sources of energy supply, modes of energy transformation, and energy service demands such as passenger and freight transport, industrial energy use across subsectors, and residential and commercial energy service demands. The model achieves equilibrium between energy supply and demand in each represented sector, accounting for the changes in energy prices resulting from changes in fuels and technologies used to satisfy energy-service demands in these sectors. It operates on a 'recursive dynamic' cost-optimisation basis, meaning that decision-makers do not know the future when making a decision today, and solves for the least-cost energy system (constrained by observed technological preferences) in a given period before moving onto the next period and performing the same process. GCAM trades for natural gas trade in each region using an Armington approach, i.e., regions are allowed to choose between domestically produced products or globally traded products when making a consumption decision. For the purposes of this study, we use a version of GCAM explicitly representing LNG and pipeline gas as separate trade pathways. In particular, LNG is traded in a single, global market, following the Heckscher-Ohlin approach, while pipeline gas is traded in six regional pipeline networks (Europe, Russia+, Africa and Middle East, Asia-Pacific, North America, and Latin America). The pipeline networks that a given GCAM region may import from are dependent on historical country-level bilateral trade flows. It should be noted that the version of GCAM used in this analysis disaggregates EU regions as follows:

- EU_Central (Austria, Czech Republic, Hungary, Slovakia, Slovenia, Croatia, Poland)
- EU_Southwest (Italy, Malta, Portugal, Spain, Andorra, Gibraltar, San Marino, Vatican)
- EU_Southeast (Romania, Bulgaria, Cyprus, Greece)
- EU_Northwest (Belgium, Germany, France, Monaco, Netherlands, Luxembourg, Denmark)
- EU_Northeast (Finland, Sweden, Estonia, Latvia, Lithuania)

EU_UK+ (United Kingdom, Ireland, Channel Island, Faroe Island, Guernsey, Greenland, Jersey, Saint Helena)

The model is document in: Calvin et al., (2019).

1.3.2 TIAM Model Description

TIAM (Times Integrated Assessment Model) is also a partial equilibrium, technology-rich IAM which covers the full energy chain from extraction of energy resources through conversion technologies, to the provision of energy service demands to end-users [49]. It achieves similar equilibrium between energy supply and demand in each sectoroperating on a 'perfect foresight' welfare cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction, and energy price changes over the entire time horizon are considered when minimising the cost of the energy system to provide energy-service demands within specified emissions constraints. Exogenous inputs of GDP, population, household size and sectoral shares of the economy are combined to project future energy service demands across all sectors in each region. Energy system data (e.g., technology costs, resource supply curves and annual resource availability) are also input into the model. TIAM disaggregates the world into 15 different regions, which are interlinked by the trade of the main energy and material commodities.

The model is document in: Loulou and Labrie, (2008).

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1.3.3 PROMETHEUS Model Description

PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level, allowing to assess mitigation pathways and low-emissions development strategies, analyse the energy system, economic, and emissions implications of a wide spectrum of policy instrument differentiated by region and sector, and explore the economics of fossil-fuel production to quantify the impacts of climate policies on the evolution of global energy prices. It notably features world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements. Much like GCAM and MUSE, it operates 'myopically', meaning each time step is solved without full knowledge of the future.

The model is document in: Fragjos et al., (2015)

1.3.1 MARIO Model Description

MARIO (Multi-functional Analysis of Regions through Input-Output) is an open suite for input-output analysis based on the DynERIO (Dynamic Extraction and Recycling Input-Output) framework, a comparative-static simulation model able to assess the impacts of implemented macroscopic trends and scenarios from an economic and environmental perspective—here with respect employment implications of the IAM-modelled pathways. With respect to typical input-output models, DynERIO allows to quantitatively assess the extraction of raw materials for selected technologies driven by regional production of commodities provided by the Leontief Production Model.

The model is documented in: Tahavori et al., (2022) and Rinaldi et al (2022)

1.4 Results

Figure 1 below illustrates the projected transport final energy carrier distribution in the EU under the NDC_LTT baseline scenario and the percentage changes across alternative trade scenarios from 2050 to 2100. The results reveal the shifts in the EU's transport energy portfolio when trade patterns are altered. The baseline scenario (left panel) demonstrates a transport system that increasingly relies on electricity (blue) and hydrogen (purple) over time, with liquids (pink) maintaining a substantial but gradually declining share. When examining the alternative scenarios, all exhibit dramatic decreases in electricity utilisation ranging from -48.6% in the Brazil partnership scenario to -53.0% in the EU domestic production scenario in 2050. This reduction in electrification persists through 2100, though with slightly diminished magnitude (-37.1% to -40.1%). These substantial decreases in electricity use are counterbalanced by remarkable increases in hydrogen deployment across all scenarios. The EU domestic production scenario shows the most dramatic shift with a +126.9% increase in hydrogen utilisation by 2050, whilst the Brazil partnership scenario exhibits the smallest (though still substantial) increase at +119.4%. The consistency of this pattern across all scenarios indicates a fundamental technological substitution effect, where disruptions to EV supply chains trigger a compensatory shift towards hydrogen-based transport solutions. The magnitude of hydrogen adoption gradually moderates over time but remains significantly elevated even in 2100 (+91.4% to +96.6% across scenarios). Gaseous fuels also see modest but consistent increases across all alternative scenarios (+8% to +11%), suggesting a diversification in the transport energy mix when optimal electrification pathways are constrained. Changes in liquid fuels remain minimal across all scenarios, indicating their persistent role in the transport sector regardless of trade arrangements.

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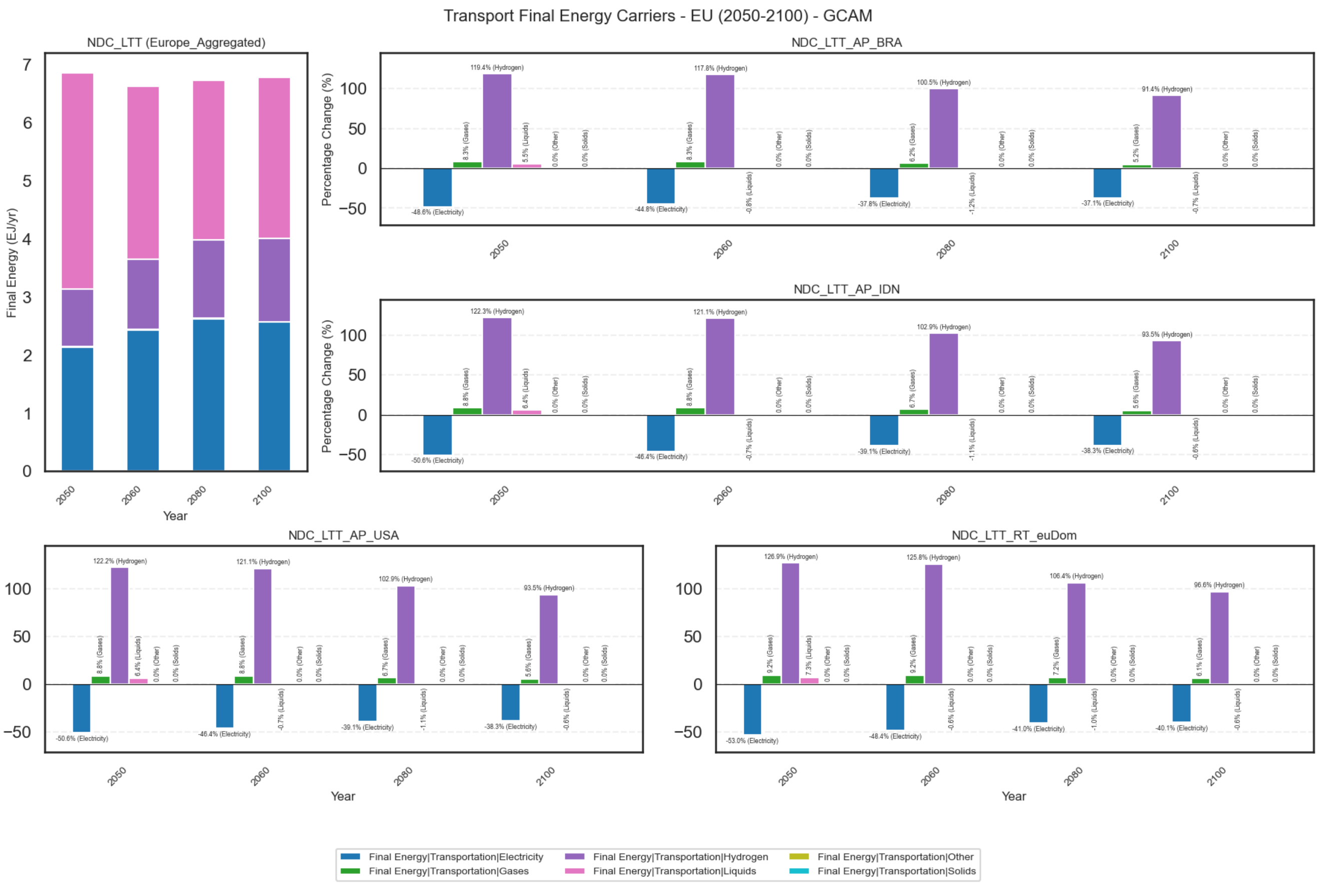

Figure 1: Transport Final Energy Carriers - EU (2050-2100) – GCAM. Projected transport final energy carrier distribution in Europe (aggregated) under the NDC_LTT baseline scenario (left panel) and percentage changes in energy carrier composition across alternative trade scenarios from 2050 to 2100. The right panels illustrate changes under partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom). Values are expressed as percentage changes relative to the baseline scenario, with carrier-specific impacts labelled.

Figure 2 below presents the corresponding transport CO2 emissions trajectories, revealing that all alternative trade scenarios result in increased emissions in 2050 compared to the baseline. The EU domestic production scenario exhibits the highest emissions increase (+4.5%), followed by the USA and Indonesia partnerships (both +4.0%), whilst the Brazil partnership shows the smallest increase (+3.4%). Interestingly, all scenarios show minor emissions reductions (-0.5% to -0.9%) in the longer term (2060-2100) compared to the baseline. This suggests that while near-term disruptions to EV supply chains have immediate negative emissions consequences, the transport system adapts over time through alternative decarbonisation pathways that eventually yield small emissions benefits. Collectively, these results demonstrate that any alteration to existing EV supply chains—whether through alternative partnerships or domestic reshoring—triggers a substantial shift away from electrification towards hydrogen-based transport solutions. This technological substitution effect has measurable emissions consequences in the near term, with the magnitude of impact directly proportional to the degree of supply chain disruption. The findings suggest that current global supply chains, which likely involve significant Chinese components, are optimised not only for economic efficiency but also for near-term emissions reduction in the transport sector.

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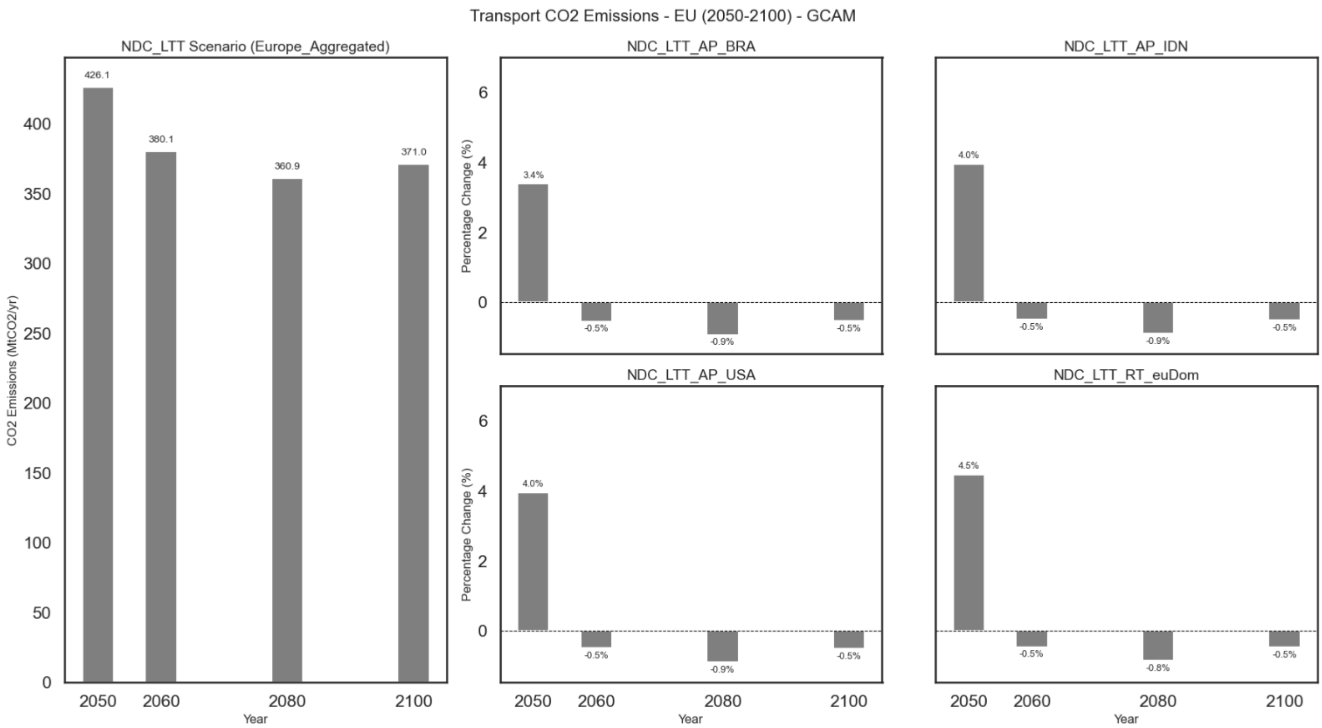

Figure 2: Transport CO_2 Emissions - EU (2050-2100) – GCAM. Projected transport CO_2 emissions in Europe (aggregated) under the NDC_LTT baseline scenario (left panel, in $MtCO_2/yr$) and percentage changes in emissions across alternative trade scenarios from 2050 to 2100 (right panels). The alternative scenarios include partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom). Results show initial emissions increases in 2050 followed by slight reductions in later periods across all alternative scenarios.

Figures 3 and 4 below illustrate the projected transport final energy carrier distribution and CO_2 emissions in the EU28 under the NDC_LTT baseline scenario and alternative trade scenarios for 2030, 2040, and 2050, as modelled by PROMETHEUS.

The baseline scenario (left panel in Figure 3) reveals a transport system that begins with heavy reliance on liquid fuels (pink) but transitions to a more balanced mix with increasing electrification (blue) over time. By 2050, the share of electricity in final energy consumption grows substantially, indicating significant progress towards transport decarbonisation. This transition is reflected in the corresponding emissions pathway (left panel in Figure 4), which shows a dramatic reduction from 716.7 $MtCO_2/yr$ in 2030 to just 136.2 $MtCO_2/yr$ by 2050. When examining the alternative scenarios, all exhibit modest decreases in electricity utilisation ranging from -1.0% to -2.0% in 2030, growing to -3.3% to -5.9% by 2050. This indicates that disruptions to EV supply chains have a progressively greater impact on electrification as the transition advances. The EU domestic production scenario consistently shows the largest reductions in electricity use, reaching -5.9% by 2050.

These decreases in electricity use are counterbalanced by substantial increases in hydrogen deployment across all scenarios. The EU domestic production scenario demonstrates the most pronounced shift, with hydrogen utilisation increasing by +65.0% in 2030, growing to +65.3% by 2050. The Brazil partnership shows the most modest increases in hydrogen, ranging from +16.2% in 2030 to +17.0% in 2050. Unlike the GCAM model results, PROMETHEUS projects significant increases in gaseous fuels across all scenarios, with particularly strong growth in the EU domestic production scenario (+37.2% by 2050) and the USA partnership scenario (+21.8% by 2050). Liquid fuels also see modest increases, particularly in later periods, suggesting a greater role for these conventional energy carriers when optimal electrification pathways are constrained.

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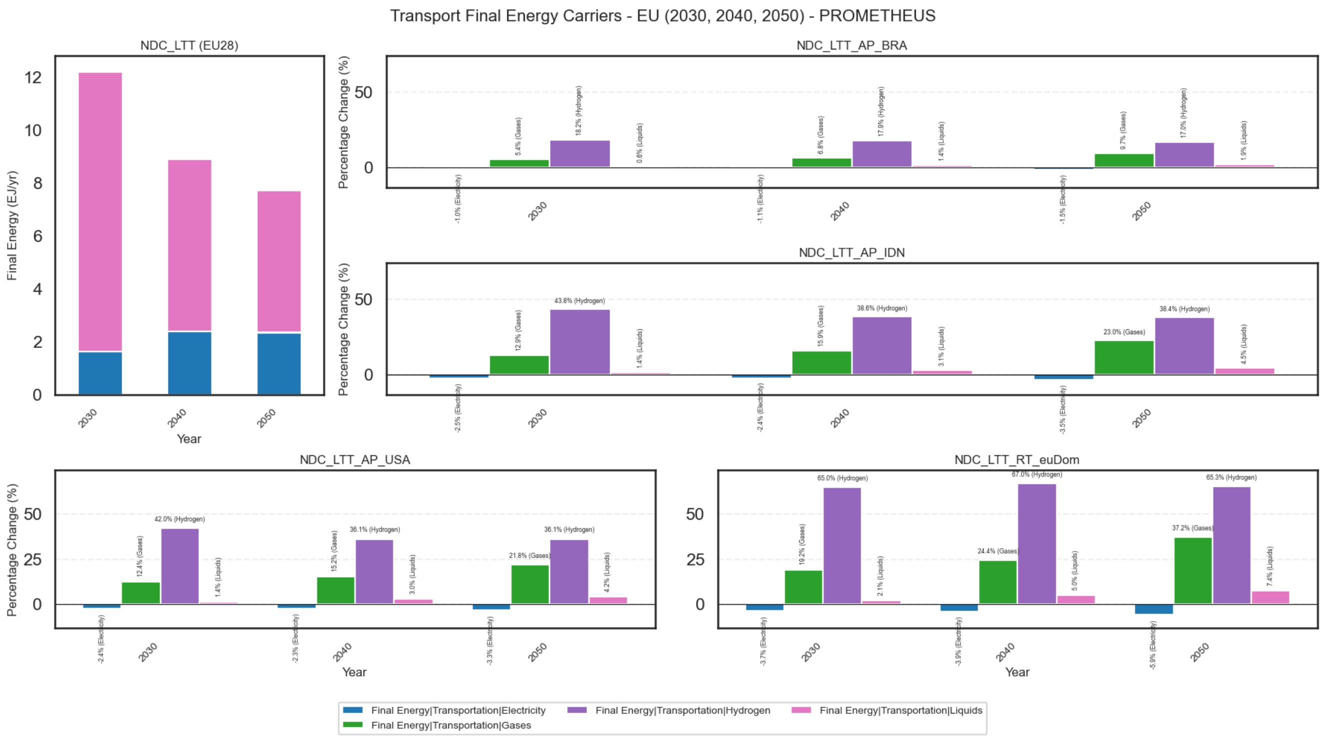

Figure 3. Transport Final Energy Carriers - EU (2030, 2040, 2050) – PROMETHEUS. Projected transport final energy carrier distribution in EU28 under the NDC_LTT baseline scenario (left panel) and percentage changes in energy carrier composition across alternative trade scenarios from 2030 to 2050. The right panels illustrate changes under partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom). Values are expressed as percentage changes relative to the baseline scenario, with carrier-specific impacts labeled.

Figure 4 below presents the corresponding transport CO_2 emissions trajectories, revealing that all alternative trade scenarios result in increased emissions compared to the baseline. These emissions penalties grow progressively larger over time, with relatively modest impacts in 2030 (+0.6% to +2.0%) evolving into substantial increases by 2050 (+2.8% to +10.9%). The EU domestic production scenario exhibits the highest emissions increase (+10.9% by 2050), followed by the USA partnership (+6.2%), the Indonesia partnership (+6.6%), and the Brazil partnership (+2.8%). Comparing the 2050 results between PROMETHEUS and GCAM reveals important similarities and differences. Both models agree on the fundamental directionality of change, demonstrating decreased electricity use, increased hydrogen utilisation, and higher CO_2 emissions across all alternative scenarios. Both models also identify Brazil as the least harmful alternative partnership and EU domestic production as the most detrimental option. However, PROMETHEUS projects smaller decreases in electricity use but larger emissions penalties compared to GCAM, suggesting differences in technological substitution dynamics and emissions factors between the two models. These convergent findings across different modelling frameworks strongly indicate that disruptions to established EV supply chains—through either trade restrictions or alternative partnerships—lead to technological substitution patterns that compromise the EU's transport decarbonisation objectives. The consistency in ranking Brazil as the most favourable alternative and EU domestic production as the least favourable option underscores the importance of supply chain considerations in climate policy development.

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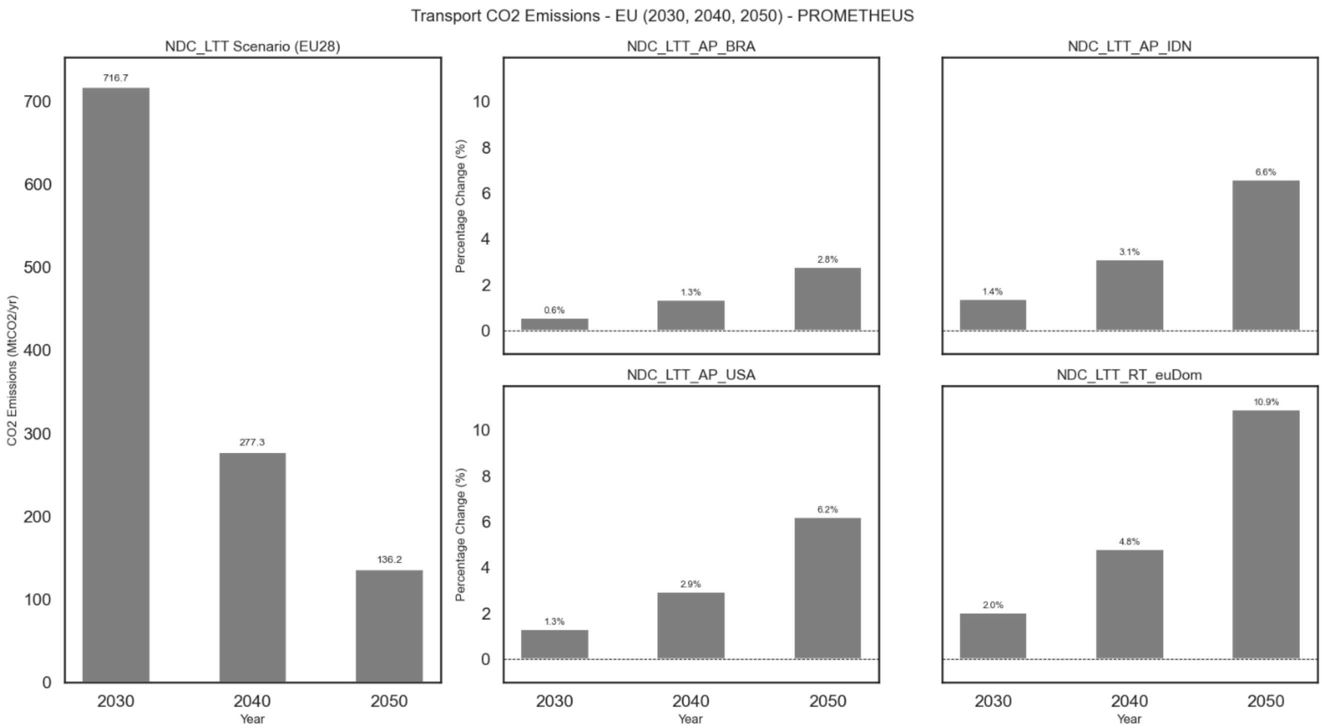

Figure 4: Transport CO_2 Emissions - EU (2030, 2040, 2050) – PROMETHEUS. Projected transport CO_2 emissions in EU28 under the NDC_LTT baseline scenario (left panel, in $MtCO_2$/yr) and percentage changes in emissions across alternative trade scenarios from 2030 to 2050 (right panels). The alternative scenarios include partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom). Results show progressively increasing emissions penalties over time, with EU domestic production exhibiting the largest impact

The TIAM model results, shown in Figures 5 and 6, present notably different patterns compared to GCAM and PROMETHEUS, largely attributed to regional aggregation differences. TIAM uses broader regional definitions (WEU, EEU, FSU) that do not align precisely with the EU regions represented in other models.

Figure 5 reveals the underlying transport energy carrier dynamics. In the baseline scenario, electricity (blue) gradually increases its share over time, hydrogen (purple) maintains a relatively stable contribution, whilst liquids (pink) remain the dominant energy carrier throughout. However, the alternative scenarios show consistent decreases in electricity utilisation (~24-28%) and substantial reductions in hydrogen deployment (~50%) across all time periods, compensated by significant increases in liquid fuels (~20-30%) and modest increases in gases. This pattern diverges notably from GCAM and PROMETHEUS, where electricity decreased but hydrogen increased substantially. The difference may be attributable to how TIAM models the economic competitiveness of hydrogen pathways under trade constraints across its broader regional definitions. The model suggests that under all alternative trade scenarios, the transport sector in the European regions reverts more substantially to conventional liquid fuels rather than shifting to hydrogen alternatives when optimal electrification pathways are constrained.

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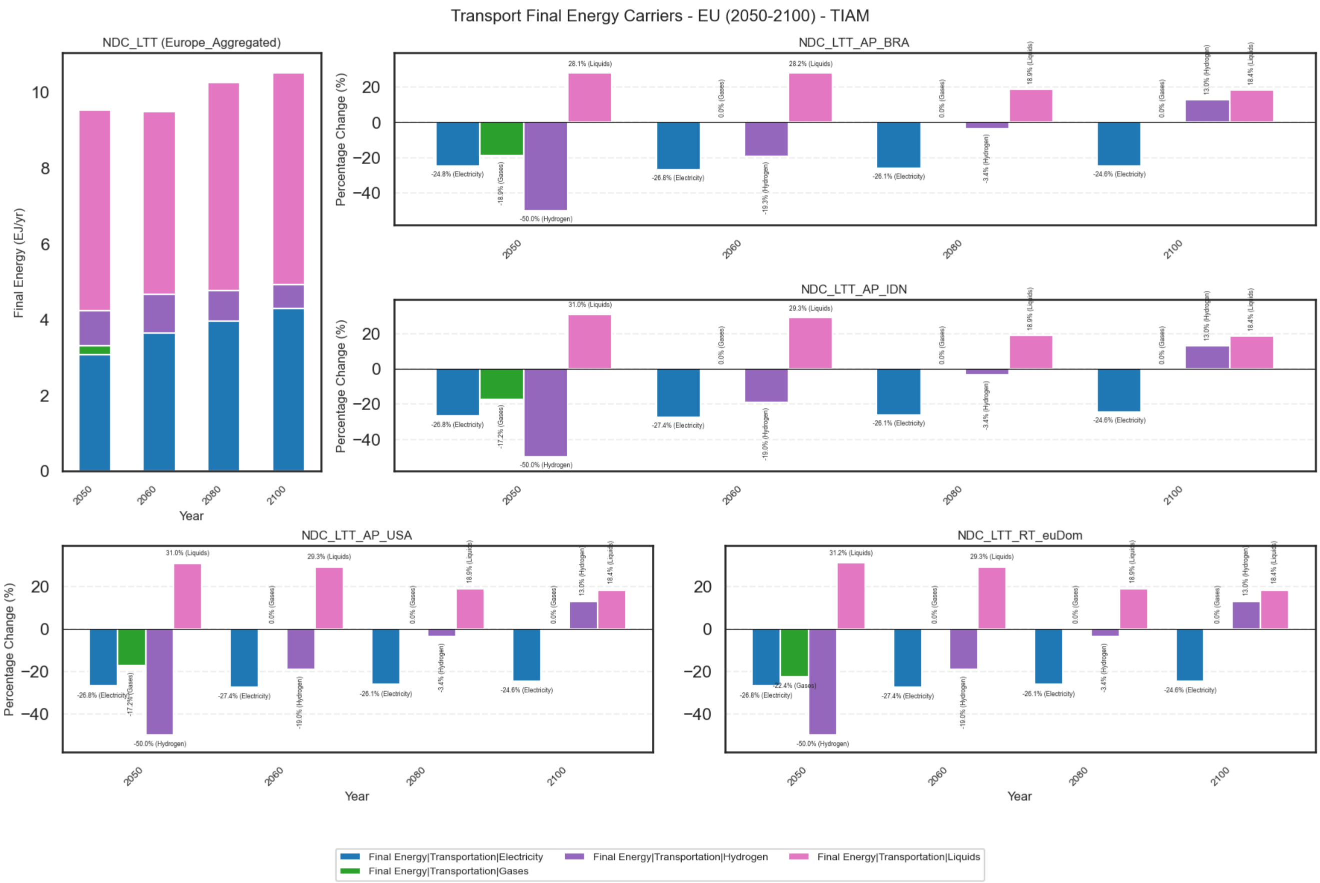

Figure 5: Transport Final Energy Carriers - EU (2050-2100) – TIAM. Projected transport final energy carrier distribution in European regions under the NDC_LTT baseline scenario (left panel, in EJ/yr) and percentage changes in energy carrier composition across alternative trade scenarios from 2050 to 2100. The right panels illustrate changes under partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom). Values are expressed as percentage changes relative to the baseline scenario. All alternative scenarios show decreases in electricity (24-28%) and hydrogen (50%) utilisation, compensated by increases in liquid fuels (~20-31%) across all time periods.

Figure 6 below illustrates the projected transport CO2 emissions trajectory under the NDC_LTT baseline scenario and percentage changes across alternative scenarios. In the baseline, emissions start at 190.8 MtCO2/yr in 2050, peak at 217.3 MtCO2/yr in 2060, then decrease substantially to 114.2 MtCO2/yr by 2080 and 102.0 MtCO2/yr by 2100, reflecting a long-term decarbonisation pathway. However, all alternative scenarios show consistently higher emissions relative to the baseline across all time periods, with the magnitude of this difference following a distinctive pattern: substantial increases in 2050 (~54-60%), moderate increases in 2060 (~36-38%), then rising again to ~62.5% in 2080 and peaking at ~75.3% by 2100. This contrasts with GCAM and PROMETHEUS, which projected initial emissions increases followed by slight reductions in later periods. The difference may reflect how trade restrictions and supply chain reconfigurations propagate through the different regional structures in TIAM, affecting long-term technology adoption pathways.

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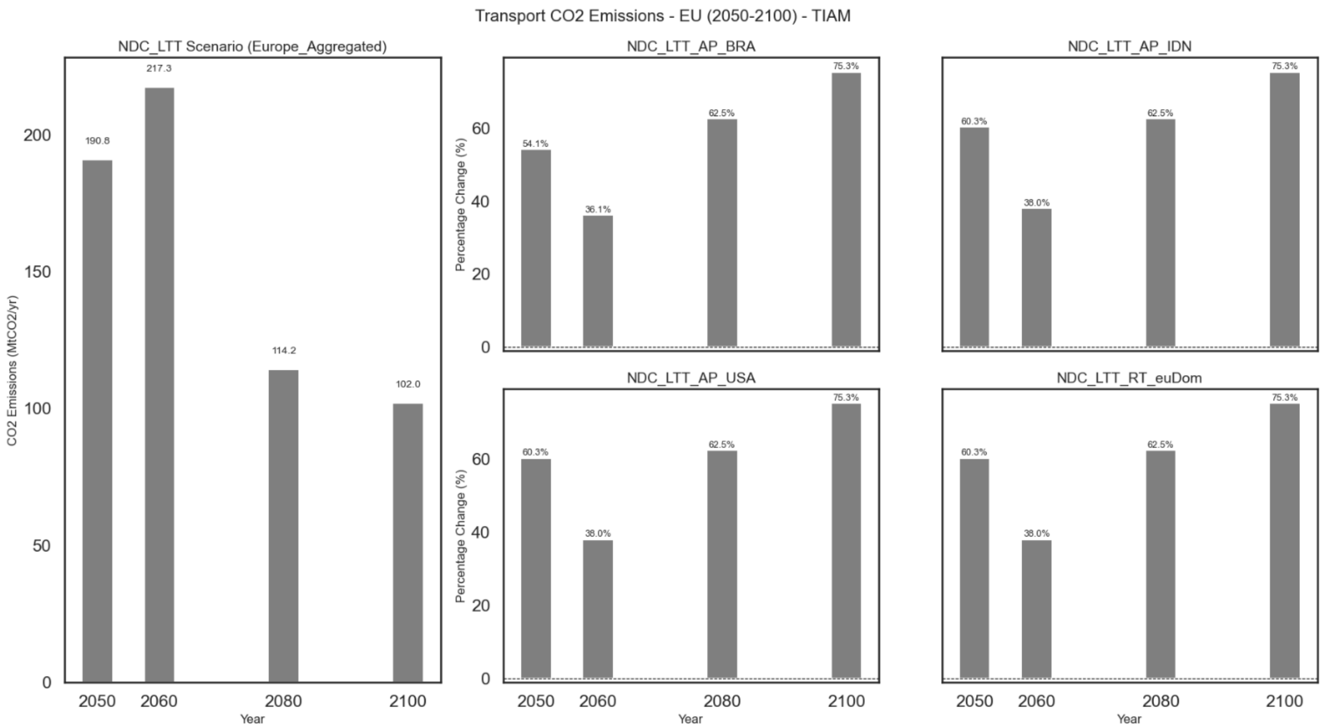

Figure 6: Transport CO2 Emissions - EU (2050-2100) – TIAM. Projected transport CO2 emissions in European regions under the NDC_LTT baseline scenario (left panel, in MtCO2/yr) and percentage changes in emissions across alternative trade scenarios from 2050 to 2100 (right panels). The alternative scenarios include partnerships with Brazil (NDC_LTT_AP_BRA), Indonesia (NDC_LTT_AP_IDN), USA (NDC_LTT_AP_USA), and EU domestic production (NDC_LTT_RT_euDom).

The comparative analysis across GCAM, PROMETHEUS, and TIAM reveals both convergent and divergent patterns regarding the impacts of trade restrictions and alternative partnerships on the EU's transport decarbonisation pathways. All three models consistently indicate that disruptions to established EV supply chains lead to reduced electricity use in the transport sector across all scenarios, suggesting a fundamental technological substitution effect when EV adoption is constrained. However, the models differ in their projections of compensatory pathways. GCAM and PROMETHEUS indicate substantial increases in hydrogen utilisation (up to +126.9% and +65.3% respectively) when EV adoption is constrained, whilst TIAM projects decreased hydrogen use (~50%) alongside increased reliance on conventional liquid fuels. This difference likely stems from variations in how the models represent regional hydrogen production capabilities, infrastructure requirements, and cost structures under constrained trade scenarios. Despite these differences, all three models reach the common conclusion that disruptions to existing EV supply chains result in higher transport emissions in the near term (2030-2050). GCAM and PROMETHEUS project emissions penalties ranging from +0.6% to +10.9% by 2050, whilst TIAM indicates substantially higher penalties of +54-60%. Regarding alternative partnerships, there is consensus across models that the Brazil partnership represents the most favourable alternative among those examined, with the smallest emissions penalties and cost increases for EV batteries. The EU domestic production scenario consistently emerges as the most challenging option, with the highest emissions penalties and cost implications across all models. These findings collectively underscore the importance of stable, efficient supply chains for the EU's transport decarbonisation goals and highlight the economic and emissions trade-offs associated with different partnership and reshoring strategies.

1.5 Discussion

Building on the modelling results, this section examines the complex interplay between trade policy, supply chains, and decarbonisation pathways in the EU transport sector. The findings demonstrate significant implications for the EU’s climate objectives when global supply chains are reconfigured.

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Shifting the production in the EU's electric vehicle battery manufacturing to the domestic markets raises several challenges. This complexity encompasses raw material extraction, refining, component fabrication, and assembly, processes historically optimised across disparate global hubs (Jones, et al., 2022). Onshoring necessitates not merely relocating production facilities but establishing comprehensive supply networks and developing specialised human capital. Despite initiatives such as the European Battery Alliance Academy, these efforts remain insufficient relative to the scale of workforce development required (European Commission, 2022).

China maintains a dominant position in clean technology networks, particularly for EV batteries and renewable energy components. Approximately 80-90% of EV battery cathodes worldwide incorporate materials processed in China, reflecting strategic investments in refining facilities and component manufacturing (IEA, 2022). This dominance extends to solar photovoltaic manufacturing and wind turbine components. Recent export restrictions on battery-grade graphite illustrate how policy decisions in Beijing can directly influence the EU's ability to pursue its clean energy objectives (Blois, 2023). This reality has prompted diversification efforts in Europe and elsewhere to reduce dependency on Chinese supplies, yet the modelling results clearly demonstrate that such reconfigurations negatively impact the EU's transport decarbonisation trajectory. All alternative scenarios show decreased electrification and increased CO2 emissions compared to the baseline, ranging from 1.7% (Brazil partnership) to 10.9% (EU domestic production) higher emissions by 2050 without any change in the carbon policy.

While certain industrial policies might accelerate domestic manufacturing capacity over the long term, the immediate effect of trade restrictions is to delay deployment of low-carbon technologies. One potential mitigation strategy involves stimulating circular economy approaches within Europe. Trade constraints that increase raw material costs create economic incentives for recovery and reuse (Duchin and Levine, 2019). The EU's Battery Regulation exemplifies this shift, establishing ambitious targets for recycling efficiencies and recycled content. Crucially, such circularity delivers co-benefits for climate mitigation, as producing metals via recycling generally has a substantially lower carbon footprint than primary extraction (OECD, 2024).

The significant shift towards increased hydrogen and alternative fuels observed in our modelling results would require corresponding skills development. Europe already faces notable shortages in battery engineering, power electronics, and renewable energy expertise (Karapidakis et al, 2024). Under scenarios of restricted trade, where domestic production must increase, demand for skilled workers would rise. Current initiatives like the European Battery Alliance Academy represent steps toward addressing this challenge, yet demographic trends and global competition for talent may constrain rapid workforce expansion. Our modelling examined partnerships with Brazil, Indonesia, and the USA as alternatives to current trade patterns. The results indicate that the Brazil partnership yields the smallest increase in the costs for EV batteries and in transport emissions (+1.7% in GCAM, +2.8% in PROMETHEUS), suggesting it represents the most viable alternative among those examined. These nations, along with others in Latin America, Africa, and Southeast Asia, possess significant resources or growing manufacturing bases that could supplement European supply chains. However, governance and infrastructure constraints in many potential partner countries necessitate capacity-building support to ensure reliable supply. Beyond mineral deposits or manufacturing potential, the logistical capabilities of alternative partners significantly influence their viability.

The trade-off between carbon intensity of production and geographical proximity emerged as a critical consideration in our analysis. However, many geographically proximate regions currently lack mature clean-tech industries, creating tension between prioritising low-carbon production versus minimising transport distances and developing regional expertise. The modelling results demonstrate the vulnerability of decarbonisation pathways to supply chain disruptions.

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2. National Mitigation Pathways of Major Emitters

2.1 USA: Increasing the ambition

2.1.1 Stakeholder Engagement Process

2.1.1.1 Overview

America Is All In Stakeholder Engagement

The America Is All In coalition is a group of leaders from U.S. cities, states, tribal nations, businesses, schools, and more in support of climate action. As the analytical lead of the America Is All In analytical team, CGS partners with various think tanks and NGOs including Rocky Mountain Institute (RMI), Ceres, World Wide Fund for Nature (WWF), Bloomberg Sustainable Cities Fund, and FGS Global. Last year, CGS worked with America Is All In to drive a robust 2035 NDC consultation process, with an emphasis on policy implementation.

Over the course of March through July 2024, we held 12 stakeholder listening sessions across multiple sectors, convening representatives from various sectors of the economy including transportation, commercial and residential buildings, power and energy, and industry to discuss each sector's contributions and barriers to reaching 2035 climate targets.

During these sessions, CGS presented preliminary current and enhanced ambition scenarios. Participants then shared feedback reflecting their subject matter expertise and firsthand experience through verbal comments, written brainstorming activities, and small-group discussions. The feedback was then integrated throughout CGS's new report on how to achieve an ambitious NDC to help inform the feasibility of its assumptions and results and to provide additional context around the opportunities and challenges associated with ambitious climate actions across different sectors.

Across the twelve listening sessions, 214 individual stakeholders participated, representing 140 organisations from nonprofit, corporate, and federal, state, and local government entities; several membership-based organisations participated in the listening sessions, covering all 53 states and territories, more than 350 cities, 400 higher education institutions, and 250,000 individuals. The listening sessions also featured high-level participation from key actors in the national climate conversation, including John Podesta (Senior Advisor to the President for Clean Energy Innovation and Implementation), Mayor Vi Lyles (Charlotte, NC), Mayor Satya Rhodes-Conway (Madison, WI), Gina McCarthy (America is All In Managing Co-Chair and former White House National Climate Advisor), and Ann Shikany (Deputy Assistant Secretary for Transportation Policy at the U.S. Department of Transportation).

Other forms of engagement

CGS also continued to engage regularly with other stakeholders in the policy and research community, including the federal government (e.g. State Department, EPA, DOE, White House Climate Policy Office), the UN, the State of Maryland, and more.

2.1.1.2 Common themes

Workforce development: Across sectors, the workforce needs comprehensive education, resources, and investment to prepare for a clean energy future.

Public education and messaging: Keeping the public well-informed and motivated to participate in meeting

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climate targets will require disseminating accurate and digestible information with tailored messaging to the community.

Tax incentives and rebates: While the clean energy tax incentives included in the Inflation Reduction Act (IRA) represent a significant opportunity to galvanize investment in clean energy projects and technology, listening session participants reported concern about the uptake of these incentives and the need for further education and technical and capacity support.

Need for streamlined processes: Participants pointed to bureaucratic permitting and siting processes as barriers to large-scale projects, particularly in regards to transmission buildout. Residents and stakeholders are also growing frustrated with continued disruption from infrastructure buildout. These stakeholders become more inclined to push back against project development, making it necessary to expedite permitting, siting, and construction processes as much as possible.

Regional collaboration: Grid upgrades and transportation redesign projects greatly benefit from collaboration and communication between cities and counties in a given region. Additionally, collaboration between states and local jurisdictions is necessary to efficiently utilize federal resources for climate investments.

Cross-sectoral collaboration: Building codes and standards, tax credits, energy efficiency resource standards, and industrial decarbonisation incentives offer opportunities for partnership between the power industry, state, and local governments to deliver on climate goals.

Community design: Participants expressed keen interest in vehicle miles traveled (VMT) reductions as a promising near-term emissions reduction strategy and a potential area for federal, state, and local collaboration. Many existing communities will need to reimagine design and planning decisions in order to decrease dependence on personal vehicles.

Local participation: Alongside states, cities maintain a unique and crucial local perspective on issues that affect climate targets and emissions reduction. As much as possible, conversations about climate targets must include participation at the local level.

Freedom of choice: Maintaining individuals' ability to choose between transportation and energy options will be key in how decarbonisation methods are introduced and marketed.

Extreme weather: Communities across the country already face disruptions to daily life caused by extreme weather. Future decarbonisation project planning must take into account the already-realized impacts of climate change

2.1.1.3 Modeling improvements

Overall improvements

Notably, stakeholders have had some concern on the gas CCS levels being too high in our scenarios, so we dialed back on these assumptions in the updated scenarios. We have also received feedback that a methane fee for the agriculture sector is not politically feasible; as a result, the final product frames the driver of agricultural methane emissions reductions as an incentive instead of a fee. In response to feedback on other high-ambition policies, we also incorporated federal industry CCS standards and state-level biofuels policies into our high ambition scenario. We also increased the upper bound of our state-level buildings energy efficiency standards to from 3% to 4% annual savings by 2035.

State level improvements

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To improve modeling results at the state level and also as a part of our work to help develop pathways for Maryland's climate action plan, we have regular meetings with different agencies from the State of Maryland.

For example, bilateral meetings with the Maryland Department of Transportation focused on improving the vehicle miles traveled and EV projections for the State of Maryland. With their data, we adjusted GCAM inputs to better reflect Maryland's trajectory after COVID-19.

Lands sector improvements

As GCAM has limitations in lands sector modeling, we partnered with key research and policy organisations to improve the understanding of emissions reduction potential in the U.S. lands sector.

Stakeholders advised us to emphasize the importance of fully implementing the lands sector funding from the Bipartisan Infrastructure Law and the Inflation Reduction Act, as these funds have the potential to be used for other purposes if policymakers do not think they will be impactful. As such, we created three scenarios: a no policy/BAU scenario, a scenario with current policies fully implemented, and a scenario with enhanced policies.

For our high ambition scenario, stakeholders also advised us to assume that cities/counties have their own land policies, and that expansion is reduced. As a result, we chose to use the Shared Socioeconomic Pathway 1 for that scenario to represent the lowest settlement expansion.

2.1.2 Scenario Development & Harmonisation

Scenario Design

Two scenarios -- *Current Policies* and *Enhanced Ambition* -- were developed in 2024, with consultation from a variety of stakeholders (see above) in an effort to inform the U.S. 2035 NDC. Projections from these scenarios extend to 2050. Both scenarios include specific federal and non-federal policies through 2035. For *Enhanced Ambition*, we use an emissions constraint after 2035, assuming a linear trajectory from 2035 to net zero in 2050.

Under the new U.S. administration, expansive federal rollbacks of climate policies, regulations, and legislation are possible in the coming months, given recent executive orders,[1] precedent under the previous Trump administration,[2] and stated targets in policy planning documents.[3] Both climate legislation and regulations, such as the recently finalized rules on tailpipe emissions and the Inflation Reduction Act, are at risk of being overturned. However, enhanced climate leadership from non-federal actors can help bridge the gap and build progress toward the global climate goals needed to mitigate the worst impacts of climate change.

We include two additional sets of scenarios -- *Federal Rollbacks* and *Non-Federal Leadership* -- given the new political climate in the United States in 2025. Due to uncertainties with the state of current federal climate policies, each set of scenarios provides a "High" and "Low", which can be thought of as the upper and lower bounds of emissions reductions, respectively, for that scenario. Both scenarios include specific federal and non-federal policies through 2035.

For all scenarios, the model's base year is 2015, with calibrations for 2020 to match historical data.

1. **Current Policies:** Includes key existing, on-the-books policies from federal and non-federal actors as of December 2024.
2. **Enhanced Ambition:** Expands upon the *Current Policies* scenario with new and enhanced climate policy actions at the federal and non-federal levels.
3. **Federal Rollbacks:** Assumes a range of federal rollbacks, from a full repeal of both climate legislation and

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regulations to a full repeal of only regulations, with existing non-federal policies.
   i. **Federal Rollbacks Low:** Full repeal of both climate legislation and regulations
   ii. **Federal Rollbacks High:** Full repeal of only regulations
4. **Non-Federal Leadership:** Assumes a range of federal ambitions, from a full repeal of both climate legislation and regulations to renewed federal ambition after 2028, with enhanced non-federal policies.
   i. **Non-Federal Leadership Low:** Full repeal of both climate legislation and regulation
   ii. **Non-Federal Leadership High:** Renewed federal ambition after 2028

2.1.3 Overview of GCAM-USA-CGS

Our analysis uses a version of the open-source Global Change Analysis Model (GCAM) to estimate the aggregate impact of federal and non-federal climate policies and actions on economy-wide emissions reductions in the United States. Specifically, we use GCAM-USA, a state-level version of GCAM. We refer to the version of GCAM-USA used in this study as GCAM-USA-CGS.

GCAM is an integrated assessment model (IAM) that covers the energy, land, water, climate, and socioeconomic systems. The global version of GCAM groups the world's countries into 32 geopolitical regions with representation of the energy and socioeconomic systems for each region. The United States is one of the 32 regions. GCAM represents the global climate system and uses 235 water basins and 384 land regions to represent global water and land systems. GCAM tracks emissions and sinks of carbon dioxide (CO_2), 16 other GHGs, and several air pollutants.

The state-level version of GCAM used in this analysis, GCAM-USA, disaggregates the U.S. energy and economy components into 50 states and the District of Columbia while maintaining the same level of detail as GCAM for water and land sectors. The energy system in GCAM-USA has representations of depletable primary sources such as coal, gas, oil, and uranium, in addition to renewable resources such as biomass, hydropower, solar, wind, and geothermal. Energy transformation processes like oil refining and electricity generation are represented at the state-level in GCAM-USA. These energy carriers, in turn, are used to deliver services to state-level end users in the buildings, transportation, and industrial sectors. The electric power sector includes representations of a range of power generation technologies, including those fueled by fossil fuels and bioenergy (with and without CCS), renewables, and nuclear power.

GCAM-USA is a market equilibrium model. The model solves for equilibrium in each period by finding a set of market prices such that supplies and demands are equal to one another in all markets as the actors in the model adjust the quantities of the commodities they buy and sell. GCAM operates in 5-year time-increments, with each new period starting from the conditions that emerged in the last, with most technologies vintaged such that a portion of existing stocks at any point carry over into future time periods.

GCAM-USA-CGS is based on the open-source release of GCAM-USA 6.0.[31] GCAM-USA-CGS has been updated for the purposes of this study to reflect changes such as the most recent estimates of future renewable energy costs.[32] The model is also calibrated to the latest non-CO_2 marginal abatement cost curves from the U.S. Environmental Protection Agency (EPA).[33]

2.1.4 Modeling Approach

Policy representation in our modeled scenarios builds upon bottom-up aggregation tools and data analysis to evaluate and quantify the impacts of policies and climate actions in isolation and within specific sectors. Throughout, we took care to avoid potential double counting of potential emissions reduction drivers from nested governance levels. We then used this information in GCAM-USA-CGS to estimate the economy-wide implications of associated policies.

All modeled policies in GCAM-USA-CGS are implemented at the state and/or national levels. Therefore, policies and actions from city governments, businesses, and institutions were aggregated to the state-level or assumed

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to be embedded within or supportive of the state and/or national level policy representation in the model, and therefore not explicitly modeled to remove risk of double counting potential emissions reductions.

Model parameters in GCAM-USA-CGS varied according to information from our bottom-up aggregation analysis or changed directly for policy drivers where bottom-up aggregation was either not feasible or not necessary in the case of small-scale potential impacts. The purpose of this analysis is to assess the national emissions reduction potential in the United States for the policies modeled in our scenarios. Accordingly, non-federal policies and actions are only modeled to the extent that doing so would have a meaningful impact on the national-level emissions outcome. In some policy areas, we did not specify state-level variation in policy implementation – for example, with bus electrification – as assessment of the national-level emissions impact does not require state-level precision.

State tiering approach

State-level climate action in the United States varies considerably from across the country. For example, some states aim to achieve 100% ZEV sales in light duty vehicle (LDV) markets by 2035, while other states have less ambitious ZEV sales targets, and some lack ZEV sales targets entirely. Therefore, to account for the unequal ambition and urgency with which states implement policies and actions to reduce emissions, and to facilitate our scenario analysis, we group states into three different tiers. State-level tiering reflects the propensity of a state to take further climate action based on the strength of their past and current climate policies. Tier 1 states have been leading the way on climate action in the United States, while Tier 2 states have some policies in place, but tend to move slower. The rest of the states, categorized as Tier 3, have taken limited steps to advance climate action, and are assumed to be least likely to enact ambitious climate legislation.

- **Tier 1 states:** California, Colorado, Connecticut, Delaware, the District of Columbia, Hawaii, Illinois, Maine, Maryland, Massachusetts, Minnesota, New Hampshire, New Jersey, New Mexico, New York, Oregon, Pennsylvania, Rhode Island, Vermont, and Washington
- **Tier 2 states**: Arizona, Iowa, Michigan, Missouri, Nevada, North Carolina, Ohio, Virginia, and Wisconsin
- **Tier 3 states:** Alabama, Alaska, Arkansas, Florida, Georgia, Idaho, Indiana, Kansas, Kentucky, Louisiana, Mississippi, Montana, Nebraska, North Dakota, Oklahoma, South Carolina, South Dakota, Tennessee, Texas, Utah, West Virginia, and Wyoming

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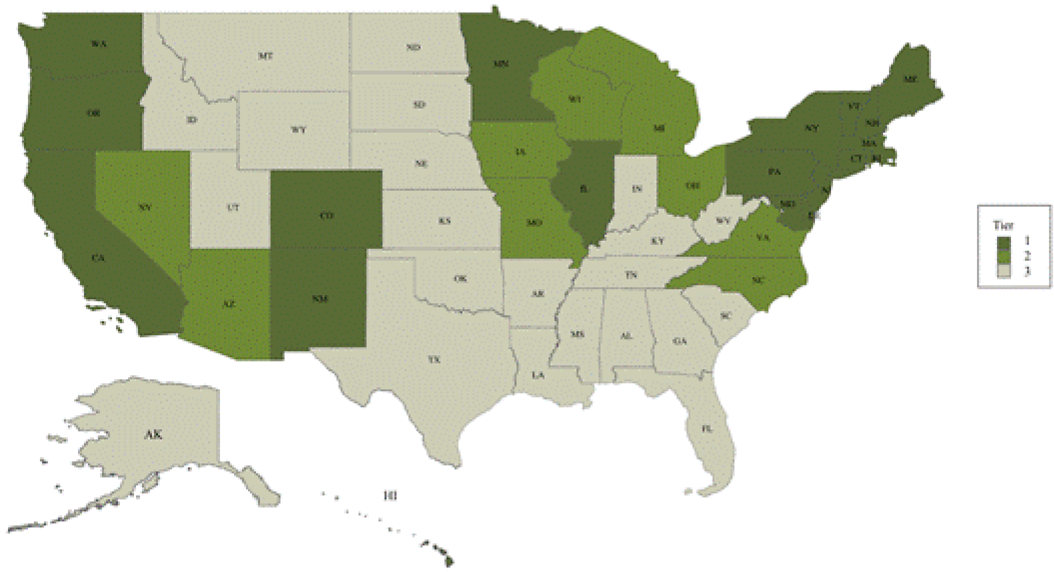

Figure 4: State tiers used in the *Enhanced Ambition* and *Non-Federal Leadership* scenarios

2.1.4.2 Modeling assumptions

Federal Assumptions

Table 1: Modeled federal policies across a range of federal ambitions. For detailed descriptions about how specific policies were modeled in GCAM-USA-CGS for *Current Policies* and *Enhanced Ambition* scenarios, see our previous analysis here.

Policy type	Policy	*Federal Rollbacks Low, Non-Federal Leadership Low*	*Federal Rollbacks High*	*Non-Federal Leadership High*	*Current Policies*	*Enhanced Ambition*
Federal legislation	IRA (Inflation Reduction Act)	Repealed after 2025	Maintained, expires as written	Maintained, then extended at full value through 2035.	Maintained, expires as written	Extended through 2035
	BIL (Bipartisan Infrastructure Law)	Repealed after 2025	Maintained	Maintained	Maintained	Maintained
	AIM Act (American Innovation and Manufacturing Act)	Repealed after 2025	Maintained	Maintained	Maintained	Maintained
Federal regulations	Regulations for new gas and coal generation	Repealed after 2025	Repealed after 2025	Maintained	Maintained	Enhanced
	CAFE (Corporate Average Fuel Economy) standards and GHG standards	Repealed after 2025	Repealed after 2025	Maintained, then enhanced after 2030	Maintained	Enhanced

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	for LDVs.					
	Oil and gas methane regulations	Repealed after 2025	Repealed after 2025	Maintained	Maintained	Maintained
	GHG emissions standards for freight trucks	Repealed after 2025	Repealed after 2025	Maintained, then enhanced after 2030	Maintained	Enhanced
	Standards on oil refineries	-	-	Requires CCS capabilities for 25% of oil by 2035	-	Requires CCS capabilities for 50% of oil by 2035
Direct Air Capture		-	-	Achieves 12 MtCO2 removals by 2035	-	Achieves 20 MtCO2 removals by 2035

Non-Federal Assumptions

Table 2: Non-federal climate actions assumed in all modeled scenarios. For detailed descriptions about how specific policies were modeled in GCAM-USA-CGS, see here.

Policy Type	**Sector**	***Current Policies + Federal Rollbacks* Scenarios**	***Non-Federal Leadership + Enhanced Ambition* Scenarios**		
			Tier 1 States	**Tier 2 States**	**Tier 3 States**
Non-federal	Electricity – RPS	Current state-level RPS targets are modeled	Tier 1 states achieve RPS target of 75% and 95% zero-carbon by 2035	Tier 2 states achieve RPS target of 55% and 95% zero-carbon by 2035	Tier 3 states achieve RPS target of 55%
	Electricity - CES	Not explicitly modeled in this scenario	***Non-Federal Leadership* scenario only**: Tier 1 and 2 states achieve 95% zero-carbon by 2035		-
	Electricity - Cap and trade	The Regional Greenhouse Gas Initiative (RGGI) is modeled as a 30% reduction in power sector emissions below 2020 levels by 2030 in participating states			
	Transportation - LDV sales targets	California and the 14 other states that have adopted ZEV sales targets consistent with California's Advanced Clean Cars (ACC) II legislation are assumed to achieve their passenger car sales target of 68% electric in 2030 and 100% in 2035. Additionally, the 2 states that have only adopted legislation consistent with California's ACC I legislation are modeled to have ZEV sales reach 22% in 2025.	Tier 1 states are assumed to achieve ZEV sales shares equivalent to California's ACC II targets.	Tier 2 states are assumed to achieve sales shares equivalent to California's ACC II targets but on a delayed schedule, 3 years later than Tier 1 states.	Tier 3 states are assumed to achieve sales shares equivalent to California's ACC II targets but on a delayed schedule, 6 years later than Tier 1 states.
	Transportation - EV incentives	Major existing incentives for LDV ZEVs at the state-, utility-, and district levels from the Alternative Fuels Data Center are modeled at the state level as reductions in per-vehicle capital cost. Altogether, these are equivalent to a national average capital cost reduction	No additional policy action is modeled for Tier 1, Tier 2, or Tier 3 states		

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		for LDV EVs of $826 per vehicle.	

Policy Type	Sector	*Current Policies + Federal Rollbacks* **Scenarios**	*Non-Federal Leadership + Enhanced Ambition* **Scenarios**		
			Tier 1 States	**Tier 2 States**	**Tier 3 States**
Non-federal	Transportation - M/HDV sales targets	California and 11 other states achieve sales targets for electric trucks by 2035 consistent with California's ACT legislation	Tier 1 states achieve ZEV sales shares equivalent to California's ACT targets.	Tier 2 states are assumed to achieve sales shares equivalent to California's ACT targets but on a delayed schedule, 3 years later than Tier 1 states	Tier 3 states are assumed to achieve sales shares equivalent to California's ACT targets but on a delayed schedule, 6 years later than Tier 1 states
	Transportation - Bus electrification	Not explicitly modeled in this scenario	All states achieve 100% electrification of new bus sales by 2030		
	Transportation - VMT reductions	Not explicitly modeled in this scenario	Tier 1 states achieve 1.25% annual VMT reductions by 2035	Tier 2 states achieve 1.00% annual VMT reductions by 2035	Tier 3 states achieve 0.75% annual VMT reductions by 2035
	Transportation - Low carbon fuel standards	Not explicitly modeled in this scenario	Tier 1 states achieve biofuels share of 20% in 2030 and 25% in 2035	No additional policy action is modeled for Tier 2 or Tier 3 states	
	Buildings - Energy efficiency	Current state-level EERS were modeled by reducing state-level building service demands	Tier 1 and Tier 2 states achieve 4% annual efficiency savings by 2030		No additional policy action is modeled for Tier 3 states
	Buildings - Zero-emission appliance standards	Not explicitly modeled in this scenario	Tier 1 states achieve 100% electric space heating and water heating sales by 2030	Tier 2 states achieve 100% electric space heating and water heating sales by 2035	No additional policy action is modeled for Tier 3 states
	Buildings - Zero-emission construction standards	Not explicitly modeled in this scenario	Tier 1 and Tier 2 states achieve 100% new electric construction by 2035		No additional policy action is modeled for Tier 3 states
	Industry - CCS targets	Not explicitly modeled in this scenario	All states with cement production install CCS capability for 40% of cement produced by 2035, consistent with California's 40% goal		
	Methane - oil and gas	Not explicitly modeled in this scenario	*Non-Federal Leadership* **scenario only**: All states achieve 0.2% methane emissions intensity target for oil and gas production		
	Methane - waste diversion	Not explicitly modeled in this scenario	*Non-Federal Leadership* **scenario only**: All states achieve 50% landfill methane emissions reduction target		

Policy Type	Sector	*Current Policies + Federal Rollbacks* **Scenarios**	*Non-Federal Leadership + Enhanced Ambition* **Scenarios**		
			Tier 1 States	**Tier 2 States**	**Tier 3 States**

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Coal phaseout	Electricity	Not explicitly modeled in this scenario	Tier 1 states phase out unabated coal by 2030	Tier 2 and Tier 3 states phase out unabated coal by 2035
HFCs		National HFC phasedown is implemented consistent with the American Innovation and Manufacturing (AIM) Act	Tier 1 states additionally adopt Significant New Alternatives Policy (SNAP) and Refrigerant Management Programs (RMP) programs	No additional policy action is modeled for Tier 2 or Tier 3 states

2.1.5 Modelling results

2.1.5.1 Overall Emissions Impacts

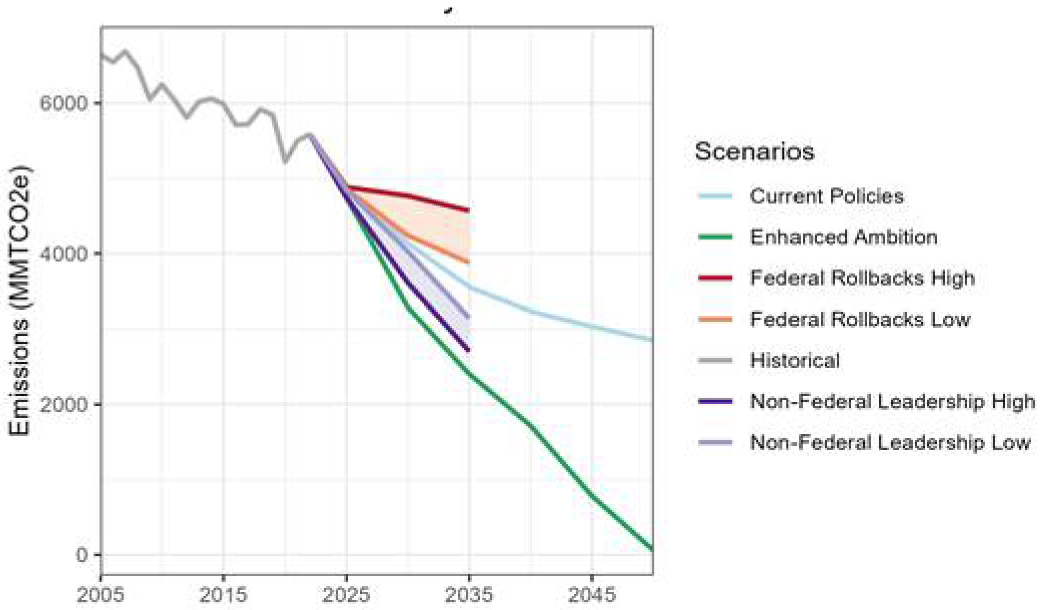

Figure 5: U.S. GHG emissions from 2005 - 2050. Historical emissions through 2020 are taken from the latest available U.S. Environmental Protection Agency (EPA) inventory. The Current Policies scenario achieves 48% emissions reductions below 2005 levels by 2035 in the central case. The Enhanced Ambition scenario achieves 65% reductions in the central case. The Federal Rollbacks scenario and Non-Federal Leadership scenarios achieve a range of 33-43% and a range of 54-62% emissions reductions by 2035, respectively.

The *Current Policies* scenario delivers a 39% reduction in GHG emissions in 2030 and a 48% reduction in 2035, relative to 2005 levels (Fig. 1). By 2050, the scenario achieves 57% GHG emissions reductions. In contrast, the *Enhanced Ambition* scenario includes expanded and new actions from both the federal government and non-federal actors, and delivers 52% in emissions reductions by 2030, at the upper end of the current U.S. NDC range. By 2035, emissions reductions reach 65%, and by 2050, net zero is achieved. The *Federal Rollbacks* scenario achieves a range of 33-43% GHG emissions reductions by 2035; whereas the *Non-Federal Leadership* scenario achieves a range of 54-62% emissions reductions by 2035 (Fig. 5).

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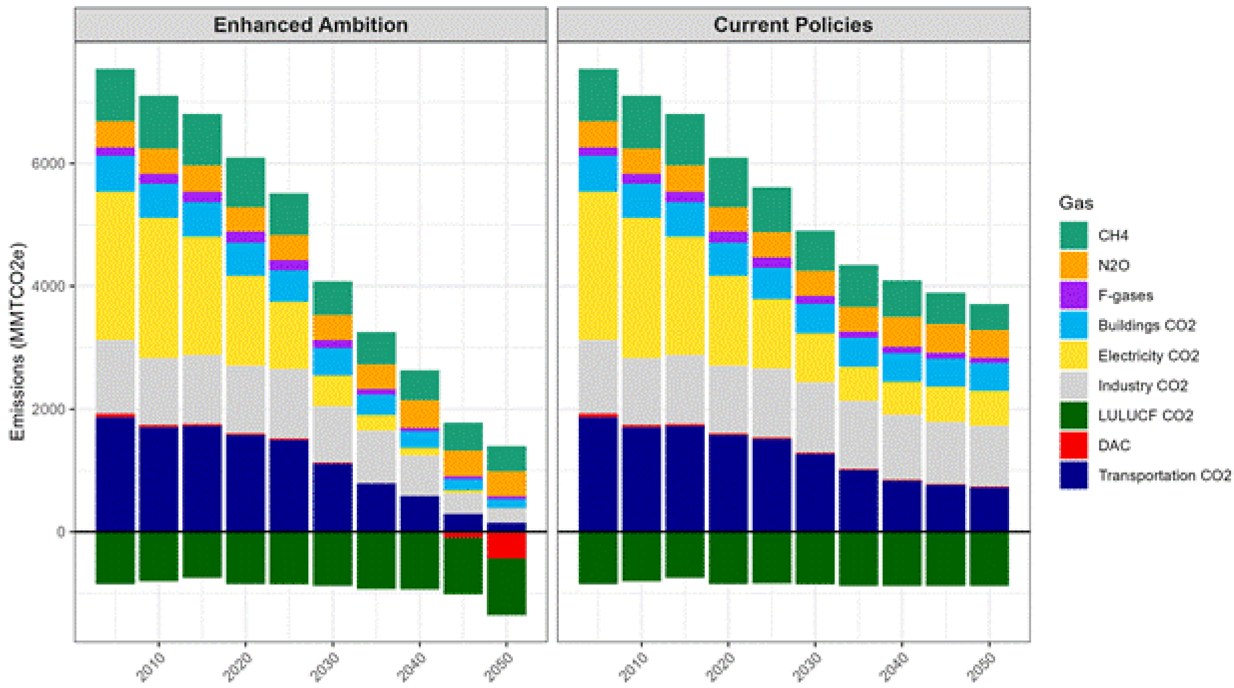

Figure 6: U.S. GHG emissions by gas and sector from 2005 - 2050 under *Current Policies* and *Enhanced Ambition* scenarios.

Major contributions toward the 65% reductions in the *Enhanced Ambition* scenario come from the electricity and transport sectors, which make up 41% (or 1,203 $MtCO_2e$) and 27% (or 790 $MtCO_2e$) of overall emissions reductions from 2020 to 2035 (Figure 6). However, the results also place an increased emphasis on other sectors like buildings (7%, or 211 $MtCO_2e$), industry (8%, or 243 $MtCO_2e$), and methane (10%, or 285 $MtCO_2e$). Other sectors, including direct air capture, land use, and HFCs, contribute the remaining 7% of overall emissions reductions collectively. Based on the EPA's GHG emissions inventory and marginal abatement cost curves, methane mitigation contributes only 10% to overall emissions reductions [4]; however, by assessing its immediate climate impacts over a shorter time frame and by taking into account the potential underestimated inventory, methane abatement can be as important as carbon reductions in the electricity sector through 2035.

Our results show that beyond measures in the electricity and transport sectors, methane mitigation, electrification and efficiency improvements in the buildings and industry sectors, sequestration from CCS technologies, and enhanced land sink sequestration are also important for achieving an ambitious 2035 NDC.

2.1.5.2 Decarbonising the Electricity Grid

The power sector is the second largest source of U.S. GHG emissions, and work remains to decarbonise the sector and achieve a 100% clean grid. Furthermore, as demand for electricity rises in other sectors, like transportation and buildings, the power sector faces the dual challenge of reducing its carbon intensity and providing greater quantities of clean electricity to end-use sectors. Renewable technologies have become significantly cheaper over the years, and replacing fossil fuels with low-cost renewables will be key to decarbonisation.

Under the *Current Policies* scenario, the IRA's tax credits and Energy Infrastructure Reinvestment provision, recent EPA regulations on power plants, and state-level renewable portfolio standards drive up clean generation while phasing down coal and gas generation, reducing emissions by 61% (887 MtCO2e) between 2020 and 2035. By 2035, clean technologies make up 75% of the electricity generation mix. Unabated coal generation is nearly phased out by 2035, while unabated gas generation still makes up 24% share of the generation mix.

Under the *Enhanced Ambition* scenario, emissions fall by 83% (1,203 MtCO2e) between 2020 and 2035. All coal-fired power plants are retired by 2030 as a result of strengthened regulations, coal exit policies, and increasing costs. Additionally, unabated gas generation is reduced as a result of expanded EPA regulations on existing gas

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plants that have a capacity factor greater than 20%, and makes up only 9% of the generation mix by 2035. Meanwhile, a combination of federal action to promote the accelerated deployment of clean electricity sources, including permitting and siting reform, extended IRA tax credits, and increased state ambition accelerate the transition to clean technologies. Solar and wind technologies increase ninefold and nearly sixfold, respectively, enabling a power grid that is 91% clean by 2035. Overall electricity demand increases by 33% in 2035 compared to 2020 levels.

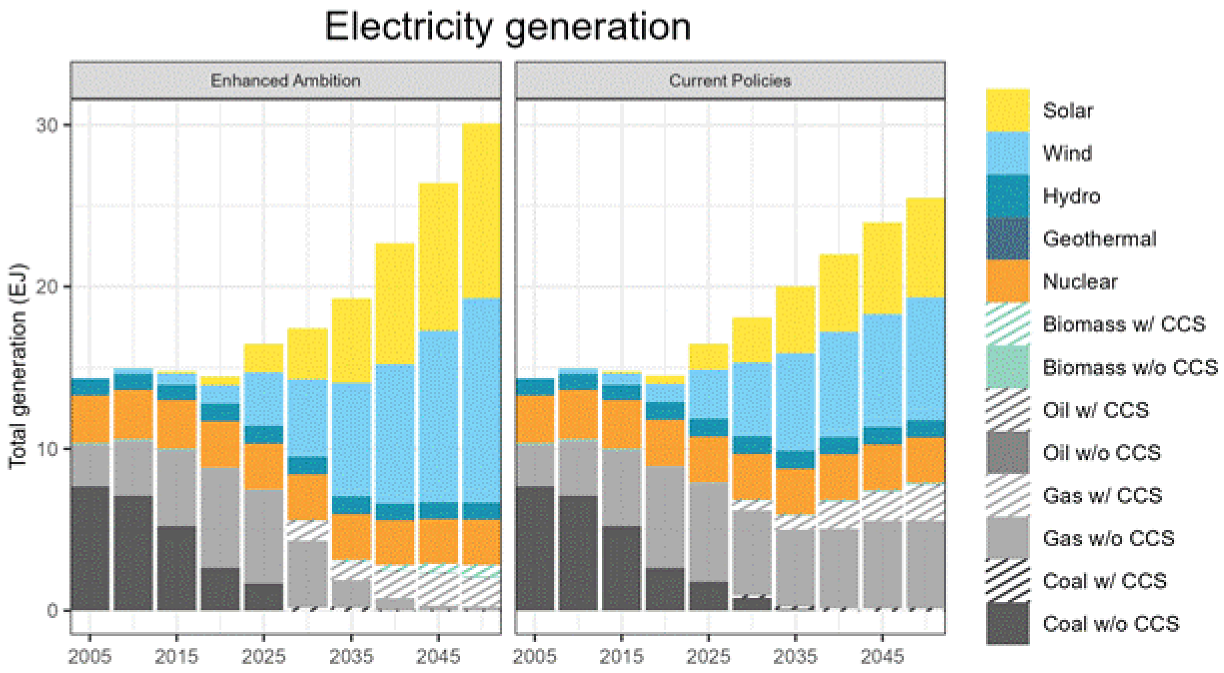

Figure 7: Electricity generation mix in units of exajoules (EJ) under *Current Policies* and *Enhanced Ambition*.

2.1.5.3 Electrifying Passenger and Freight

As the largest source of U.S. GHG emissions, the transportation sector will be critical for near-term emissions reductions. To signal the market trends toward electrification, a growing number of states have started adopting California's Advanced Clean Cars (ACC) II regulations, and 9% of national light-duty vehicle (LDV) sales were electric in 2023. On the medium- and heavy-duty vehicle side, 15 states signed a 2020 Memorandum of Understanding to accelerate freight electrification, aiming for 30% of new medium and heavy-duty sales to be zero-emission by 2030 and 100% by 2050, and 11 states have officially adopted California's Advanced Clean Trucks (ACT) rules.

However, successful implementation of these sales targets will hinge on supportive state policies and initiatives. Additionally, national vehicle miles traveled (VMT) is projected to increase by 0.6% annually through 2040.[5] As such, plans that incorporate sustainable modes of transportation and discourage the use of single-occupancy vehicles will also be important for decarbonising the sector.

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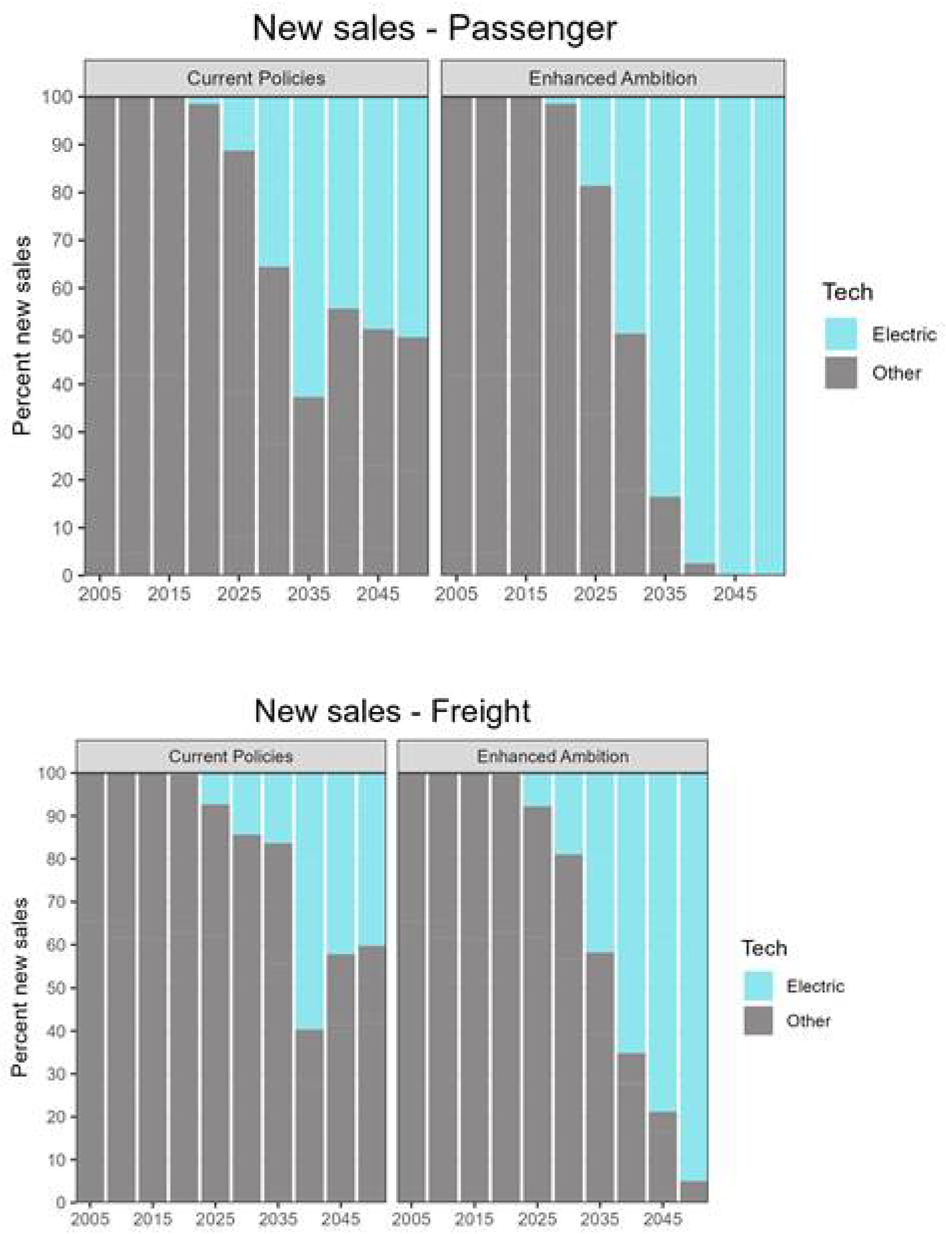

Figure 8: New sales for road passenger (top) and road freight (bottom) vehicles.

Under *Current Policies,* existing actions including IRA tax credits for electric vehicles (EVs), Corporate Average Fuel Economy (CAFE) standards, and state-level incentives and zero-emission vehicle (ZEV) mandates achieve GHG emissions reductions of 36% between 2020 and 2035 (573 $MtCO_2e$). New LDV electric sales reach 68% in 2035, while electric sales for freight trucks reach 16%. Overall road passenger demand increases by 23% between 2020 and 2035.

Under *Enhanced Ambition*, a combination of extended IRA tax credits for EVs, and enhanced state-level EV sales targets, low-carbon fuel standards, and VMT reduction targets drive emissions reductions of 50% between 2020 and 2035 (790 $MtCO_2e$). New LDV electric sales reach 84% in 2035, with the share of LDV electric stock growing to 44%. Electric truck sales reach 42% by 2035. Beyond electrification, states increase the use of biofuels through low-carbon fuel standards and implement VMT reduction policies that reduce the use of single-occupancy vehicles while increasing the use of sustainable modes of transportation. This leads to an increase in road passenger service of only 8% from 2020 levels by 2035, which is a 65% decrease compared to under *Current Policies.*

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2.1.5.4 The Role of Buildings and Industry

The buildings sector in our model accounts for residential and commercial buildings; industrial buildings are accounted for in the industrial sector.

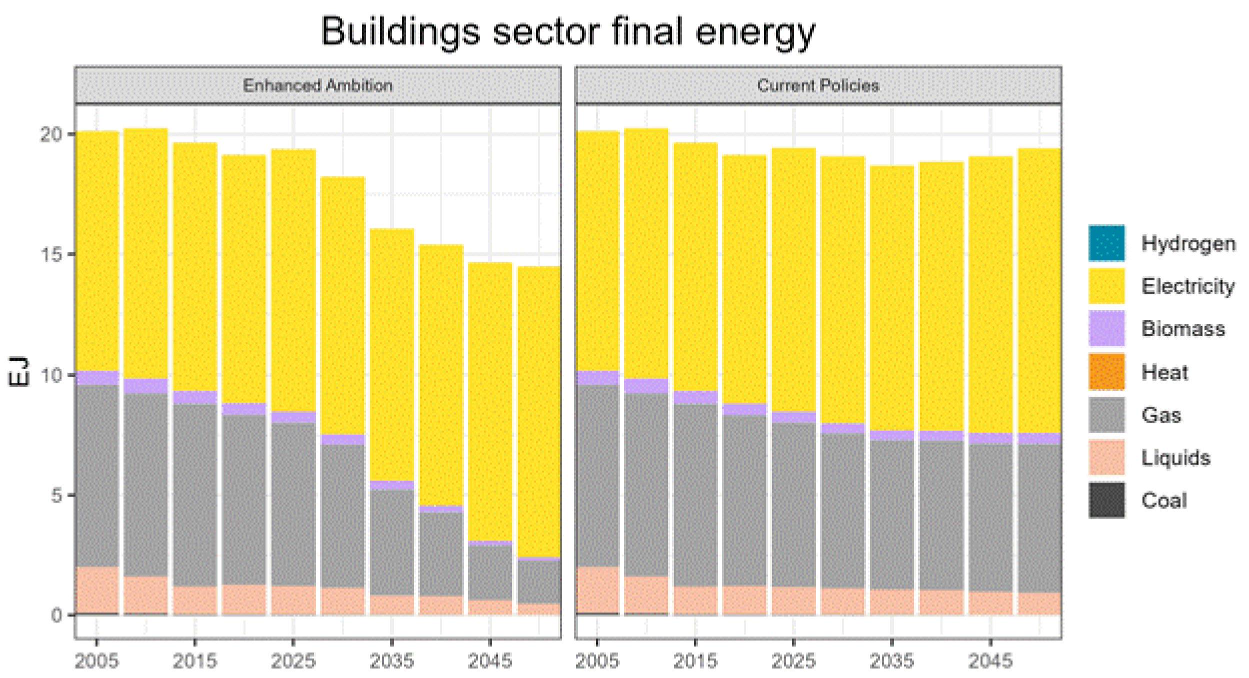

Figure 9: Buildings sector final energy demand in the *Current Policies* and *Enhanced Ambition* scenarios, in units of exajoules (EJ).

In the buildings sector, *Current Policies* including IRA tax credits for building electrification and efficiency and state energy efficiency resource standards (EERS) drive emissions reductions of 14% between 2020 and 2035 (77 $MtCO_2e$). As a result of these policies, the electric share of hot water and space heaters increases from 20% in 2020 to 29% by 2035, and building electrification increases from 54% in 2020 to 59% in 2035. Energy demand stays relatively stagnant (a 2% decrease in 2035, relative to 2020 levels).

Under *Enhanced Ambition*, the extension of IRA incentives alongside the expansion of state-level efficiency and electrification initiatives and standards reduces building sector emissions by 39% between 2020 and 2035 (211 $MtCO_2e$). Final energy demand falls by 16% between 2020 and 2035 due to additional efficiency gains. Building electrification expands under *Enhanced Ambition,* rising to 65% of the final energy share in 2035. As most electrification standards target hot water and space heating appliances, the electricity share for these specific appliances will increase to 38% by 2035.

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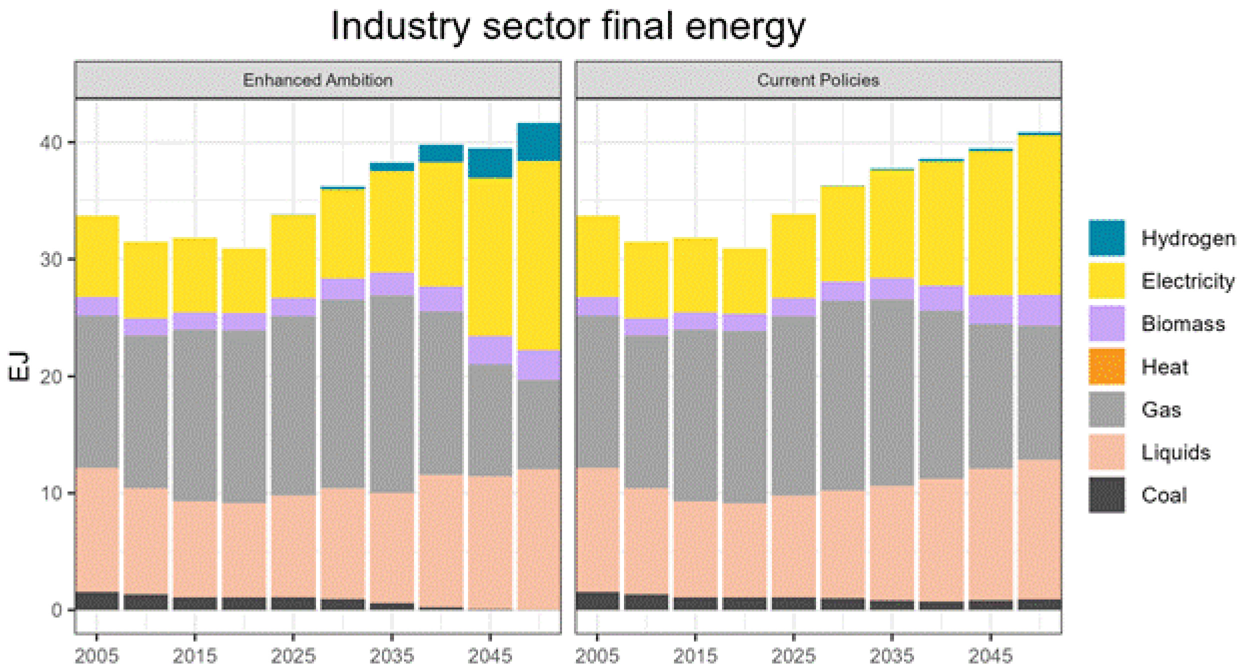

Figure 10: Industrial sector final energy, excluding feedstocks, in the *Current Policies* and *Enhanced Ambition* scenarios, in units of exajoules (EJ).

Industry has lagged behind other sectors in terms of decarbonisation. The sector's diversity and reliance on high-temperature processes, like cement production, create challenges for decarbonisation. While the IRA and BIL provide substantial funding and tax credits for clean fuels, carbon capture, and technology demonstrations, further efforts are needed to continue decarbonising the sector.

In the *Current Policies* scenario, industrial GHG emissions remain flat from 2020 to 2035, with expansion of industrial production outweighing reductions achieved through IRA's credits for captured CO_2, production of clean hydrogen, and manufacturing investment.

Under *Enhanced Ambition*, additional policies reduce industrial emissions by 22% (243 $MtCO_2$) in 2035. While the electricity share of final energy hovers around 25% in 2035, which is similar to *Current Policies*, CCS plays a larger role in this scenario. We assume enhanced uptake of IRA's 45Q tax credit for CCS, complemented by regulations on oil refining that require CCS installation and state-level CCS targets, achieve 154 $MtCO_2$ sequestered in cement, ethanol, oil refining, hydrogen, and pulp and paper sectors, compared to just 15 $MtCO_2$ under *Current Policies*. Moreover, the introduction of direct air capture technology after 2030 sequesters 20 $MtCO_2$ annually by 2035.

The industrial sector will require acceleration in technological advancements and deployment of low-carbon fuels, feedstocks, and energy sources (LCFFES) and carbon capture and storage (CCS). However, these technologies need further development and demonstration to be commercially scaled, with supportive policies that promote their deployment.

2.1.5.5 Setting the Stage for 2050: Methane Abatement, Carbon Removal Technologies, Land Sector Policies

Methane has a critical role to play in slowing near-term warming and has emerged as a new focal point for climate mitigation. On a 100-year time horizon, methane has a global warming potential (GWP) of 28, which means that it is 28 times more potent than CO_2. While the 100-year GWP is used in country-level emissions accounting by convention, methane is much more potent in the near term, with a 20-year GWP of 84, meaning that it is 84 times more potent than CO_2 on a 20-year time horizon. Given methane's high greenhouse warming impact per

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molecule and short atmospheric lifetime compared with CO_2 emissions, methane mitigation can contribute substantially to near-term GHG emissions reductions.

With a methane fee that covers all sources, including agriculture and waste, to incentivize emission reduction measures, *Enhanced Ambition*'s methane emissions decrease by 35% (285 $MtCO_2e$) between 2020 and 2035. This is more than double the rate of methane abatement under *Current Policies*, emphasising the opportunities not yet realized.

Negative emissions through both natural and technological carbon removal also play a role in 2035, and will be increasingly important over the longer term for meeting net zero, as they help to balance the hard-to-abate emissions sources.[48] Historically, the LULUCF sink has remained stable or growing, but there is the possibility of it shrinking in the future if policies related to forest regrowth, forest management, and fire mitigation are not put into place, as well as uncertainties in the impact of climate change itself.[49,50] As a result of full implementation of BIL and IRA funds, and more ambitious state-level policies related to the lands sector under *Enhanced Ambition*, LULUCF sequestration increases by 96 $MtCO_2$ from 2021 to 2035, resulting in a sink of -928 $MtCO_2$ in 2035. In contrast, under the *Current Policies* scenario, the land sector increases carbon sequestration by 52 $MtCO_2$/yr compared to 2021 levels, reaching -884 $MtCO_2$ in 2035.

Additionally, direct air capture (DAC) of CO_2 is introduced as a new technology after 2030 in the *Enhanced Ambition* scenario. As a result of IRA tax credits, which allow up to $180/t$CO_2$ captured for storage from DAC, and state-level initiatives, DAC sequesters 20 $MtCO_2$ in 2035.

2.1.6 Policy Implications & Insights

Under the *Enhanced Ambition* pathway, major transformations will be required across all sectors and gases, including driving down methane emissions in the oil and gas, coal, agriculture, and waste sectors; the transition to a grid that is powered by clean technologies; the acceleration of EV adoption and EV infrastructure buildout while reducing vehicle miles traveled; electrification and efficiency improvements in the buildings and industry sectors; sequestration from CCS technologies; and additional investments in wildfire mitigation programs, afforestation programs, and more to enhance the land sink. Negative-emissions technologies in the form of DAC, biomass with CCS, and LULUCF, will be especially important after 2045 to offset emissions from hard-to-abate sectors and non-CO2 gases. In contrast, the *Current Policies* scenario places a smaller emphasis on emissions reductions from sectors other than power and transportation, and the emissions reductions slow after 2030 due to expiring policies.

In the electricity sector, the Enhanced Ambition scenario includes continued, rapid reductions in unabated fossil power, with all coal-fired power plants either retired or retrofitted with CCS by 2030, no new natural gas plants without CCS by 2035. This level of fossil fuel phaseout is possible through the full implementation of IRA's Energy Infrastructure Reinvestment provision, which provides up to $250 billion to transition away from fossil fuels, finalisation and enforcement of proposed EPA regulations to equip new and existing coal- and natural gas-fired power plants with CCS technologies, and rapid expansion of non-federal renewable energy goals. However, updating and expanding existing transmission and distribution systems will also be needed to better support renewable and clean energy integration, which currently has 1 TW of zero-carbon generation capacity currently stuck in the interconnection queue.6 Additionally, in response to growing demand and the increase in variable renewable energy sources, it will be critical to maintain grid reliability through enhanced grid management practices and investment in storage technologies.7

The rapid electrification of end use sectors will also pose challenges for 2035. In the transportation sector, key new policies include the widespread adoption and implementation of California's regulations for passenger car and freight truck EV sales, the early retirement of old, inefficient vehicles, and expanded incentives that lower the costs of EVs. Though not explicitly modeled in our study, this level of EV adoption entails additional policies in the forms of commitments from automakers, municipal fleet targets, subsidies for low- and middle- income

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consumers, and additional investments in the buildout of sufficient EV charging infrastructure. Scaling the electrification of freight trucks will be especially challenging, given the limited supply of electric trucks at present, the charging needs across state borders, and high associated costs, especially for long-haul trucks.[8] Additionally, some uncertainties remain about the capacity of vehicle supply chains to meet these goals, as many materials necessary for EV production have been classified as critical or near-critical supply risks, such as lithium, cobalt, nickel, and platinum.[9] Moreover, the extraction process for critical minerals is associated with substantial environmental justice concerns.[10]

Across all sectors, the extension of IRA provisions beyond their legislated sunset dates will be another important element for 2035 reductions. In the year since its passage, IRA has accelerated renewable energy deployment, leading to the announcement of 272 new clean energy projects in EV, wind and solar, and battery manufacturing, totaling over $270 billion in new investments.[11] This level of clean energy investment in the United States is unprecedented, surpassing eight years' worth of historical clean energy investments.[12] Beyond clean energy technologies, IRA also allocates over $20 billion in funds for various land sector initiatives and introduces a substantial fee for oil and gas methane, which would apply to facilities not covered by the EPA methane regulations. By lowering the costs of clean energy, IRA investments can motivate both federal and non-federal actors to seek more ambitious climate action. For instance, the recent proposed standards from EPA address technologies that receive subsidies from IRA, including CCS and hydrogen.[13] This level of momentum and innovation across all levels of society could stall if IRA's provisions are left to expire as written.

This analysis assumes a full implementation of IRA climate and energy provisions. However, the effectiveness of some provisions is dependent on the uptake by state, local and individual actors. Lack of outreach and education may lead to missed opportunities in taking advantage of the full tax credit for provisions such as residential building rebates. Furthermore, it is also possible that some policies could be watered down upon finalisation. IRA's clean vehicle tax credit, for example, may not deliver the full scale of emissions reductions as assumed in this analysis if automakers face challenges meeting the eligibility requirements on mineral sourcing and battery assembly for this tax credit.

Importantly, the transformations under Enhanced Ambition will require the ability to overcome various political, social, and technological barriers, which can create uncertainties around policy uptake and durability. The new administration as well as ongoing lawsuits around current regulations present significant market uncertainty and potential additional hurdles to overcome. In the face of potential federal rollbacks, however, we find that non-federal actors can still drive significant progress. Strong climate leadership from these actors will be critical for the U.S. to stay on track toward its near-term targets and long-term net zero goal.

2.1.7 Discussion

The model used for our research, GCAM-USA-CGS, has many features that make it well-suited for this type of analysis. These include its ability to offer full coverage of all emitting sectors across the economy, beyond standard energy sector CO_2-only studies, as well as its ability to link the U.S. states with regions in the rest of the world. Additionally, the model includes dynamic feedbacks across sectors, a rich technological representation, and emissions, energy, and trade details for 50 states. Even so, our analysis has some limitations. The model has difficulty capturing the uncertainty in building out transmission and distribution infrastructure– which other studies have shown to be critical in power sector decarbonisation.[14] Additionally, though our analysis shows a key role for CCS technologies towards 2035, there is still considerable uncertainty as to the viability of these technologies at scale.[15]

Despite these limitations, our analysis provides valuable information on the magnitude and variety of actions needed to set a high-ambition and achievable U.S. 2035 NDC target. While no strategy can generate absolute certainty, embedding ambitious climate action at multiple levels of government can support a more effective and durable climate strategy, and can mitigate potential political backsliding if future elections return less climate-

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friendly governments.

Critically, accelerated leadership from non-federal actors can keep the U.S. on a path of progress and contribute significantly toward the existing U.S. climate pledges and global climate goals. This initial CGS assessment of the emissions impacts associated with potential federal rollbacks underscores the importance of accelerated non-federal climate action in maintaining the momentum of the U.S. clean energy transition. In addition to increased climate impacts, slowing down this transition may have significant health, economic, and social effects on U.S. communities, which will be further assessed in a forthcoming analysis.

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2.2 India: Decarbonising the building sector

2.2.1 Stakeholder Engagement Process

Summary of Stakeholder Engagement Workshop on "Building Sector and India Net Zero 2070" held at IIM Ahmedabad in August 2024

Context and Objective

The workshop, centred on India's commitment to achieving Net Zero by 2070, focused on decarbonising the building sector. India's building sector plays a crucial role in the nation's energy landscape, accounting for 33% of its total final energy consumption, which is projected to grow by approximately 8% per annum. Final energy consumption in building sector is driven by the rising demand for housing, space cooling appliances, increased ownership of household appliances, and greater access to modern cooking fuels. Both building and construction sectors contribute nearly one-third of India's greenhouse gas emissions, from operational activities as well as embodied emissions in materials and construction. Hence addressing emissions from these sectors is vital for India's transition to a Net Zero future.

List of Stakeholders Participated in Workshop

The event aimed to deliberate a thoughtful discussion between building sector experts, real estate financial managers, and academicians (professors, researchers, post graduate and PhD students). Total 65 stakeholders participated in the workshop which included about 8 building sector experts, 5 real estate financial managers, and remaining 52 of academicians. The participants engaged in discussions around opportunities and challenges in building sector decarbonisation, addressing energy demands, policy priorities and implementation gaps.

Brief Summary of Workshop

The workshop highlighted the critical role of building sector in achieving India's Net Zero 2070 target. Key recommendations included strengthening policy frameworks, advancing green building practices, improving financial mechanisms, and fostering cross-sector collaboration. The discussions emphasized upon the need to prioritize resource efficiency, accelerate retrofitting efforts, and enhancing demand- side management practices. The workshop emphasized the urgency of addressing the rising energy demand in the building sector. There is a need for stronger collaboration between the government, building and construction industry to tackle challenges related to energy efficient appliances in building sector to align their efforts to create energy-efficient and environmentally responsible solutions.

Various stakeholders participated in the workshop also highlighted that there is a need to prioritise the decarbonising India's building sector because of huge policy gap both at design and implementation level. Furthermore, lack of scientific and peer-review literature necessitates to deep-dive into decarbonisation/ Net Zero pathways for residential buildings in India towards achieving its updated NDC targets to the UNFCCC by 2030.

Key Questions to the Workshop Stakeholders

1. What are the NZ pathways for residential buildings towards India's NZ 2070?
2. What are the high impact opportunities (policy priorities) for residential buildings towards India's NZ 2070?

2.2.2 Scenario Development & Harmonisation

Two scenarios will be developed based feedback received from stakeholder engagement workshop in India.

1. **Business as Usual (BAU) scenario:** 2018 as base year with projections until 2050
2. **Net Zero scenario (NZS):** 2018 base year with projections until 2050

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NZS will focus on increase share of EE appliances i.e. super-efficient ACs, energy efficient ceiling fans, LED lights, clean cooking appliances, other EE appliances, etc. in residential sector of India.

The results of the study are part of "Study 13 – Household decarbonisation" and will be reported in Deliverable D5.7: Behaviour, social, and disruptive innovation – Update, due in August 2025.

2.3 China: Understanding the impacts of the EU CBAM on China's export industries

2.3.1 Stakeholder Engagement Process

Context and Objective

A Stakeholder Engagement Workshop on "Green Barriers or Transformational Opportunities? EU Carbon Tariffs on China's Export Industries" was held in Beijing in January 2025. The workshop explored the impact of EU CBAM (carbon boundary adjustment mechanism) on China's related industries and aims to facilitate collaboration between the IAM COMPACT modelling team and policymakers, representatives of the ISAP (iron, steel, and aluminium products) sectors.

China is the EU's largest import source and the embodied emissions of its exports to the EU are increasing (Li et al., 2020; Xiao et al., 2015). Among the goods covered by EU CBAM, China's exports include iron, steel, aluminium, cement, and fertilizers. In particular, iron and steel, aluminum, and their products (ISAP) dominates exports, with China shipping 7.43 Mt worth €13 billion to the EU in 2023, surpassing other goods (Pan et al., 2025). ISAP production accounts for around 20% of China's total carbon emissions (Chen et al., 2023), making it highly vulnerable to the impact of CBAM. While CBAM currently targets direct emissions from ISAP and requires reporting of indirect emissions from electricity use, its scope may be expanded in the future to cover emissions from the entire industrial chain.

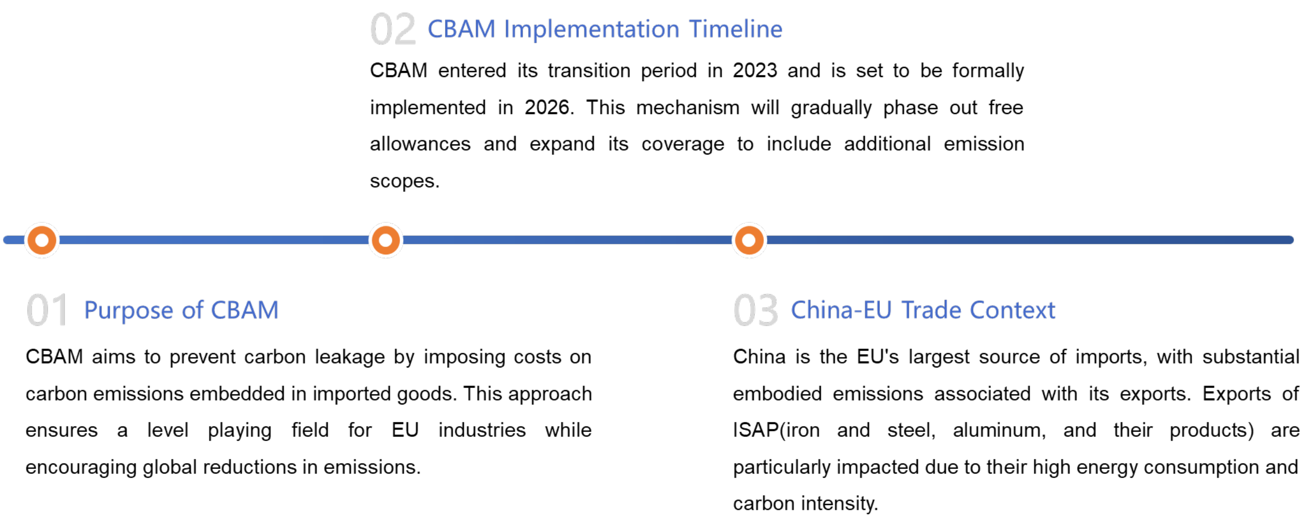

Figure 11: Background of EU CBAM

List of Stakeholders Participated in Workshop

The aim of the event was to deliberate a thoughtful discussion between policy makers, ISAP sector engineers and experts, and academicians (professors, researchers, postgraduate and PhD candidates). A total of 20 stakeholders participated in the workshop, including about 5 policy makers, 7 ISAP and energy sector experts, and the remaining 8 academicians. The participants engaged in discussions around opportunities and challenges of adapting the ISAP sector to the EU CBAM, the dynamic impact assessment of EU CBAM and the future decarbonization technology roadmap.

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The workshop started with a brief introduction of the IAM COMPACT project, and the aims of the workshop was presented by Yu Wag. Then, Tianpeng Wang briefly presented the modelling, scenario design and results of our research.

Summarising the key findings from stakeholder inputs:

The EU CBAM kicked off testing in October 2023 and will be formally implemented in 2026, expanding from an initial scope of six products - iron and steel, cement, aluminium, fertilisers, electricity and hydrogen - to eventually cover more than 50% of emissions from sectors covered by the EU's Carbon Emissions Trading Scheme (CETS).

China's **Ministry of Commerce** has initiated several rounds of discussions on the EU CBAM in the multilateral trading system. Ministry of Commerce hopes to work with all parties to promote thematic discussions on green trade policies, including the EU CBAM, to prevent them from becoming new trade barriers.

From the perspective of the **Ministry of Industry and Information Technology** (MIIT), the impact of the EU CBAM on China's industrial sector should not be underestimated, especially on industries with high energy consumption and emissions. Once fully implemented, the EU CBAM will mean that China's exports of relevant industrial products to the EU, such as steel and aluminium, may have to bear additional carbon tariff costs. This will not only weaken the price competitiveness of China's industrial products in the EU market, but may also trigger a trade diversion effect, causing some orders to go to countries and regions with lower carbon costs, which will in turn affect the international market share and industrial development of China's related industries. The lack of clarity, transparency and arbitrariness in the implementation rules of the EU CBAM will create a lot of uncertainty for Chinese companies in the process of responding and will increase compliance costs and business risks.

China's **iron and steel** products exported to the EU in 2023 account for 76% of the total exports of the six categories, directly facing the impact of the policy. As the EU tightens its emission reduction policy and expands the scope of CBAM, it faces the twin challenges of rising costs and eroding global competitiveness. Since the start of CBAM transition phase in October 2023, enterprises have taken proactive measures: first, accelerated low-carbon R&D, working with the government and scientific research institutes to promote the application of technologies such as hydrogen-rich carbon-cycle blast furnace, CCUS; second, production structure adjustment, some long-process enterprises increased the ratio of electric furnace short-process steel production to reduce carbon emission costs. Despite these efforts, carbon tariffs will still significantly inflate production costs and weaken price competitiveness. Enterprises are mitigating compliance risks and market losses by cooperating with importers on emissions reporting, deepening policy research, and accelerating green transformation.

The **aluminum industry** is also a key target for CBAM due to its high energy consumption. To maintain market share in the EU, companies must accurately account for their carbon emissions or pay high fees for exceeding emissions standards. During the transition period, the industry has explored solutions through multi-party collaboration: some companies have introduced advanced electrolyser technology to optimize production processes and reduce energy consumption per unit of product; and they have sought to collaborate with foreign institutions to improve their carbon management capabilities. However, capital requirements for technological change are high and slow, and SMEs are generally under pressure. If the EU subsequently extends the scope of CBAM or raises the standard, the industry will face greater challenges.

2.3.2 Scenario Development & Harmonisation

The uncertainties surrounding the impact of CBAM costs on China's ISAP exports primarily stem from three interconnected factors: the future trajectory of carbon mitigation targets, the technological development paths chosen, and the evaluation of global trade trends. In particular, the interplay between abatement targets and technology choices not only shapes the dynamics of carbon pricing but also determines the specific emission profiles and energy use characteristics of the Chinese steel industry in different regions. This study discusses the impact of CBAM on China's ISAP under different emission targets in China and technology mix scenarios for the iron and steel sector by 2035.

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China's 2035 carbon emissions (GtCO₂)

8.0	8.5	9.0	9.5 (default)	10.0	10.5	11.0

Table 3: Iron and steel production structure in 2034

iron and steel's production technologies	High	Medium (default)	Low
BF-BOF (blast furnace-basic oxygen furnace)	0.461	0.530	0.604
BF-BOF with CCS (carbon capture and storage)	0.1054	0.144	0.1854
DRI-EAF (direct reduced iron-electric arc furnace)	0.0474	0.036	0.022
DRI-EAF with CCS	0.055	0.042	0.025
Hydrogen-based DRI-EAF	0.037	0.027	0.015
Scrap-EAF	0.293	0.222	0.148

2.3.3 Modelling Approach & Results

Modelling Approach

In this study, we have developed a new modelling framework that integrates a global multi-regional input-output (GMRIO) table embedding Chinese provinces with an integrated assessment model (IAM) embedding Chinese provinces to estimate carbon emissions and CBAM costs from China's ISAP exports to the EU (Pan et al., 2025). Unlike previous studies that rely on static assumptions, this framework incorporates dynamic changes in emissions intensity, sector development and carbon pricing in line with NDCs. It extends the exiting literature by accounting for provincial-level heterogeneity and by integrating the three emission scopes potentially covered by CBAM: direct carbon emissions (DCE), direct carbon emissions and indirect carbon emissions from power use (DICE), and embodied carbon emissions (ECE). This comprehensive and dynamic approach provides new insights into the implications of CBAM for China's ISAP exports, taking into account mitigation targets, technological advances and regional differences. The framework can also be applied to other industries and countries, potentially inspiring IO-IAM coupling for broader environmental, economic, and policy impacts assessment.

(1) ***China-More model***

The China Multi-Gas Optimal Reduction Evaluation Model is based on the TIMES (The Integrated MARKAL-EFOM System) framework and uses the Veda 2.0 platform. As a typical bottom-up, technology-rich model, it provides a detailed representation of greenhouse gas emissions, including CO_2, N_2O, CH_4 and F-gases, as well as comprehensive modelling of abatement technologies. A key feature of the model is its power dispatch module, which captures the challenges of integrating variable renewable energy sources into the power system. In addition, the model includes a sensitivity analysis module to assess the impact of key factors and parameters, ensuring robust and reliable results.

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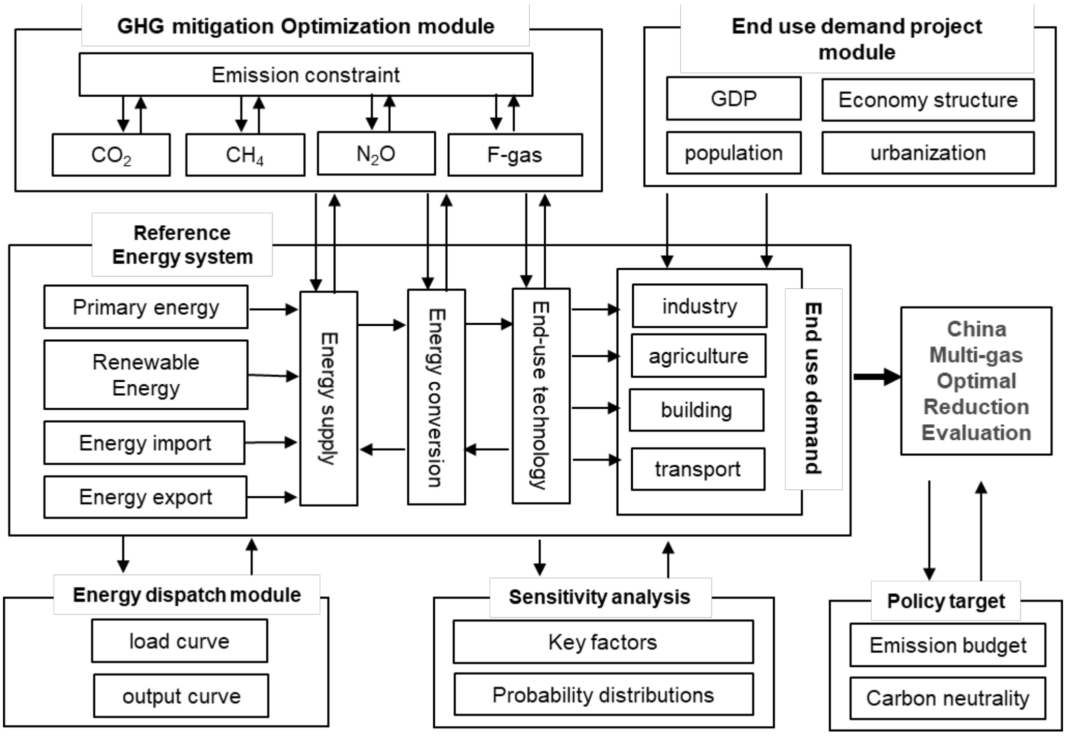

Figure 12: The framework of China-MORE model

(2) *IMACLIM-CHN model*

This study builds an 18-sector single-region general equilibrium model of China, IMACLIM-CHN, on the MPSGE platform in GAMES, which includes 6 energy sectors and 12 non-energy sectors.

Table 4: Energy and non-energy sectors covered by IMACLIM-CHN

code	Energy sector	code	Non-energy sector
COA	Coal mining and washing	**AGR**	Agriculture
OIL	Crude oil extraction	**MIN**	Mining
GAS	GAS extraction and transmission	**FOOD**	Food and Beverage Tobacco Processing
REF	Oil refining	**CHM**	Chemical
COKE	Coking	**STE**	Steel
ELE	Power and heat supply	**NFM**	Non-Ferrous Metals
		NMM	Non-metallic mineral products
		EQUT	Equipment manufacturing
		OTHIND	Other industry
		CON	Construction
		SERV	Service
		TRAN	Transportation

In this research, we developed the hybrid energy-economy dataset by using China's 2015 input-output table, energy balance table, and market price survey.

- Aggregate the I-O table into 18 sectors.

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- Aggregate the energy balance table into 18 sectors.
- The original price matrix was calculated by dividing the value matrix by the volume matrix.
- Adjusting the original price matrix based on market price information.
- A new energy value matrix by derived by multiplying the adjusted price by the volume.
- Replace the matrix with the adjusted energy value matrix and rebalance it.
- Adjusting the energy costs and energy volume in the BU model, according to the dataset.

(3) *TIMES and CGE Model Hard link*

A tightly coupled energy economic assessment framework has been constructed. The abatement pathways and costs for each sector are given by the TIMES model from a technology perspective, and the industrial structure and demand for energy services are derived from the CGE model from a general equilibrium perspective.

Before constructing the CGE model and the TIMES model, this study constructs a hybrid SAM matrix based on the unification of physical quantity-price quantity-value quantity of energy based on input-output table, energy balance table and research on energy market price, and constructs the CGE model based on this matrix.

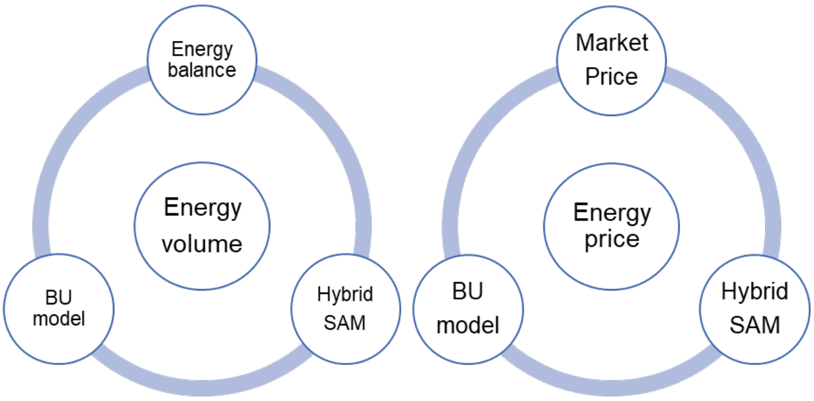

Figure 13: Hybrid SAM matrix based on the unification of physical quantity-price quantity-value quantity of energy based on input-output table

Based on this matrix, the CGE model is constructed, and the energy quantity and energy price in the TIMES model are calibrated according to this matrix.

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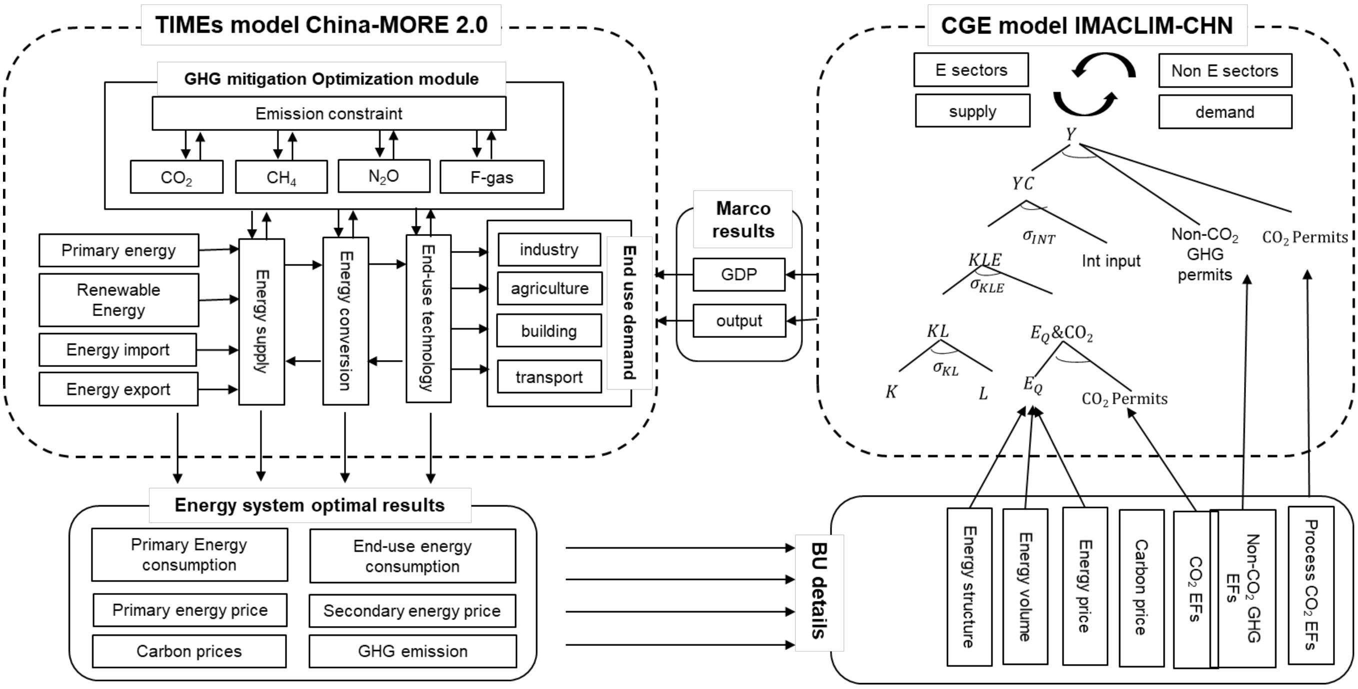

Figure 14: Modelling framework and soft-linking of TIMES model China-MORE 2.0 and CGE model IMACLIM-CHN

(4) *GMRIO*

The GMRIO table used in this study, developed by Li et al. (2017), integrates data from the OECD's inter-country IO table and China's inter-provincial IO table. Unlike other IO tables that treat China as a single region, this table disaggregates China into 31 provinces and divides the rest of the world into 96 countries and regions, including the EU-27. It provides detailed trade links between Chinese provinces and world countries, allowing the analysis of value-added flows and CO2 emissions at both provincial and international levels. The table has been used in recent studies to examine carbon emissions and value chain dynamics. However, due to data limitations, this study focuses on 30 Chinese provinces, excluding Xizang, Hong Kong, Macau and Taiwan. The framework of the table is shown in Figure 15 and the latest available year is 2017.

<table>
<tr><td colspan="3" rowspan="3"></td><td colspan="7">Intermediate use</td><td colspan="7">Final use</td><td rowspan="3">Total output</td></tr>
<tr><td rowspan="2">Country 1</td><td rowspan="2">…</td><td colspan="3">China</td><td rowspan="2">…</td><td rowspan="2">Country Q</td><td rowspan="2">Country 1</td><td rowspan="2">…</td><td colspan="3">China</td><td rowspan="2">…</td><td rowspan="2">Country Q</td></tr>
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<tr><td rowspan="7">Intermediate input</td><td colspan="2">Country 1</td><td colspan="7" rowspan="7">Z</td><td colspan="7" rowspan="7">Y</td><td rowspan="7">X</td></tr>
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<tr><td rowspan="3">China</td><td>Province 1</td></tr>
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<tr><td>Province P</td></tr>
<tr><td colspan="2">⋮</td></tr>
<tr><td colspan="2">Country Q</td></tr>
<tr><td colspan="3">Taxes and subsidies</td><td colspan="7">T</td></tr>
<tr><td colspan="3">Value-added</td><td colspan="7">V</td></tr>
<tr><td colspan="3">Total input</td><td colspan="7">X</td></tr>
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Figure 15: The framework of the global multi-regional input-output table embedding Chinese province

(5) *Coupling GMRIO and Hard link Model*

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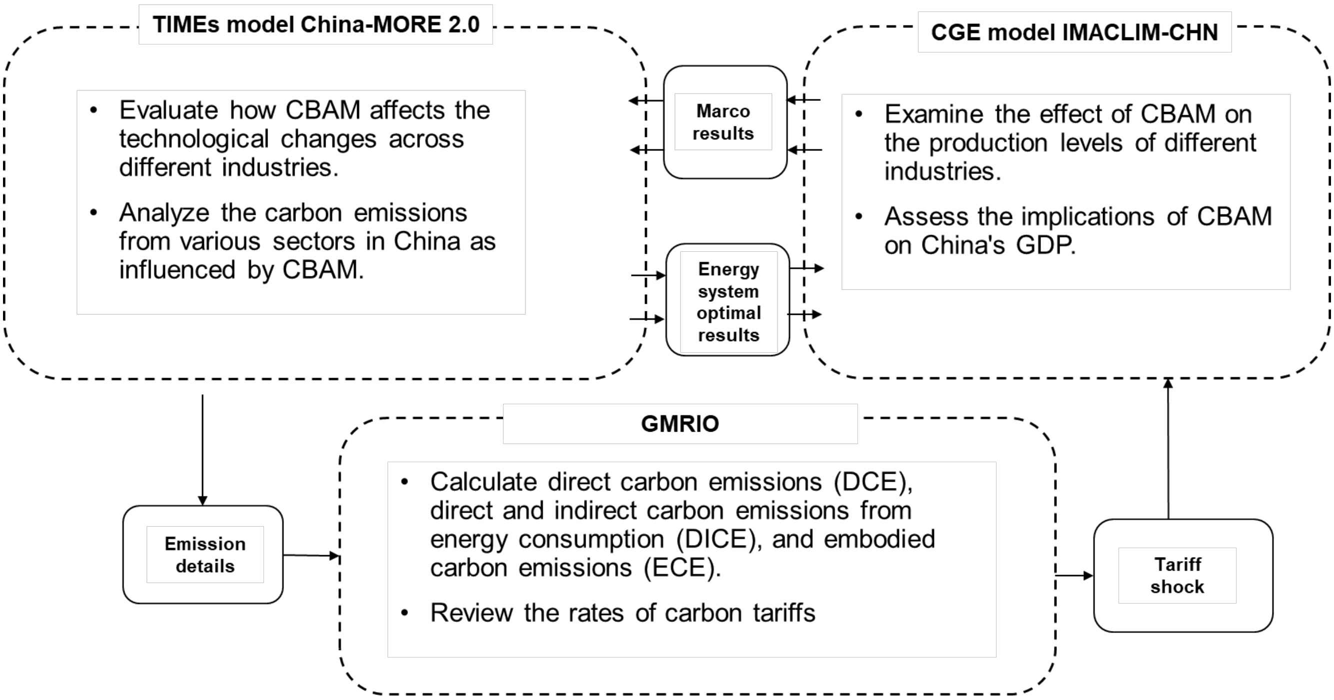

Figure 16: Modelling framework and links among TIMES model China-MORE 2.0, CGE model IMACLIM-CHN, and GMRIO table

Results

(1) Carbon Emissions from China's iron and steel, aluminium, and their products (ISAP) Exports to the EU

In 2017, China exported 6.1 million tons of CO_2 equivalent ($MtCO_2$) in DCE to the EU. In addition, indirect carbon emissions from electricity sue for these exports amounted to 2.7 $MtCO_2$, bringing the total to 8.8 $MtCO_2$ when combined with DCE. If the EU's CBAM is extended to cover embodied carbon emissions along the entire industrial chain, emissions would rise to 17.7 $MtCO_2$, almost three times the DCE.

By integrating an accounting methodology with GCAM-China simulations, the study estimates future trends in carbon emissions from exports, taking into account factors such as improvements in emission factors and changes in trade volumes. By 2026, the DCE, DICE and ECE are projects to increases slightly to 6.5 $MtCO_2$, 9.2 $MtCO_2$ and 18.8 $MtCO_2$ respectively. By 2034, as China's carbon emissions peak and begin to decline, these figures are projected to fall to 5.4 $MtCO_2$, 7.4 $MtCO_2$ and 15.8 $MtCO_2$, respectively.

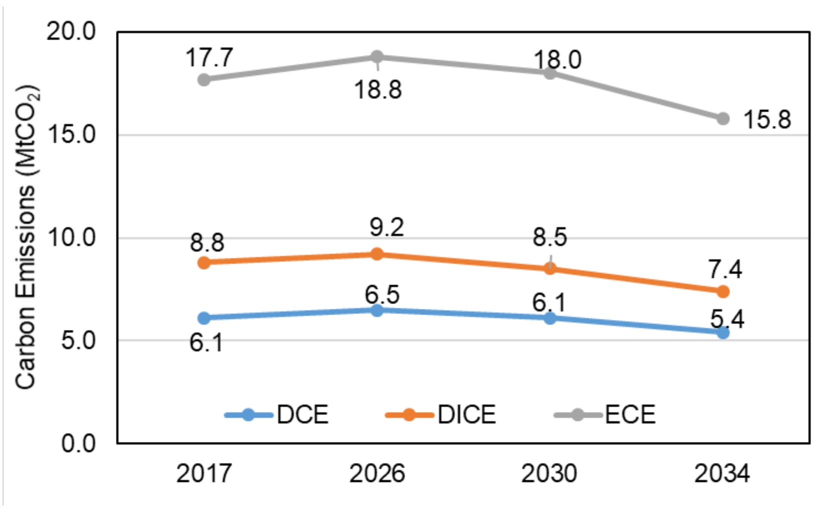

Figure 17: Carbon emissions of China's ISAP exports to the EU

(2) The implementation of the CBAM imposes additional costs on Chinese ISAP exports to the EU

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EU carbon prices are project to reach 200 €/tCO_2, 278 €/ tCO_2 and 309 €/ tCO_2 in 2026, 2030 and 2034 respectively, while China's carbon prices are projected to 30 €/ tCO_2, 41 €/ tCO_2 and 95 €/ tCO_2 in the same period. CBAM costs faced by China's ISAP exports depend on the EU-China carbon price gap and export emissions.

In 2026, DCE-related costs are estimated at € 185 million, rising to € 499 million in 2030 and € 1,157 million in 2034 as the EU phases out free carbon allowances. By 2034, CBAM costs under the DCE account for 14% of China's ISAP export value in 2017. Including indirect emissions from electricity use increases costs to € 407 million, € 940 million and € 1,572 million in 2026, 2030 and 2034 respectively. If CBAM also includes ECE, the costs escalate to € 1,727 million, € 3,101 million and € 3,378 million over the same period.

The carbon price differential has a significant impact on CBAM costs. From 2026 to 2030, China remains in its carbon peak phase, with widening price differentials leading to cost increases of 33%, 40% and 57% for DCE, DICE and ECE respectively. After 2030, as China transition to carbon neutrality under its 2035 NDC, the price gap narrows, reducing CBAM costs by -13%, -20% and -123% for the three emission scopes. However, the phasing out of free allowances continues to drive up cost until 2034.

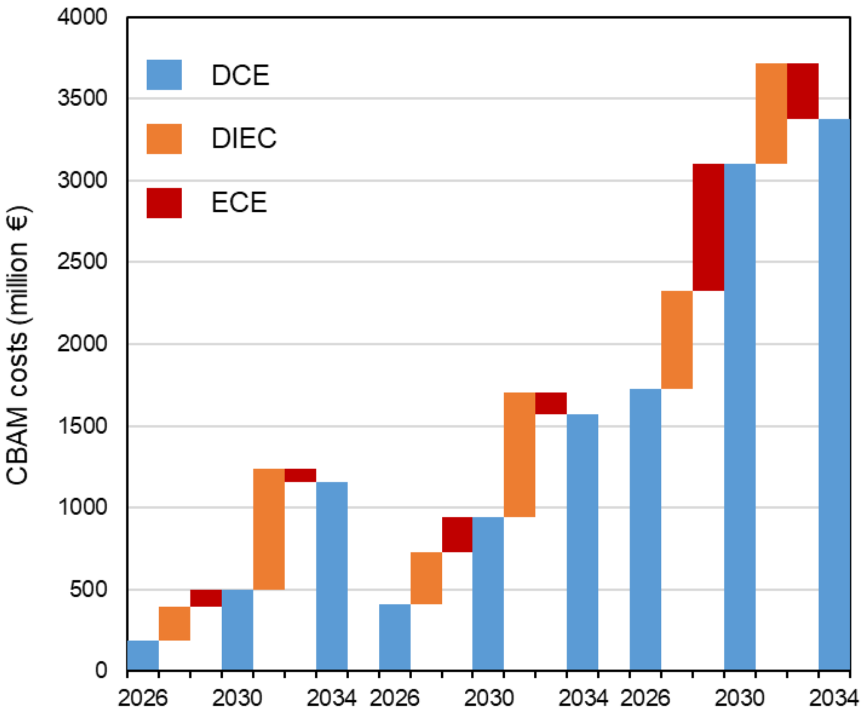

Figure 18: CBAM costs of China's ISAP exports to the EU

(3) CBAM costs of China's ISAP exports to the EU in 2034 under different mitigation targets and technology penetration

Under a less ambitious mitigation target, the estimated CBAM costs for China's ISAP in 2034 would increase compared to the default results: €1.5 billion for DCE (28% increase), €2.1 billion for DICE (31% increase) and €4.5 billion for ECE (34% increase). For every 0.5 GtCO_2 increase in emissions mitigation, the costs decrease by about €98.5 million for DCE, €152.8 million for DICE, and €56.4 million for ECE.

In contrast, under an ambitious target of reducing emissions to 8 GtCO_2 by 2035, the ISAP CBAM costs for 2034 are projected to drop to €0.9 billion for DCE (23% decrease), €1.2 billion for DICE (27% decrease) and €2.4 billion for ECE (29% decrease). In particular, the smaller cost reduction for DCE reflects the inherent challenges of decarbonising ISAP-related industries.

Technological progress, in particularly the adoption of EAF (Electric Arc Furnace) technology, plays a crucial role in shaping the ISAP CBAM costs. A shift from medium to high EAF penetration cuts CBAM costs by up to €26/t and system costs by €27. Notably, more than 40% of the system cost increases are offset by CBAM costs saving

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under higher EAF penetration. Accelerating EAF penetration not only helps reduce CBAM costs but also reduces the risk of carbon lock-in in China's iron and steel sector. From medium to high EAF penetration, China's direct emissions from iron and steel production in 2034 decrease from 397 $MtCO_2$ to 360 $MtCO_2$.

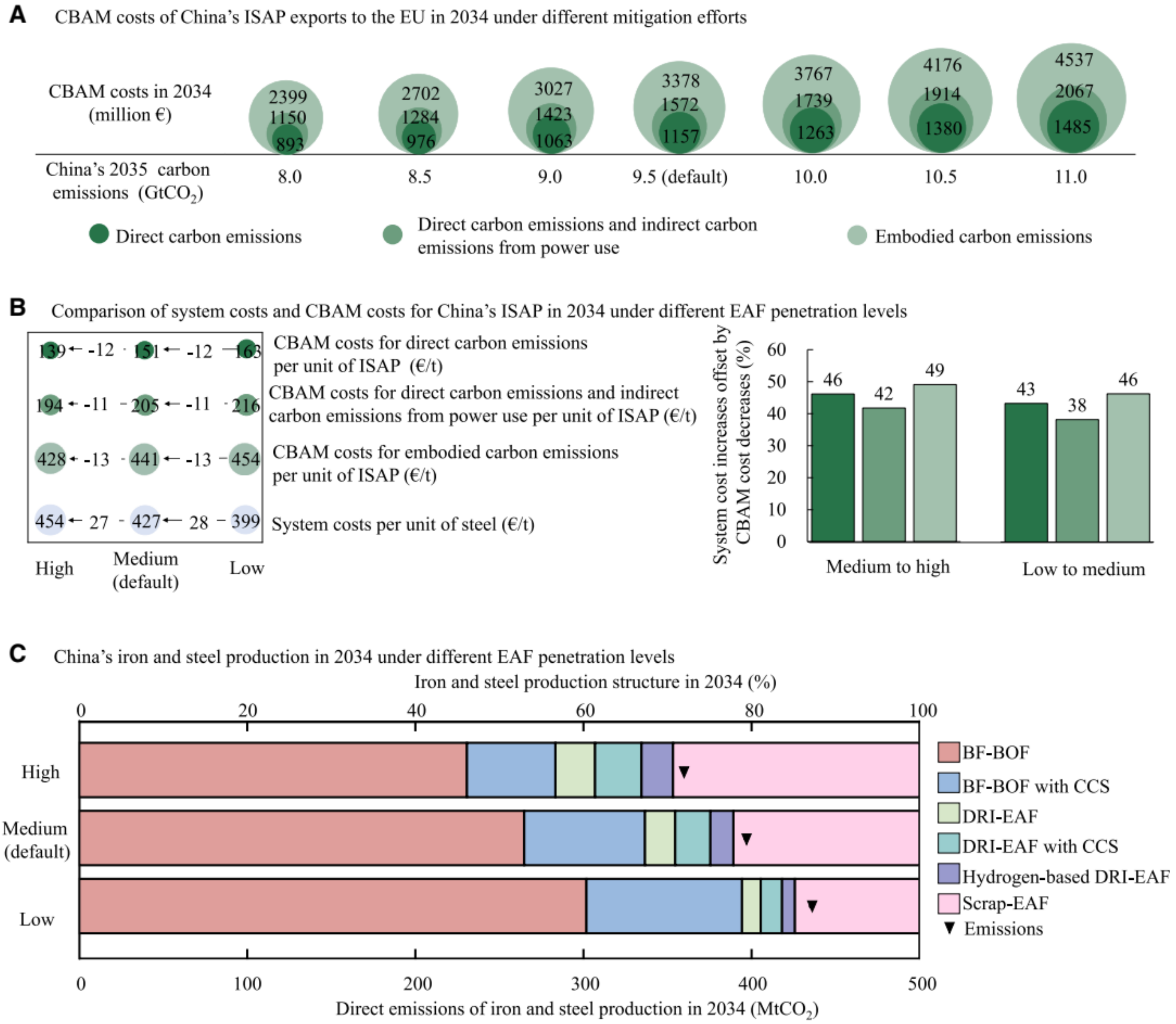

Figure 19: CBAM costs of China's ISAP exports to the EU in 2034 under different mitigation targets and technology penetration

2.3.4 Policy Implications & Insights

(1) Strengthen international cooperation and mechanism construction

EU trading partners (including China) should pay close attention to the formulation and implementation of CBAM rules and the development of carbon price in the EU, and at the same time accelerate the improvement of domestic carbon trading and pricing mechanism to cover steel, electrolytic aluminium and other industries covered by CBAM, so as to enhance international competitiveness.

(2) Increase emission reduction targets and industrial upgrading

China should set higher emission reduction targets in the 2035 Nationally Determined Contribution (NDC) and promote low-carbon transformation and green upgrading of the steel and aluminium processing industries by eliminating outdated production capacity, promoting advanced production technologies (such as EAF and short process steelmaking) and strengthening technological innovation. This will not only lay the foundation for

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achieving carbon neutrality by 2060, but also significantly reduce the impact of CBAM on China's exports. For example, reducing emissions from 11.0 $GtCO_2$ to 8.0 $GtCO_2$ in 2035 could reduce the cost of ISAP CBAM by 40% (DCE), 44% (DICE) and 47% (ECE) in 2034.

(3) Optimise energy structure and green transformation

China should accelerate the development of non-fossil energy sources, promote the renovation or decommissioning of coal-fired power plants, and reduce the carbon emission factor of the power system. Relevant enterprises should actively purchase green power (such as photovoltaic and wind power) to reduce indirect carbon emissions in the production process.

(4) Promote the green and low-carbon development of the industrial chain

As CBAM may be extended to downstream machinery and equipment in the future, China should guide the upstream and downstream industries of steel and aluminium processing industries to develop in the direction of green, low-carbon and high-efficiency, and promote the whole industrial chain to achieve the goal of carbon neutrality, so as to gain an advantage in international cooperation and competition.

2.3.5 References

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