ENhancing our understanding of Trade Impacts on Climate, industries, and the Environment

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D1.3 – State of the Art of TCI Economic Theory, Political Science, Economic Modelling

WP1–Framing – theoretical underpinnings, public perceptions, and policy needs

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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 deliverable provides the groundwork for work in subsequent work packages. Specifically, the insights from the literature review informed the development of the TCI framework (D1.2). Moreover, the results of the literature review on modelling capacities (chapter 6) will be complemented by additional work surveying related research projects, analysing in detail the documentation of existing integrated assessment models and other relevant models and an export survey. All of this will be reported as deliverable D1.4. Beyond internal purposes, the main target audience for this deliverable is the scientific community. To better reach this audience, the authors plan to submit chapters 4 (systematic review of the economic literature) and 5 (systematic review of the political science literature) as two separate academic research article manuscripts to appropriate outlets.

3. Short summary of results (<250 words)

This deliverable synthesizes the state of the art on the trade–climate–industry (TCI) nexus for ENTICE WP1 across three strands: (i) economics of trade and the environment; (ii) political science on governance of climate, industrial policy, competitiveness and trade; and (iii) the representation of trade policy in modelling. Using a systematic protocol (Web of Science/Scopus searches, PRISMA-style documentation, shared codebook, Taguette), we screened ~3,881 economics and ~3,608 political-science records to core sets of ~193 and ~165 articles, respectively; a targeted modelling scan retained ~147 recent papers. Economics findings, organized by the scale–composition–technique (CST) framework, show scale effects raise emissions, composition effects are modest and heterogeneous, and technique effects (regulation, innovation, diffusion) generally dominate, yielding declining emission intensities. Evidence on the Pollution Haven/Halo and Porter hypotheses is mixed and context-dependent; Environmental Kuznets Curve patterns are not universal. Global value chains complicate production- versus consumption-based responsibility. Political science maps enabling and constraining governance themes: carbon leakage and competitiveness; carbon pricing and trade; border carbon adjustments; green industrial subsidies; North–South equity; embodied-emissions accounting; WTO compatibility; environmental provisions in trade agreements; and climate clubs/minilateral cooperation. These raise design, legitimacy and fairness considerations for climate-compatible trade policy. Modelling evidence shows CGE models (often GTAP-based) predominate; most adopt Armington trade, neglect firm heterogeneity, and treat technological change exogenously – limiting analysis of instruments such as BCAs and green subsidies. The report highlights priorities for ENTICE: better integration of policy instruments, GVC/transport channels, endogenous innovation, and producer–consumer responsibility into modelling to inform coherent trade-climate policy design.

4. Evidence of accomplishment

This report.

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Preface

In today's interconnected global economy, understanding the trade-climate nexus is more critical than ever. Trade policies significantly influence environmental outcomes, while climate change affects trade flows. However, the complex relationship between these areas remains insufficiently explored, often due to data limitations, gaps in economic modeling and the evolving nature of global supply chains. The ENTICE project aims to bridge these knowledge gaps by advancing our understanding of the trade-climate-industry (TCI) nexus. It examines how trade policies impact environmental sustainability and how climate policies shape global trade dynamics. By developing fact-based insights and innovative modeling tools, ENTICE supports informed decision-making at this crucial intersection of trade, climate, and sustainability.

E3M – E3-MODELLING AE	EL	
CMCC – FONDAZIONE CENTRO EURO-MEDITERRANEOSUI CAMBIAMENTI CLIMATICI	IT	
WI – WUPPERTAL INSTITUT FUR KLIMA, UMWELT, ENERGIE GGMBH	DE	
REFORM – FUNDACJA INSTYTUT REFORM	PL	
VUA – STICHTING VU	NL	
HOL – HOLISTIC IKE	EL	
ENEXTGEN – ENEXTGEN S.R.L.	IT	
UoS – UNIVERSITY OF SOUTHAMPTON	UK	
UNIVR – UNIVERSITA DEGLI STUDI DI VERONA	IT	
SEURECO – SEURECO SOCIETE EUROPEENNE D'ECONOMIE SARL	FR	
ICCS – EREVNITIKO PANEPISTIMIAKO INSTITOUTO SYSTIMATON EPIKOINONION KAI YPOLOGISTON	EL	
POLIMI – POLITECNICO DI MILANO	IT	
Purdue – TRUSTEES OF PURDUE UNIVERSITY	US	
ZEW – LEIBNIZ-ZENTRUM FUR EUROPAISCHE WIRTSCHAFTSFORSCHUNG GMBH MANNHEIM	DE	
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Executive Summary

This deliverable presents the state of the art on trade–climate–industry (TCI) interactions for ENTICE Work Package 1. It synthesizes three complementary streams: (i) economics of international trade and the environment; (ii) political science on global governance of climate, industrial policy, competitiveness and trade; and (iii) the representation of trade policy in modelling frameworks. The first part provides a comprehensive synthesis of the economic literature on trade and the environment, emphasizing the theoretical and empirical mechanisms – scale, composition, and technique effects – through which trade and globalization shape environmental outcomes and emissions patterns. For the political science part, wo guiding questions structure the review: How do trade and trade policies enable or constrain climate and environmental policymaking, and how do climate policies reshape trade patterns and competitiveness? Finally, the third part scopes to which extent trade policy has been explored in integrated assessment, macroeconomic, and global economic modelling research.

We adopt a systematic review protocol to ensure transparency and replicability, drawing primarily on Web of Science and Scopus searches with harmonized inclusion/exclusion criteria and PRISMA-style documentation. After de-duplication and citation/date filters, thousands of records were screened by title and abstract, followed by full-text coding using a shared codebook with inter-coder checks. The economics stream began from 3,881 records and the political science stream from 3,608, yielding a core set of 193 economics and 165 political science articles for qualitative synthesis, while the modelling stream, being more targeted to recent advances, began with 328 records, yielding a core set of 147 articles.

Key insights from the economics literature are organized via the scale–composition–technique (CST) framework. Across pollutants and contexts, scale effects (more output) raise emissions, composition effects (sectoral shifts) are generally modest and heterogeneous, and technique effects (cleaner processes via regulation, innovation, and technology diffusion) consistently dominate, driving declines in emissions intensity. The literature links these mechanisms to prominent hypotheses: Environmental Kuznets Curve dynamics (income-driven technique effects offsetting scale at higher income); mixed and context-dependent evidence on the Pollution Haven Hypothesis; and firm- and policy-induced innovation consistent with the Porter and "pollution halo" perspectives. Global value chains sharpen production- vs consumption-based accounting, complicating responsibility and policy design.

The political science strand maps governance debates that condition TCI outcomes: carbon leakage and competitiveness concerns; carbon pricing and trade; border carbon adjustments; green industrial subsidies; North–South equity; embodied emissions/accounting; WTO rules and trade law; environmental provisions in trade agreements; and climate clubs/cooperation. These themes illuminate enabling conditions, constraints, and legitimacy issues for climate-compatible trade policy.

The literature review part, conducted to survey the modelling capacity, offers a comprehensive synthesis of how different classes of economic models address trade policy within the trade-climate nexus. The analysis reveals that (computable) general equilibrium models predominate in this area, particularly those calibrated using the GTAP Data Base. The majority of models neglect firm heterogeneity, instead representing international trade through the conventional Armington specification, while, technological change is mostly treated as exogenous, based on pre-determined shifts in productivity parameters.

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1 Introduction

The ENTICE Horizon Europe project (Grant 101184775) investigates trade-climate interactions (TCI), and Work Package 1 (WP1) is dedicated to framing the theoretical underpinnings, including a comprehensive literature review of relevant research. Subtask 1.1.1 of WP1 entails a **systematic literature review** (Milestone 5) covering multiple streams of literature: firstly, the economic literature on international trade and the environment; secondly, the political science literature (especially in international relations) on global governance of climate, industrial policy, competitiveness, and trade. The review maps how trade policies and environmental/climate policies have been documented to interact – identifying economic dimensions, potential synergies, as well as conflicts and trade-offs between trade and climate mitigation efforts. A third component assesses how trade policies that are related to trade-climate nexus have been treated in state-of-the-art integrated assessment and macroeconomic models.

To organize this work, the literature review team split the task into **three parallel parts**: an **Economic Literature** review (led by UNIVR and UoS) examining the impact of international trade on the environment, a **Political Science Literature** review (led by WI) focusing on the global governance of trade, climate, and industrial policy, and a **Modelling Research** review (led by ICCS) evaluating current trade-climate modelling capabilities. The first two parts (economics and political science) have been conducted in tandem using a coordinated approach, while the third (modelling) is scheduled to commence in July 2025. Each part addresses specific research questions – for example, **(1)** *How do trade and trade policies enable or restrict climate and environmental policymaking at national and global levels?* and **(2)** *How do environmental and climate policies affect trade patterns and industrial competitiveness?* These guiding questions ensure that both directions of the trade-climate nexus are examined. Ultimately, the goal is to produce a **critical review of the academic literature** to understand the impact of trade policies on the environment and climate change (and reciprocally, climate policies on trade) as a key project deliverable (Deliverable D1.3).

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2 Methodology of the Task: How Is the Literature Review Conducted?

Approach Overview: The three sub-groups adopted a **systematic literature review** methodology to ensure rigor and transparency across disciplines. This approach, widely used in academic research, provides a structured process that is transparent, **replicable and comprehensive**, making the findings reliable and potentially publishable in scholarly outlets. Given the multidisciplinary team, a systematic approach also facilitated coordination, by imposing a common protocol and clear criteria for inclusion/exclusion of studies in the review. The review process was resource-intensive, as the volume of literature to be assessed was larger than initially expected. To manage this, the team followed the systematic review standards, guided by best practices such as PRISMA (Preferred Reporting Items for Systematic Reviews) for documentation.

Review Process: The literature review follows a structured sequence of steps, applied similarly in both the economics and political science streams, and slightly differently in the modelling capacity one:

1. **Formulate Research Questions and Scope:** We defined clear research questions and identified a "test list" of key papers and studies known to be relevant, to ensure our search would capture these seminal works. This step established the thematic boundaries of the review (covering trade-environment linkages, policy interactions, etc.) and provided a benchmark for the search strategy's completeness.
2. **Develop a Search Protocol:** The team jointly developed a search strategy, specifying keywords, Boolean operators, and inclusion/exclusion parameters. Care was taken to include **trade-related terms**, **climate/environment-related terms**, and additional terms reflecting each sub-group's focus. For example, all groups' queries contained general terms for trade (e.g. *"international trade"*, *"global trade"*) and climate (e.g. *"climate change", "pollution"*), while the economics search included terms for concepts like *"carbon leakage"* or *"scale effect"*, the political science search included governance terms like *"trade policy"* or *"international relations",* and the modelling capacity search included terms like "CGE model" or "integrated assessment model". The search was configured to look in titles, abstracts, and keywords, balancing breadth with precision (to avoid irrelevant hits from generic words like "trade-off").
3. **Comprehensive Search in Databases:** Using the finalized search strings, we conducted systematic searches in major scholarly databases, primarily **Web of Science** and **Scopus**, to ensure broad coverage of peer-reviewed literature. These databases were chosen for their extensive indexing of relevant journals. The searches were restricted to journal articles in English, and we recorded the results for transparent reporting. The first two sub-groups ran their searches in parallel, yielding thousands of initial results (as detailed in the Progress section) before filtering, while the modelling capacity group followed a similar approach, starting a bit later, in order to make use of the insights coming from the other two streams.
4. **Apply Selection Criteria (Screening):** We applied several layers of selection to narrow down the results to the most relevant and high-quality studies. First, we removed duplicates and non-article items (e.g. conference papers) from the dataset. Next, we implemented filters – for instance, excluding older papers with low citation counts as a proxy for relevance and impact. Specifically, we concentrated on papers published before 2020, we ranked them by citations and then excluded the bottom 20% in each group. This resulted in a cut-off of fewer than 40 citations for economics and fewer than 20 citations for political science. This *citation threshold* filter was used judiciously () to focus on recent influential work. Additionally, the modelling capacity stream constrained the search within the last decade, since our objective was to capture state-of-the-art capabilities rather than dated works – besides, model enhancements typically build on previous work in addition to

continuous computational capacity improvements. Subsequently, a **title screening** was carried out: multiple researchers independently reviewed the titles of each paper to judge relevance (Yes/No/Maybe), followed by group discussion to resolve any disagreements and calibrate the inclusion criteria. Papers clearly out of scope (e.g. unrelated use of the word “trade”) were eliminated at this stage. We then examined abstracts of the remaining papers to further exclude studies that did not substantively address the trade-environment nexus (for example, papers that turned out to be narrow case studies with no general implications or were themselves literature reviews rather than new research). The screening process was carefully documented and aligned between the subgroups to ensure consistency.

5. **Data Extraction and Coding:** For the studies that passed the title/abstract screening, we performed full-text analysis. Each selected article was assigned to team members for in-depth reading and **qualitative coding** of relevant content. We employed *Taguette*, an open-source collaborative coding software, to annotate and categorize findings from the literature.[1] A shared **codebook** was developed in advance, based on key topics identified during scoping (e.g. categories for economic mechanisms like the “scale technique composition effects”, categories for policy instruments like “carbon pricing” or “trade agreements”, environmental outcome categories like “emissions” or “biodiversity”, etc.). This coding framework allows the team to systematically tag portions of text (e.g. sentences or paragraphs) that relate to specific themes, enabling structured comparison across studies. We iteratively refined the codes through team discussions to ensure a common understanding of categories between economists and political scientists. *Taguette* has facilitated multi-user collaboration on the coding effort, although we encountered some technical challenges such as occasional syncing issues or the ease of inadvertently altering codes – necessitating regular backups and careful project management. We considered alternatives (like structured Excel sheets or other qualitative analysis tools) but opted to continue with *Taguette* for its shared accessibility, given the team’s distributed nature. In the modelling capacity survey, *Taguette* was not used. Instead, the useful information identified in the papers was extracted and captured into a dedicated template of table format (in Excel), allowing to collect specific features of models under consideration.
6. **Synthesis of Evidence:** As coding progresses, the team is aggregating the evidence to identify patterns, agreements, and divergences in the literature. We performed both a **quantitative analysis** (e.g. descriptive statistics on publication trends, bibliometric analysis, or meta-data patterns from the larger set of studies) and a **qualitative synthesis** (a narrative integration of insights from the coded core papers). The synthesis was structured around our research questions, ensuring that the final review provides clear answers or insights for each research question. Cross-cutting themes which emerged from the economics and political science strands (such as the role of institutions, economic impacts of policies, equity considerations, etc.) were highlighted. Importantly, to maintain rigor, we followed the PRISMA guidelines in reporting how studies were selected, how data were extracted, and how findings are combined, which adds transparency to the review process. Finally, since the modelling research survey had a different objective and was targeted to advancements made in the last decade as well as the *Taguette* framework was not adopted, quantitative analysis was beyond scope.
7. **Reporting and Writing:** In the final steps we compiled the findings into the formal literature review report (Deliverable 1.3) and associated academic outputs. The writing involved merging the contributions of the economics, political science, and modelling capacity sub-groups into one coherent document. In practice, we prepared draft sections separately for each stream and integrated them, checking for overlaps or gaps. If warranted, this work could also be refined into a scholarly publication, given the systematic approach and novelty of combining economic and political perspectives on the trade-climate nexus. Modelling capacity will be complemented with the results of Deliverable

[1] https://www.taguette.org/

D1.4, meaning that a separate, dedicated publication will reflect the entire analysis stemming from this specific survey. Throughout the writing phase, we ensured the content remains accessible and policy-relevant, as the review is intended not only as an academic exercise but also to inform other project tasks and stakeholders.

8. **Coordination and Quality Control:** Coordination across the sub-groups has been crucial. We established a structure of regular online meetings: the Economics team met weekly (on Mondays) and the Political Science team met weekly (Wednesdays), and importantly, some members and leads participated in both meetings to ensure cross-fertilization, consistency, and alignment. In the initial stages, joint sessions were held to agree on the search protocol and selection criteria collectively, so that both teams followed a harmonized methodology. The participants include a broad set of ENTICE partners – for example, the economics group involves researchers from CMCC, ICCS, ORDECSYS, UNIVR, UoS, ZEW (17 researchers in total), the political science group includes ICCS, UNIVR, WI and others (10 researchers in total), while the modelling capacity group involves ICCS, ORDECSYS, CMCC, and E3M (10 researchers in total). This interdisciplinary collaboration ensured that expertise was shared: economists contributed knowledge of trade modelling and economic theory, whereas political scientists contributed insights on governance frameworks and policy context. Both groups contributed insights to the modelling capacity task, especially on the underlying trade theories and the trade policies addressed the most through the economic modelling ensemble. We also implemented inter-coder reliability checks during the screening process to maintain consistency: for instance, before finalizing title exclusions, team members independently categorized a sample of titles and then discussed discrepancies to calibrate their judgments. Moreover, the first two sub-groups stayed in communication about borderline cases – papers that were flagged as "policy-focused" in the economics search or "economics-focused" in the political science search were exchanged or jointly evaluated so that each paper would be reviewed by the appropriate expertise/subgroup. This collaborative and systematic methodology has laid a solid foundation for a robust and credible literature review, as detailed next in the progress update.

3 Progress in the Literature Review: Which Steps Have Been Conducted?

The literature review task progressed largely **on schedule**, having completed the planning and initial execution phases as per the project timeline. According to the project's timeline for Task 1.1.1, the early months were dedicated to scoping and search design, followed by sequential filtering and analysis steps. The team has closely adhered to this timeline: by the end of March 2025 (M3 of ENTICE), we had finalized research questions and search terms and **assigned literature among team members**, allowing data extraction and coding to begin in April and May. By mid-May, preliminary results from each sub-group were being consolidated and a draft outline of the review was underway. As of end of June 2025, the Milestone 5 report was delivered, marking the successful completion of the initial literature review phase and the transition into full analysis and writing. The months of July and August were used to finalize the coding process of the identified articles. Finally, the analysis and the process of writing the deliverable was conducted in September. Below we detail the key steps to the deliverable:

- **Search and Retrieval of Studies:** Both sub-groups executed the agreed search protocol in Web of Science and Scopus. The economics search yielded an initial ~3,881 papers (after removing duplicates and irrelevant entries), and the political science search yielded ~3,608 papers. This large volume confirms the richness of literature at the trade-climate interface. We took an extra precaution of filtering out conference proceedings and other non-peer-reviewed items at this stage, focusing on journal articles.
- **Preliminary Filtering by Citation and Date:** To concentrate on the most pertinent and influential works, we applied a citation-based filter. Specifically, we excluded papers published before 2020 that had very low citation counts (under 40 citations for economics papers; under 20 for political science papers). This step was implemented to remove marginal or outdated studies while retaining seminal older works (which tend to have higher citations) and the surge of recent research in the 2020s. After this filtering, approximately **2,931 economics** papers and **2,791 political science** papers remained for screening.
- **Title Screening:** The team conducted a systematic title review of these thousands of entries. Each title was assessed for relevance to our core questions (e.g., does the title indicate a focus on trade AND environmental/climate aspects?). We coordinated this by using a shared list and marking each title as *Yes (relevant)*, *No (irrelevant)*, or *Maybe/unsure*. To ensure consistency, each subgroup performed an intercoder reliability test – a subset of titles (30 per group) was independently categorized by all members, and divergences were discussed to align interpretations. Through the title screening, we eliminated a large number of clearly off-topic works (for example, studies where "trade" referred to unrelated contexts). The outcome of this step left **1,413 economics papers** and **1,219 political science papers** identified as potentially relevant (including those marked "yes" and the "maybe" that warranted further examination).
- **Abstract Screening:** Next, we reviewed the abstracts of the remaining papers to verify their relevance and quality. The team applied defined exclusion criteria during this phase: for instance, we screened out papers that did not explicitly examine the impact of trade on environmental or climate outcomes, that turned out to be general discussions with no original analysis, that were extremely narrow case studies with no generalizable insight, or that were themselves literature reviews (to avoid redundancy). This step required significant reading and judgment. After abstract screening, the list was further distilled to about **745 papers in the economics stream** and **390 papers in the political science stream** that clearly met our inclusion criteria. (During abstract screening, we also identified a small number of papers that belonged in the other sub-group – e.g. ~53 papers from the

econ list were purely about policy with no economic analysis, and ~99 from the pol. sci list were fundamentally economic studies – these were flagged and set aside for reallocation to ensure no pertinent study is missed by either side.)

- **Final Selection of Core Papers:** Although ~745+390 papers remained relevant after abstracts, it was neither feasible nor necessary to fully code every one of these for the narrative synthesis. Thus, a final selection was made to identify the **most important and representative papers** that would be read in full and qualitatively coded. To do this, we categorized the remaining studies by topic and ensured that for each major theme (e.g. carbon leakage studies, trade agreement studies, specific sectors like forestry, etc.), a few representative and high-quality papers were included. Priority was given to recent publications (post-2020, capturing the latest developments and data) and to any highly cited papers that form the foundation of the field. This careful curation was done by small teams of senior researchers in each subgroup to maintain consistency in judgment. The result is a working set of approximately **193 economics-focused articles** and **165 political science-focused articles** selected for in-depth review and coding. These numbers reflect a balance between breadth (covering all relevant sub-topics) and depth (keeping the set manageable for thorough analysis). Notably, the papers that were not selected for full coding are not discarded; many will still be used in a quantitative sense (e.g. for trend analysis or citation network insights) to inform the review's background and ensure no major viewpoint is overlooked.
- **Coding and Analysis:** The coding of the selected ~358 core has been conducted until end of August 2025. Each researcher has been assigned a subset of papers to read in full and code using the Taguette software, according to the shared codebook of themes described earlier. Regular check-ins happened to discuss any ambiguities in coding and to refine definitions of codes if needed, so that a high degree of consistency is maintained across the team. This collaborative analysis allowed us to pull out key findings, quotes, and quantitative data from the literature in a systematic way. Overall, the coding process functioned well: Initial technical hurdles with the software have been managed, and the group converged on a common interpretation of codes and categories. In September the analysis took place. This included the comparison of results between the economics and political science findings, identifying overarching insights, and drafting the unified literature review report. We also decided to further rely on snowballing based on the exported material. As such, we added relevant studies and publications that were not yet part of the original export from Web of Science and Scopus. This allowed us to make our material more comprehensive.
- **Reporting and Writing**: Based on the analysis ach sub-group formulated their own report following a common structure. However, each sub-group differed to a certain extent regarding the analysis which also reflected the differences in research questions for each sub-group.

Throughout these steps, **coordination** has been actively maintained. The subgroup leads (UNIVR/UoS for economics, WI for political science) have ensured parallel progress and resolved any issues promptly via joint meetings. The successful execution of the above steps demonstrates that the literature review is proceeding methodically and according to plan.

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4 Economics

4.1 Introduction

The environmental consequences of global trade have become a central concern in economic research, particularly as shifting trade dynamics – marked by rising protectionism and geopolitical tensions – continue to reshape patterns of production, consumption, and resource use. This literature review examines how the expansion and transformation of international trade affect the environment – including both climate change and natural resource depletion – by analysing a vast and evolving body of work through a unified analytical lens.

At the core of this literature lies the well-known scale–composition–technique (CST) framework, which provides a conceptual foundation for understanding the mechanisms through which trade influences environmental outcomes. Trade can increase pollution through the scale effect, as economic activity expands. It can also alter the composition of production, shifting output toward cleaner or dirtier sectors depending on comparative advantage. Finally, it can reduce pollution via the technique effect, as higher incomes, regulatory pressure, and technology diffusion lead to cleaner production methods.

These three channels are not only analytically distinct but also interconnected, and their interaction underpins many of the field's most influential strands of research. For instance, the Environmental Kuznets Curve (EKC) hypothesis – which posits an inverted-U relationship between income and pollution – can be interpreted as a dynamic interplay between scale effects (dominant at low-income levels) and technique effects (increasingly important at higher incomes). Similarly, the Pollution Haven Hypothesis (PHH) and its counterpoint, the Pollution Halo Hypothesis, both hinge on the composition and technique effects: the former suggests that trade shifts dirty industries to countries with weaker environmental regulation, while the latter emphasizes the potential for cleaner technologies to spread through trade and foreign direct investment. The Porter Hypothesis adds a further layer, proposing that stringent environmental regulation can itself stimulate innovation, reinforcing the technique effect.

These mechanisms are further complicated by the rise of global value chains (GVCs), which fragment production across borders and decouple the location of emissions from the location of consumption. This has sparked a growing debate over production- versus consumption-based responsibility for emissions, with important implications for how environmental impacts are measured and attributed. The CST framework remains relevant here: GVCs amplify composition effects by relocating pollution-intensive stages of production, while also shaping the diffusion of cleaner techniques across firms and countries.

Finally, the environmental impacts of trade extend beyond production to include the emissions from international transport and the pressures on land, water, forests, and biodiversity. As global value chains lengthen, rising transport activity has become a significant source of greenhouse gas emissions, often offsetting gains from cleaner production. At the same time, trade drives land conversion, deforestation, and resource depletion in exporting countries, transferring ecological burdens from consumption in richer economies to ecosystems in the less developed countries. These findings highlight that trade's environmental footprint operates through multiple, interlinked channels – production, transport, and resource use – each interacting with the scale, composition, and technique effects. A comprehensive understanding of the trade–environment nexus therefore requires integrating these dimensions into a comprehensive analysis.

Although the core research questions in this field have remained relatively stable over time, the methods used to address them have evolved significantly. Early studies relied on cross-country regressions and aggregate emissions data. More recent work has leveraged firm-level data, structural models, and multi-regional input–output (MRIO) frameworks to trace emissions across borders and along supply chains. This methodological shift has enabled a more nuanced understanding of the CST mechanisms and their empirical relevance across different contexts.

This review begins with Section 4.2, which presents a quantitative analysis of the systematic literature review, mapping trends in publication, methodology, and thematic focus across decades. It then moves to a qualitative analysis, structured to reflect the interconnections among key mechanisms and research questions. Section 4.3 introduces the CST framework and its empirical decomposition, providing the conceptual foundation for understanding how trade affects the environment through scale, composition, and technique effects. Section 4.4 and 4.5 examines how CST mechanisms underpin respectively the Pollution Haven, Pollution Halo, and Porter Hypotheses, and the Environmental Kuznets Curve (EKC), highlighting their conceptual overlaps and empirical tensions. Section 4.6 explores the implications of global value chains (GVCs) and the shift from production- to consumption-based emissions accounting, which reframes questions of environmental responsibility. Section 4.7 focuses on the climate impact of international trade through international transports, which represents the most direct channel in the trade-environmental nexus and must be deeply analysed to provide a complete picture of all the dimensions playing a role in this framework. Section 4.8 shifts the objective of study from the pure impact of trade on emissions towards the broader environmental footprints across different dimensions of sustainability, like land, water, forest usage and biodiversity. Finally, Section 4.9 and 4.10 respectively discuss the main results of the review and conclude.

The qualitative analysis draws primarily on the core set of papers selected through the systematic review, while also incorporating additional relevant studies identified through snowballing and citation tracking. By organizing the literature in this way, the review highlights both the individual contributions of each strand and their interdependencies – offering a comprehensive view of how trade, growth, regulation, and innovation interact to shape environmental outcomes in a globalized economy.

4.2 Quantitative Statistics

The current work is a systematic literature review with the main objective of providing the updated state of the art of the scientific research focused on the environmental consequences of global trade, and to analyse the main policy implications that could be drown from this. The *systematic* nature of the review affects the methodological approach through which the papers are gathered and reviewed, and it has the key goal of minimizing the selection bias that could generally arise in a standard *narrative* approach to a scientific survey. The review process followed specific criteria described in detailed in the Sections 2 and 3 of the current Deliverable, which has led us to reach two initial samples of papers for the two sub-groups of Economics and Political Science, and to filter and select papers trough 5 different steps ending up with the final samples of publications reviewed.

The objective of this section is to provide, for the Economics sample of papers, a series of informative descriptive statistics that could be useful to evaluate in a transparent way the quality and the precision of the selection process throughout the different steps and make some considerations regarding the trends in methodological approaches and topics of the literatures over time. After the execution of the search protocol defined exploiting the research question-related keywords, the initial sample of papers for the Economics subgroups counts 3881 papers. Among these papers, 35% were only available on Web of Science while the rest were both downloadable from both sources and has been gathered from Scopus (see Figure 1, left). In terms of fields of the journals in which papers have been published, most of the papers of the original sample comes from journal that can be classified as either interdisciplinary (34%) or environmental and climate science journals (34%), with also a significantly high fraction of pure economics journal (23%) and only a minority of works coming from management and policy issues journals (6%), consistent with the idea that the latter should be the main focus of the sub-group of Political Science (see Figure 1, right)[2].

Figure 1: Source of papers in the initial sample (left) and journal's field of the papers in the initial sample (right).

Looking at the year of publication, the distribution of the papers over time clearly reports a prevalence of papers published in the last decade, with the higher frequencies registered in the period 2021-2024. Given that papers at this step have been only selected through the search strings of keywords without any other constraint, this evidence suggest that the research questions at the centre of our review are relatively new, or better, the interest surrounding them in the scientific literature in strongly increasing over time (see Figure 2a). This feature has likely an impact on the number of citations associated to each paper, which should theoretically reflect the degree of influence that papers published on the topics is able to generate. Indeed, looking at some generic interval of citations, most of the papers in the initial sample have less than 50 citations, with the highest frequency registered by papers with only 0 to 5 citations. Only a small number of papers, as reasonable, has a strong impact factor in the literature and holds more than 200 citations (see Figure 2b). As argued, these results are likely interpretable as consequence of the relatively recent nature of the bulk of publications selected, since normally it takes time even for a potentially high-impactful paper to gain the related consensus and popularity.

[2] Journal's fields have been retrieved directly from Web of Science and Scopus during the collection of papers.

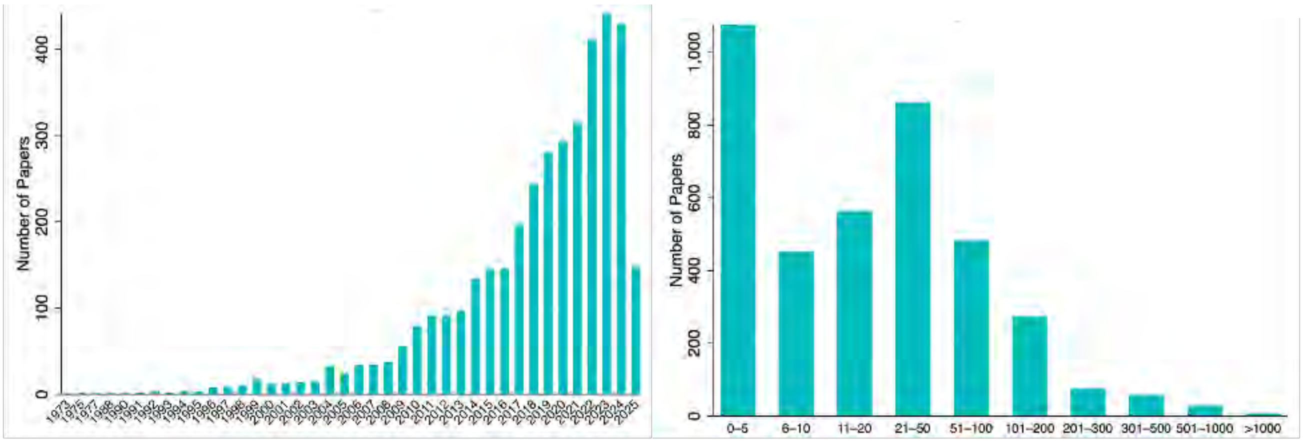

Figure 2: (a) Number of papers for year of publication. **(b)** Number of papers for range of citations.

To evaluate how the distribution of papers over time and the citations distribution are affected by the filtering of papers within the selection process, we compute these two statistics also after each step. The four steps evaluated include: getting rid of papers published before 2020 with less than 40 citations (i.e., the citation cutoff); eliminating clearly not relevant papers looking only at the title (i.e., step 1); eliminating papers that either do not look at the impact of trade on climate or are too specific with no general implications looking at the abstracts (i.e., step 2); reducing the number of papers to guarantee and adequate coverage of all relevant topics and focusing on most impactful papers (i.e., step 3). Results suggest that the screening steps do not significantly alter the distribution of papers over time (see Figure 3), since the initial sample and the final one are roughly similar, and that the step-by-step selection tends to increase the average number of citations signaling that we are likely keeping most impactful papers over the process (seeFigure 4).

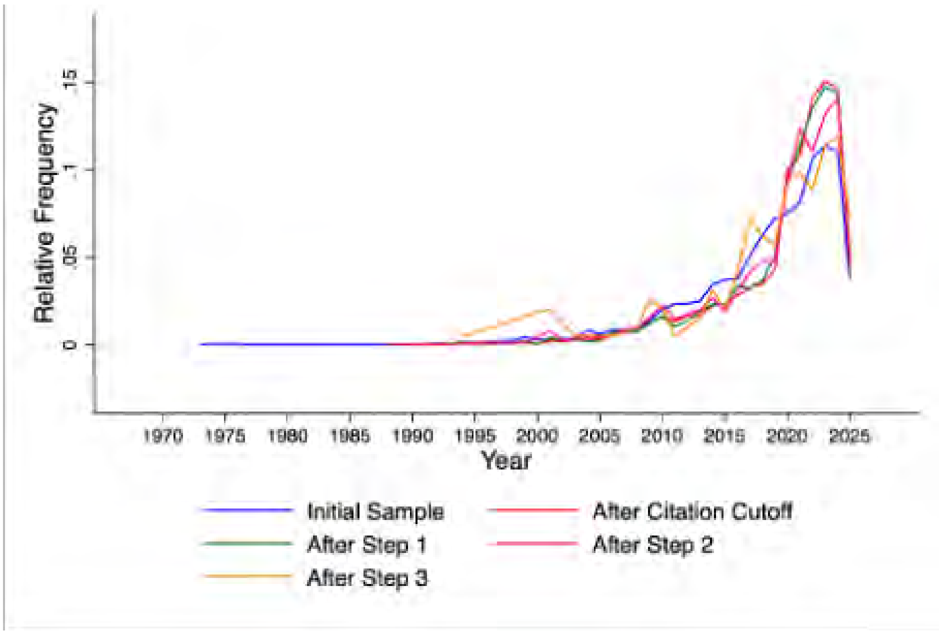

Figure 3: Number of papers over time after each selection step.

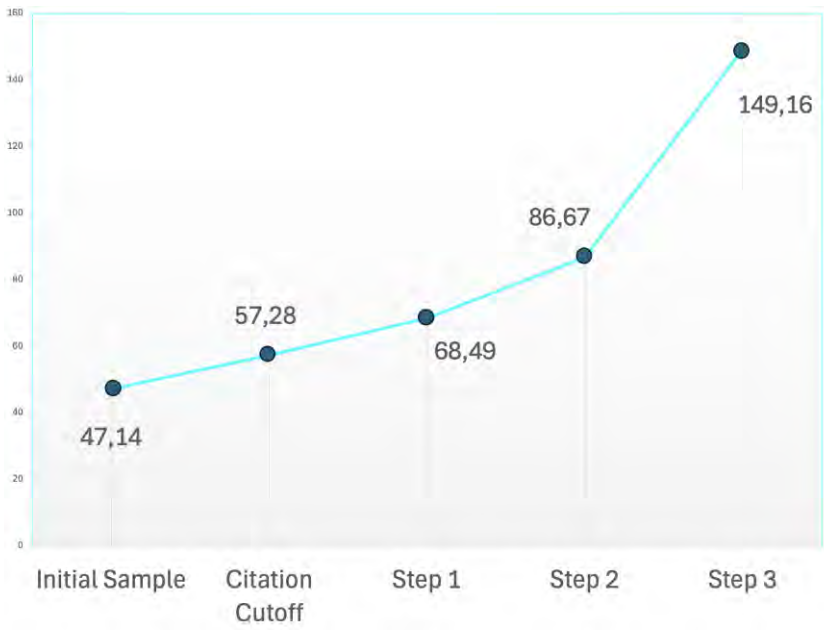

Figure 4: Average number of citations after each selection step.

Afterwards, we evaluate the effectiveness of the selection process by computing three specific quality measures before and after each step of the filtering. Specifically, we compute:

- The percentage of papers ranked in the top 1000 IDEAS;
- The percentage of papers published in well-reputed high ranked journals;
- The percentage of papers published in predatory journals;[3]

The results are carefully summarized in Table 1, in which we also report the number of papers kept at each selection step. To this extent, Step 3 is the most selective one, keeping only around 25% of the papers promoted at Step 2. Results suggest that the fraction of high-quality papers significantly increases throughout the selection procedure, since both the percentage of top 1000 IDEAS papers raises from around 44% to almost 73% after the four steps and the percentage of papers published in well reputed journals reached almost 90% in the final sample. Intuitively, Step 3 is the most effective in this sense, leading to the highest increase in absolute terms in the fraction of high-quality papers. Consistently with this evidence, the fraction of papers retrieved from predatory journals is significantly decreasing due to the filtering procedure, reaching almost 0% in the final pool of papers. The main message of the dynamic evolution of these simple statistics is that during the selection processes we are likely doing an efficient job in keeping high-quality, most impactful papers.

[3] We exploit, for this purpose, the database of https://www.predatoryjournals.org/

Table 1. Quality statistics after each selection step in the systematic literature review. The first line refers to the whole initial sample of papers (3881); the second line focuses only to fraction of those papers which are ranked in the top-1000 IDEAS (1715); the third line only refers to articles published in high-ranked journals (1090); and the last line includes predatory journal's papers.

3881	**2931**	**1413**	**745**	**193**
1715 (44.18 %)	1300 (44.35 %)	730 (51.66 %)	416 (55.83 %)	140 (72.53 %)
1090 (28 %)	877 (29.92 %)	494 (34.96 %)	299 (40.13 %)	172 (89.12 %)
237 (6.1 %)	198 (6.75 %)	77 (5.4 %)	24 (3.22 %)	1 (0.51 %)

Finally, we also provide a rapid look at the topic's coverage in the very last two steps of the selection process. Looking at Figure 5, it emerges that the most trended topics in our initial sample of papers are the Pollution Haven Hypothesis, the Production vs Consumption debate, the Composition-Scale-Technique framework and Water/Land/Bio and that this distribution across topics tends not to vary significantly when restricting the pool of paper to analyse in the last two steps.

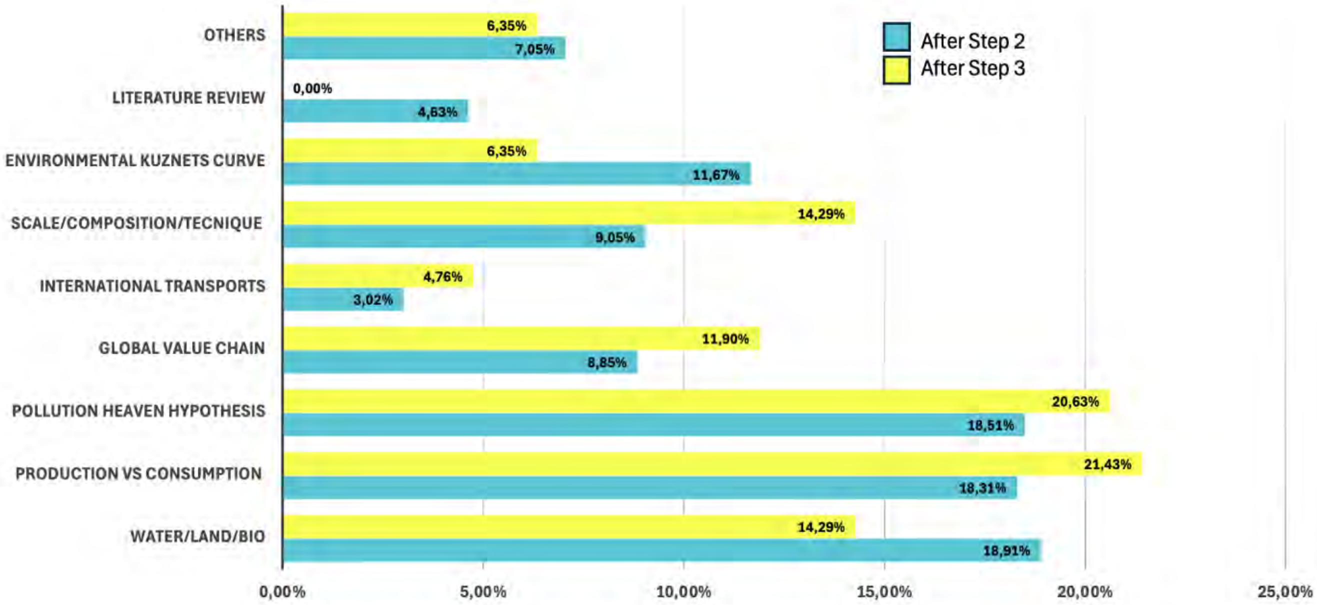

Figure 5: Distribution of topics across papers in the last two steps of the selection process in the systematic review.

In the following we will review the main theoretical and empirical contributions associated with six topics: Composition, Scale and Technique (CST); Pollution Haven, Pollution Halo and Porter Hypothesis; Environmental Kuznets Curve (EKC); Consumption vs Production Responsibility including Global Value Chain; International Transports; and Water, Land and Biodiversity.

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4.3 Composition, Scale and Techinque (CST)

Grossman and Krueger's (1991) study represents a seminal and highly influential contribution to the literature on the environmental consequences of trade liberalization. Motivated by the policy debate surrounding the ratification of the North American Free Trade Agreement (NAFTA), the paper advanced many of the arguments that continue to shape research on this topic. Most importantly, it identified three distinct mechanisms through which trade can affect environmental outcomes and provided the first empirical evidence on their relative importance. The first is the scale effect: if trade and investment liberalization expand economic activity while its nature remains unchanged, total pollution will rise. The second is the composition effect: trade liberalization shifts the sectoral structure of production as countries specialize according to their comparative advantage – arising either from conventional sources such as factor endowments and technology, or from relatively weaker environmental regulations. The net impact of the composition effect on pollution depends on whether comparative advantage is driven primarily by traditional factors or by differences in environmental regulation. The third is the technique effect: trade and investment can promote cleaner technologies, while rising incomes may generate public demand for stricter environmental standards, thereby reducing pollution intensities.

Together, these effects raise fundamental questions regarding the environmental consequences of liberalization: Which effect dominates after liberalization? Does comparative advantage primarily reflect differences in environmental policies or in factor endowments? Can the technique effect outweigh the scale effect, such that trade openness ultimately reduces pollution as income grows? Grossman and Krueger (1991) provided one of the first empirical attempts to address these questions. Using data on three air pollutants from urban areas in 42 countries, they studied the link between air quality and income growth. Their panel regressions revealed that concentrations of sulphur dioxide and particulate matter increase with per capita income at low levels of development but decline once income surpasses a certain threshold – an early empirical observation of what later became known as the Environmental Kuznets Curve (EKC). In addition, they presented evidence from U.S. imports and the Mexican maquiladora sector suggesting that comparative advantage stemmed mainly from traditional sources (such as differences in technologies and factor endowments), with environmental regulation playing a minor role in driving trade and investment patterns.

The contribution of Grossman and Krueger (1991) extends far beyond its empirical results. By delineating the scale, composition, and technique effects, the paper established a conceptual framework that not only reflected the arguments of the political debate on trade liberalization at the time but also balanced them against insights from standard economic theory. This framework effectively laid out a research agenda that has shaped the field over the following decades. One major line of studies built on their early observation of EKC which assesses the relative strength of the scale versus the technique effects and inspired a vast empirical literature examining whether economic growth, mediated by trade openness, can deliver environmental improvements over time. A second strand of research developed around the question of whether differences in environmental policy influence trade and investment flows, leading to the formulation of the Pollution Haven Hypothesis (PHH). Here, the composition effect was pushed further to assess the extent to which countries with laxer regulations attract pollution-intensive industries, and whether this dynamic undermines the gains associated with trade liberalization. Research in this area has yielded two closely related concepts: the pollution haven effect (PHE) and the pollution haven hypothesis (PHH). The PHE holds that the stringency of environmental regulations shapes comparative advantage and thus affects production and trade, while the PHH extends this idea by suggesting that, if the PHE is sufficiently strong, trade liberalization will induce countries with weaker environmental standards to specialize in pollution-intensive industries. Closely related is the countervailing Pollution Halo and Porter Hypothesis, which link back to the technique effect: rather than inducing firms to relocate to low-income countries with weaker standards, trade and financial liberalization may reduce pollution intensities and spur innovation-driven gains by encouraging the adoption of cleaner and more efficient production methods. More recently, debates have shifted toward the question of how to attribute environmental responsibility in a globalized economy. The fragmentation of production across borders through global value chains (GVCs) has sharpened the distinction between production-based accounting of emissions, which assigns responsibility to the producing country, and consumption-based accounting, which traces environmental impacts to the final consumers. One way of interpreting this is through the composition effect: trade-induced specialisation leads country's production-related emissions to often differ from the emissions embodied in the goods and services it consumes, shaping its pollution footprint. With the specialization induced by GVCs, this gap has widened, as pollution-intensive stages of production are often concentrated in specific locations while consumption occurs elsewhere. This reframing has important implications for evaluating the scale, composition, and technique effects of trade, as pollution may be outsourced geographically while environmental benefits from technological progress remain unevenly distributed. In this way, the conceptual framework of scale, composition, and technique effects continues to structure the central questions in the literature, providing the foundation for ongoing research into the complex interplay between trade, growth, regulation, and sustainability.

The remainder of this section reviews the subsequent developments that further examine the scale, composition, and technique effects, distinguishing between theoretical models and quantitative assessments, while leaving the analysis of the literature related to the Environmental Kuznets Curve, the Pollution Haven, Pollution Halo, and Porter Hypotheses and the Consumption vs. Production Responsibility to the following sections.

In a series of papers, Copeland and Taylor provided a theoretical foundation for Grossman and Krueger's conceptual framework. Copeland and Taylor (1994) analysed the effects of trade liberalization on pollution and welfare in a framework where environmental quality is modelled as a local public good, so that damages are confined to the polluting country. They developed a two-country general equilibrium model in which the key asymmetry lies in countries' endowments of human capital which triggers divergence in environmental regulation. Governments set environmental policy endogenously, since environmental quality is treated as a normal good: as income rises, political demand for protection increases and richer countries impose stricter standards. At the same time, countries with higher human capital undertake more abatement and, if human-capital differences are sufficiently large, specialize in the production of cleaner goods under free trade. These two sources of comparative advantage – environmental policy differences and factor endowment differences – reinforce each other, pushing the composition of output toward a pattern where high-income economies regulate more strictly and produce cleaner goods, while low-income economies host the dirtier industries. In this way, the model provides a clear theoretical rationale for the emergence of "pollution havens." Importantly, the analysis also disentangles the three channels identified by Grossman and Krueger (1991) – scale, composition, and technique effects – thus offering the first theoretical decomposition of how trade affects pollution. The key contribution was to highlight the central tension in the composition effect relative to the scale and technique effects: when the specialization of low-income countries in dirty goods dominates, trade can increase world pollution even if individual governments' environmental regulation is optimal. However, because pollution is purely local and each government chooses policy endogenously in line with its citizens' preferences, there is no market failure. As a result, trade liberalization always raises welfare, even when it increases local pollution levels. Copeland and Taylor (1995) extended this model to the case where pollution is a global public bad rather than a local one, while keeping the rest of the framework unchanged. The key difference lies in the global transmission of damages: emissions affect all countries equally, regardless of their source. As in Copeland and Taylor (1994), when human-capital differences are large, trade liberalization raises world pollution by shifting dirty industries to countries with weaker regulation, creating "pollution havens". When countries are more similar, however, factor price equalization equalizes pollution-permit prices across countries, preventing the relocation of dirty production and eliminating the pollution-haven effect. Unlike the earlier case of local pollution, here free trade does not necessarily improve welfare, since unilateral regulation cannot correct the cross-border externality. Taken together, the two papers establish that while pollution havens can arise in theory, this occurs only under specific conditions – most notably when countries differ substantially in factor endowments.

Building on these theoretical foundations, Antweiler, Copeland, and Taylor (2001) shifted attention from the conditions under which pollution havens might emerge to the relative strength of the different channels through which trade affects the environment. In their framework, only the capital-intensive good generates pollution – an assumption consistent with the well-documented fact that many of the dirtiest industries are also highly capital-intensive. As a result, higher-income countries are both capital abundant and subject to stricter pollution policies. Thus, unlike in Copeland and Taylor (1994, 1995), these two sources of comparative advantage – factor endowments and environmental regulation – now work in opposite directions: capital abundance tends to make richer countries exporters of dirty goods, while stricter standards tend to make them importers. This shifts the focus away from the mere existence of pollution havens toward the magnitude of the pollution-haven effect, and from whether the composition effect dominates the scale and technique effects to how large it actually is in practice.

To address this empirically, the authors estimated the separate contributions of scale, composition, and technique effects using a panel of 108 cities in 43 countries between 1971 and 1996. They found that a 1% increase in the scale of economic activity raises local pollution concentrations of sulphur dioxide by about 0.25–0.5%, while the accompanying income-driven technique effect lowers them by roughly 1.25–1.5%, so that on average the technique effect dominates. To identify the composition effect, they conditioned openness on country characteristics and showed that while openness is statistically significant, its quantitative impact is small. Most importantly, they concluded that further openness will have only a modest effect on the pollution intensity of output in low-income countries, limiting the scope of a strong pollution-haven interpretation. Overall, their results suggest that trade's environmental impacts are heterogeneous, with the composition effect present but modest relative to the technique-driven improvements associated with rising income.

Together, Copeland and Taylor (1994, 1995) and Antweiler, Copeland, and Taylor (2001) established the CTS framework as the central lens for analysing the trade–environment nexus, identifying both the theoretical conditions for pollution havens and the empirical importance of the different channels. By consistently linking theory to data in a unified framework, Antweiler, Copeland, and Taylor (2001) advanced the agenda initiated by Grossman and Krueger (1991). Their work gave rise to two major strands of research: one examining the magnitude and direction of the composition effect, and another analysing the relative contribution of scale, composition, and technique effects to observed declines in U.S. manufacturing pollution.

The first line of research was extended by Cole and Elliott (2003), who investigated whether the composition effect of trade holds across a wider set of pollutants, including water pollution. Their findings suggest that, as in Antweiler, Copeland, and Taylor (2001), the relationship between trade liberalization and environmental quality depends on country-specific characteristics, with pollution intensities showing a similar pattern. They also find that the trade-induced composition effect is small relative to scale and technique effects, and that its sign and magnitude vary across pollutants. For some pollutants, the results broadly align with Antweiler, Copeland, and Taylor (2001): changes driven by factor abundance and those shaped by environmental regulation often offset each other, helping to explain the mixed empirical support for the PHH. However, this pattern does not hold for water pollutants, indicating that findings for sulfur dioxide do not necessarily generalize.

Building on this line of work, Frankel and Rose (2004) addressed the simultaneity of trade, environmental quality, and income by applying cross-country instrumental variable estimations. Using a gravity model of bilateral trade within an endogenous growth framework and a wide range of environmental indicators (from nitrous oxide to rural clean water access), they provided evidence consistent with Antweiler, Copeland, and Taylor (2001): for some pollutants, particularly sulfur dioxide, trade appears to reduce pollution, even if the precise mechanisms cannot be disentangled.

Following both Cole and Elliott (2003) and Frankel and Rose (2004), Managi, Hibiki, and Tsurumi (2009) further examined whether trade openness improves environmental quality while explicitly addressing the endogeneity of trade and income. Their results confirm the heterogeneity of effects across country groups, pollutants, and over time. In OECD countries, trade liberalization generally improves environmental quality, suggesting that technique effects dominate. By contrast, in non-OECD countries, trade tends to increase sulfur dioxide and carbon dioxide emissions while reducing biochemical oxygen demand emissions. Similar to Antweiler, Copeland, and Taylor (2001) and Cole and Elliott (2003), they also identify both environmental regulation and factor abundance effects, with regulation effects typically larger. These findings underscore that the balance of scale, composition, and technique effects is both pollutant- and country-specific.

Taken together, the literature on the composition effect reveals a consistent pattern: while trade liberalization does alter the sectoral structure of economies, its contribution to overall pollution outcomes is generally modest and highly heterogeneous across pollutants and countries.

In parallel to this composition-focused literature, a second strand has emphasized the technique effect as a central determinant of both overall pollution levels and the emissions intensity of production. Using increasingly *disaggregated data*, this research highlights how technological change, environmental regulation, and cleaner production processes shape the environmental consequences of trade.

Levinson (2009) employed U.S. industry-level data to decompose changes in manufacturing emissions into scale, composition, and technique effects and to investigate the extent to which reductions in pollution stem from advances in production or abatement processes. His findings show that nearly all of the decline in emissions is attributable to improvements in production technology, while changes in industry composition and trade patterns play only a minor role. These results are in line with Antweiler, Copeland, and Taylor (2001) and Cole and Elliott (2003), which emphasize the relatively limited contribution of composition effects compared to scale and especially technique effects. Levinson's evidence thus underscores the central role of technique effects in driving pollution reductions. To extend this line of research, Shapiro and Walker (2018) used granular product-level data for a structural estimation of a quantitative trade model that incorporates endogenous pollution and heterogeneous firms a la Melitz. This approach enables them to reinterpret changes in manufacturing emissions attributed to technique effects as the outcome of changes in environmental regulation and productivity. Their results show that stricter environmental regulation accounts for the majority of pollution reductions, with productivity also contributing, and trade explaining only a marginal share. Hence, according to their main results, in the U.S. context, domestic regulation – rather than productivity or trade – has been the dominant force behind declining pollution. There are several works closely related to the influential contribution of Shapiro and Walker (2018) that have advanced the debate in this branch of the literature in multiple directions. Duan, Ji, Lu, and Wang (2021) expanded their insights on the pollution haven effect to test the pollution haven hypothesis using a multi-country, multi-sector quantitative trade model that enriches the Caliendo and Parro (2015) framework with a pollution "production" block similar to Copeland and Taylor (1995). Their findings on the pollution haven effect are consistent with those of Shapiro and Walker (2018), suggesting that changes in environmental regulation affect emissions primarily through technique effects, as regulation and abatement shape the emissions intensity of production. At the same time, environmental regulation is not the dominant determinant of international specialization. Instead, trade costs play a much larger role, thereby limiting the importance of composition effects driven by environmental policy. Adding another contribution to this debate, Cherniwchan (2017) challenged the conclusion of Shapiro and Walker (2018), which attributes the major driver of the decline in emissions and emission intensity in the U.S. manufacturing sector to environmental regulation. He provides plant-level evidence that trade liberalization played a substantial role in the environmental clean-up of U.S. manufacturing by estimating the effects of NAFTA on the emissions of particulate matter and sulfur dioxide from manufacturing plants in the United States. His findings suggest that trade liberalization led to significant reductions of these pollutants at affected plants. On average, nearly two-thirds of the reductions in particulate matter and sulfur dioxide emissions from the U.S. manufacturing sector between 1994 and 1998 can be attributed to trade liberalization following NAFTA. Moreover, his results indicate that lower costs of importing intermediate inputs from Mexico significantly contributed to these emission reductions by inducing firms to offshore more pollution-intensive stages of production and to adjust their internal activity mix. Interestingly, this interpretation is supported by a CTS decomposition of the effects on pollution, similar to the one in Cherniwchan, Copeland, and Taylor (2017), for a Melitz-type model. Forslid, Okubo, and Ulltveit-Moe (2018) also contributed to this strand of literature by modelling and empirically testing how exporting firms can be cleaner through endogenous abatement investment. In their model with heterogenous firms a la Melitz, higher productivity and exporting lead to larger production volumes; these in turn allow firms to amortize fixed costs of abatement investment, reducing emission intensity per unit of output – a strong technique effect. Forslid et al. also show empirically, using Swedish firm-level data, that exporters indeed have lower emission intensities and undertake more abatement investment than non-exporters. Building on this strand of work, Richter and Schiersch (2017) examine whether exporting firms in German manufacturing are indeed less carbon-dioxide emission intensive than non-exporters, using a novel dataset for Germany over 2003–2011. Their main finding is that export intensity is positively related to carbon dioxide productivity (i.e. negatively related to emission intensity) for most two-digit manufacturing industries in Germany. Together, these three studies strengthen the evidence that trade (via exporting) drives technique effects: in both Sweden and Germany, firms that export more (or enter export markets) tend to adopt cleaner production per unit of output, which mitigates environmental damage even as scale expands.

Barrows and Ollivier (2021) extend this line of research into a developing-country context, using rich firm-product data from Indian manufacturers over 1995-2011 and exploiting trade partner demand shocks. They find a pronounced scale effect, in that foreign demand increases carbon-dioxide emissions via growth in output (both export and domestic), but crucially they also document that emission intensity falls, offsetting roughly 40-50% of the increase from the scale effect. The technique effect in Barrows and Ollivier is therefore strong enough to substantially mitigate the environmental cost of expanded exports, but in contrast to with the studies just mentioned the net effect is still an increase in emissions (though not always statistically significant) because the scale effect dominates. Thus, Barrows and Ollivier reinforce the idea that technique effects matter at the firm level.

Recent work using Chinese firm-level data provided important insights into the technique effect of trade and the evolution of pollution intensities. Cui, Tam, Wang, and Zhang (2020) and Pei, Sturm, and Yu (2021) both emphasized how trade liberalization shaped firms' environmental performance. Cui, Tam, Wang, and Zhang (2020) documented that trade liberalization led to a reduction in SO_2 emission intensity at the firm level, while Pei, Sturm, and Yu (2021) found that exporters were more environmentally friendly than non-exporters, in line with previous evidence reported for developed economies. Bombardini and Li (2020) shifted the focus to the prefecture level, examining how export expansion following tariff reductions affected pollution and health outcomes. They distinguished between the pollution content of exports and the value of exports per worker, showing that the former significantly increased infant mortality through higher pollution exposure, while the latter hinted at – but did not robustly deliver – income-driven improvements in environmental quality. This analysis explicitly confronted the tension between *scale* and *technique effects* in the Chinese context. Finally, Rodrigue, Sheng, and Tan (2024) provided one of the most important contributions to this strand of literature. Using Chinese firm-level manufacturing surveys and customs records over the 1999–2005 period around WTO accession, they showed that exporters were systematically less emission-intensive than non-exporters, and that this gap widened after trade liberalization. To reach this conclusion, they extended a heterogeneous-firm trade model with endogenous abatement (inspired by Shapiro and Walker, 2018; Forslid et al., 2018) and showed how exporting reduced emissions intensity both directly, by changing production technology and product scope, and indirectly, by making abatement more cost-effective as gross pollution rose (echoing Andreoni and Levinson, 2001). Strikingly, they found that abatement investments explained only a small part of the reduction in emissions intensity, with most improvements coming from shifts in production and capital upgrading. In contrast to earlier literature emphasizing external regulation, their findings suggested that trade-induced upgrading alone could drive substantial technique effects, placing firm heterogeneity at the center of the CTS decomposition in the Chinese case.

Overall, the literature on the environmental consequences of trade – structured around the scale, composition, and technique (CTS) framework introduced by Grossman and Krueger (1991) and formalized by Copeland and Taylor (1994, 1995) and Antweiler, Copeland, and Taylor (2001) – reveals a nuanced and heterogeneous picture. While trade liberalization unambiguously raises output and therefore pollution through the scale effect, the composition effect is typically modest, context-dependent, and often offset by opposing forces of factor endowments and regulation. By contrast, the technique effect emerges consistently as the dominant channel: rising incomes, stricter regulations, technological upgrading, and firm-level responses to trade exposure reduce pollution intensities and mitigate the environmental cost of expanded trade. These

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findings underscore that the environmental impacts of trade cannot be inferred from trade flows alone but are contingent upon domestic regulatory frameworks, technological capabilities, and firm behaviour. Ultimately, the CTS framework shows that while trade inevitably expands economic activity, its environmental consequences hinge less on where production occurs and more on how firms and economies innovate, regulate, and adopt cleaner technologies – making the technique effect the decisive force in shaping whether trade harms or helps the environment.

4.4 Pollution Haven, Pollution Halo and Porter Hypothesis

The environmental consequences of global trade are closely linked to the stringency of national environmental regulations and policies. A key channel operates through the extent to which such regulations influence firms' location choices and shape the inflows and outflows of production between countries. In this context, two competing views have emerged in the economics literature: the Pollution Haven Hypothesis and the Pollution Halo Hypothesis. Both perspectives build on the same theoretical framework (the composition, scale, and technique effects described in Section 4.3) yet they differ in predicting which effect dominates in the aftermath of trade liberalization or a reduction in trade barriers. The PHH emphasizes the predominance of the composition effect, which should theoretically drive global trade towards countries with law environmental standards and increase pollution. The Pollution Halo attributes, instead, a major role to the technique effect, which could decrease emissions due to a potential transfer of more efficient technologies and management practice. The Porter Hypothesis adds a further dimension by arguing that properly designed environmental regulations can stimulate innovation and productivity improvements, potentially offsetting compliance costs and even enhancing competitiveness. The current section introduces these three hypotheses in detail and reviews the main contributions in the literature which tried to theoretical explain and empirically verified them.

4.4.1 Pollution Haven Hypothesis

According to the Pollution Haven Hypothesis (PHH), countries characterized by more lenient environmental regulations hold a comparative advantage in attracting pollution-intensive productions. Conversely, strict climate regulations may induce an increase in trade outflows due to dirty firms' delocalization abroad. The distinction between countries with stronger or laxer environmental regulations often mirrors the divide between developed and emerging economies, enforcing the assumption that the degree of environmental regulation behaves as a normal good. Consequently, the comparative advantage of light or absent pollution monitoring may encourage developing countries to specialize their production in energy-intensive sectors with the objective of exporting polluted goods, becoming pollution havens for advanced economies.

From a theoretical perspective, under the PHH, reductions in trade barriers are expected to increase emissions in countries where a regulation-induced comparative advantage manifests. This outcome is mainly driven by trade patterns that push those countries to specialize in pollution-intensive production, thereby worsening the production mix, as well as by the expansion of trade volume which increases overall economic activity, income, and thus pollution. The formal theoretical foundation of the PHH is already provided in the seminal contribution of Copeland and Taylor (1994), who model international trade in a North-South general equilibrium framework in which two countries produce goods with different pollution intensity and have different levels of income. They find that the optimal choice in term of environmental regulation is different, since the higher-income country prefers a stricter protection and tends to specialize production in clean goods. Differences in policy give therefore a comparative advantage to the South in producing dirty goods. Within the scale–composition–technique decomposition, they then show that trade liberalization may increase world pollution in a setting in which the composition effect dominates the technique effect, leading trade liberalization to reallocate pollution-intensive production toward the Souths, consistently with the PHH. Antweiler, Copeland, and Taylor (2001) find little support for the PHH, since in their results trade openness tends to lower average pollution, and the large composition effects predicted by theory appear small in practice because factor endowment and regulatory effects counteract one another. Later contributions have extended and challenged these predictions. Liddle (2001), for instance, develops a dynamic simulation model linking trade, environment, and development that incorporates both production- and consumption-based pollution, endogenous abatement investment, and a traded natural resource. The model shows that while free trade generally raises overall pollution, its effects vary by country endowments and income-induced environmental investments. Contrary to the Pollution Haven Hypothesis, Liddle finds that developing countries can have lower effective pollution under autarky due to higher per capita income and stronger environmental upgrading, emphasizing that trade's environmental impact depends more on development-driven "technique effects" than on relocation of dirty industries. Ishikawa and Kiyono (2006) explicitly compare different environmental policy instruments within a simple open-economy model. They show that unilateral regulation can lead to carbon leakage, with foreign emissions rising enough to offset domestic reductions. Their results highlight that the choice of policy instrument critically shapes the extent of pollution relocation and specialization patterns. Tang (2015) embodies a game-theory perspective and develops a theoretical model comparing how host-country environmental regulations affect local-market-oriented and export-oriented foreign direct investment (FDI). Using Cournot and Bertrand competition frameworks, the model shows that export-oriented FDI is more sensitive to regulatory stringency, as its competitors are less shielded from cost increases than those of local-market-oriented FDI. This result suggests that the pollution haven effect (PHE) may be heterogeneous across FDI types, and empirical studies that pool them together may underestimate its magnitude. Duan et al. (2021) develop a quantitative trade model with endogenous environmental regulation to systematically evaluate the pollution haven hypothesis. They find that while environmental regulation provides some comparative advantage, its effect on international specialization is weak, and trade liberalization does not systematically shift pollution-intensive industries to low-regulation countries. Their results show that productivity and trade costs are the main drivers of trade patterns, while changes in environmental taxes after liberalization are generally environment-improving, consistent with the EKC (Environmental Kuznets Curve). Overall, the paper concludes that PHH receives little support once these broader mechanisms are considered. Moreover, Lodi and Bartarelli (2022) develops a Melitz-type trade model with heterogeneous firms, environmental taxes, and endogenous eco-innovation. The model shows that regulation can trigger either a Pollution Haven Effect or a strong Porter Hypothesis, depending on whether compliance costs or innovation gains dominate. Beyond factor endowments, Hamaguchi (2024) introduces technological spillovers into a trade–environment model with an international emissions trading system revealing the importance of technological gap between countries in determining the Pollution Haven dynamics. The analysis shows that when spillovers are localized and industry concentration is already high, lower trade costs push dirty production toward low-regulation regions, consistent with PHH. Conversely, when initial concentration is low, liberalization can trigger a home-market effect that draws activity to high-regulation regions, leading to cleaner global outcomes. Adding a new dimension to the debate that was strongly underexplored, recently, Shapiro (2025) analyses how the quality of institutions may shape environmental quality and, therefore, affect comparative advantage. In a structural gravity model, he finds that improving institutions in low-quality countries reduces domestic emissions but may raise foreign emissions by reallocating dirty production abroad. Importantly, his decomposition of cross-country differences in pollution reveals that composition effects are at least as important as technique effects, challenging the traditional view that composition plays only a minor role. Finally, theoretical models have begun bridging PHH with the Pollution Offshoring Hypothesis (POH), formalizing how regulation affects offshoring decisions of specific segment of productions. Iida and Mukherjee (2025) model a domestic monopolist choosing whether to offshore an upstream input under a pollution tax and show that offshoring follows an inverted U pattern such that moderate taxes encourage relocation, but very high taxes (and very low or no taxes) deter it. Their results explain why empirical studies sometimes find weak relocation effects under rising stringency and highlight that carbon border adjustments may not fully correct these distortions.

While the basic theoretical rationale for the validity of the PHH is convincing, the empirical evidence in the data is mixed and significantly heterogeneous across time and methodologies. In what follows, we review in detail the main empirical contributions that have investigated the validity of the PHH, both with econometric techniques and descriptively.

Although not explicitly employing the term "Pollution Haven", the relationship between the stringency of environmental regulation and international trade has been a central topic in the economics literature since the late 1970s. Jaffe (1995) offers one of the most extensive and systematic review of the empirical literature examining the potential effects of environmental regulation on the competitiveness of U.S. manufacturing firms, with a particular focus on whether regulatory stringency adversely affects export performance. The bulk of the studies reviewed are empirical contributions that exploit industry or plant level data within linear reduced-form econometric frameworks. Overall, the evidence is mixed and, in general, does not provide robust support for significant adverse effects of environmental policy stringency on competitiveness across a wide range of outcomes (e.g., TFP, trade flows, plant location, net exports). In sum, rather than providing evidence of a persistent pollution haven effect, the early empirical literature suggests that any pollution-related displacement of production that may have occurred was limited and likely offset by countervailing forces, discouraging the validity of the Hypothesis. In particular, rising environmental awareness and regulatory pressure appear to have been accompanied by significant technological progress and increased investment in cleaner production methods, which mitigated potential losses in competitiveness (Mani and Wheeler, 1998).

Several explanations and potential issues have been raised for this preliminary absence of strong effects. First, the limited availability of data at the time made it challenging to measure regulatory stringency with precision, which was frequently proxied by survey data on Pollution Abatement Costs. Ideally, an exogenous and unpredictable variation in the stringency of environmental regulation should be exploited, which required further narrative and empirical effort. Second, the compliance costs borne by U.S. firms at the time were relatively modest in comparison with total production costs, making it unlikely that regulation constituted a major deterrent to exports or a strong driver of plant relocation (Tobey, 1990). In more general terms, for PHH to hold a first necessary condition is that the differential across countries in the stringency of environmental policy must induce increase in production costs able to affect foreign trade volumes and firm location decisions. The latter is what is technically called Pollution Haven Effect (PHE). However, the realization of the PHE is not a sufficient condition for the validity of the PHH, since its magnitude must also be large enough, when compared to other factors impacting trade flows, to significantly affect comparative advantage (Copeland and Taylor, 2004). Finally, and perhaps most critically, some sources of endogeneity exist, since other empirical evidence figured out that environmental regulation can be distorted by countries with the objective of protecting domestic industries preserving the optimal level of trade outflows (Ederington and Minier, 2003). In other words, environmental policy is often an endogenous dimension of the mechanism.

As a result, subsequent studies have sought to address these endogeneity concerns by exploiting panel data, applying instrumental-variable or other techniques to isolate truly exogenous variations in the stringency of environmental policies, and extending the econometric framework to incorporate additional industry-specific common factors. By accounting for unobserved heterogeneity and explicitly controlling for the potential endogeneity of environmental policies, these contributions uncover statistically significant evidence supporting the PHH, with effects of economically reasonable magnitude.

A first key contribution in this regard is Levinson and Taylor (2008), one of the most widely cited empirical tests of the Pollution Haven Hypothesis. Using a panel of 132 U.S. manufacturing industries engage trade with Canada and Mexico over 1977–1986, they estimate models with industry fixed effects to control for unobserved heterogeneity and then instrument pollution abatement costs to address simultaneity bias. Their results indicate that a 1% increase in abatement costs is associated with a 0.2–0.4% increase in net imports in fixed-effects models, with even larger effects when using instrumental variables. These effects are economically meaningful and robust across specifications, providing strong causal evidence that stricter environmental regulation leads to trade patterns consistent with the Pollution Haven Hypothesis. Complementing this evidence, Kellenberg (2009) employ a novel cross-country panel of 50 countries and 9 industries to study U.S. multinational affiliate production. Using a GMM-IV strategy with instruments based on agricultural sector characteristics and strategic policy interactions, he finds that stricter enforcement of environmental regulation significantly reduces affiliate value added, with effects strongest in footloose industries. Building on this shift toward more credible identification, other studies explored the role of trade openness and income heterogeneity using multi-country data and structural decompositions. In one of the most relevant works, Kellenberg (2008) re-examines the trade–environment relationship using a balanced panel of 128 countries in the period 1990–1995 and emissions data for four different air pollutants. Employing fixed-effects and Seemingly Unrelated regressions, the paper estimates scale, composition, technique, and trade-intensity elasticities. Results confirm that trade openness is associated with lower emissions on average, but the trade-intensity effect varies systematically by income level: low and high-income countries exhibit positive trade–pollution elasticities (consistent with PHH), whereas middle-income countries display negative elasticities, suggesting that both capital abundance effects and technique effects are influencing the trade–emissions relationship.

A particular manifestation of the Pollution Haven Effect through climate policy is carbon leakage, which may occurwhen emission cuts in regulated countries lower fossil fuel demand and prices, encouraging greater consumption in less regulated regions. This is only one of the two carbon leakage channel and represents a composition effect operating through global energy markets. Aichele and Felbermayr (2015) provide the first rigorous ex post evaluation of this phenomenon by exploiting Kyoto Protocol commitments as a quasi-natural experiment. Using a gravity model of embodied carbon emission in bilateral trade, they show that Kyoto increased carbon imports from non-committed countries by about 8% and raised their carbon intensity by 3%, with most of the effect driven by trade volume rather than cleaner production. These findings offer robust evidence of carbon leakage, consistent with PHH predictions.

Another central channel through which the PHH may operate is foreign direct investment (FDI). Stricter regulations can deter inward FDI or push domestic firms to relocate abroad, while laxer regulatory regimes may attract capital inflows into pollution-intensive sectors. Chung (2014) investigates the effect of environmental regulation on South Korean outward FDI across 121 industries and 50 host countries over 2000–2007. Using a difference- in-differences framework with country-year and industry-year fixed effects, the study disentangles the impact of regulatory laxity from factor endowment effects and other con- founders. Results show a statistically and economically significant pollution haven effect, since countries with laxer regulations attract more Korean FDI in polluting industries, both in investment volume and in the number of new affiliates. Analogously but for the U.S., Tang (2015) shows environmental regulation affects different types of outward FDI using panel data for 8 industries and 50 host countries over 1999–2003. Employing GMM-IV estimation with instruments based on agricultural characteristics and neighbours' policies, the study addresses the endogeneity of environmental stringency and GDP. Results reveal robust evidence of a pollution haven effect, with stricter and better-enforced regulations significantly able to deter both local-market-oriented and export-oriented FDI. The paper also shows that the deterrent effect is particularly strong in countries with environmental standards exceeding U.S. levels and that neighbouring countries' policies affect FDI location decisions, highlighting the spatial dimension of PHH. Exploiting time series econometrics, Sun et al. (2017) examine the relationship between inward FDI and carbon emissions in China over 1980–2012 using an ARDL cointegration approach with breakpoint unit root tests to account for structural changes. Controlling for GDP, energy use, trade openness, and other macroeconomic variables, they find that a 1% increase in FDI inflows increases carbon emissions by 0.058% in the long run, providing evidence consistent with PHH. Cherniwchan (2017) employs U.S. manufacturing plant data to provide one of the first empirical analyses of the climate effects of trade barrier reductions across multiple pollutants at the firm level. He finds that NAFTA contributed to the cleanup of the U.S. manufacturing sector, mainly through declines in emission intensity but also partly through the reallocation of energy-intensive activities abroad, which is consistent with pollution haven motives. Employing a panel instrumental-variable quantile regression, instead, Kim et al. (2019) examine the impact of trade on carbon emissions using panel data for 131 countries, disaggregating trade into North–North, North–South, South–North, and South–South flows. This empirical strategy allows them to account for endogeneity and capture heterogeneous effects across the conditional distribution of emissions. Results show that South–North trade raises carbon emissions in developing countries, supporting the Pollution Haven Hypothesis, whereas South–South trade mitigates emissions, especially for less-polluted countries. As for more recent cross-country evidence, Yu et al. (2022) use a partially linear functional-coefficient panel model for 93 countries and find that exports reduce green productivity in very low-income economies, consistent with PHH, but raise productivity in middle and high-income countries through technology spillovers. Their results highlight the strong income heterogeneity in trade's environmental effects. Emodi et al. (2023) examine, instead, the effects of different FDI entry modes on carbon emissions in 68 countries from 1996–2018 using an augmented Stochastic Impacts by Regression on the Population, Affluence, and Technology (STIRPAT) framework with IV-GMM and IV-quantile regressions to address endogeneity. They find that GFDI and total FDI significantly raise per capita carbon dioxide emissions, consistent with the Pollution Haven Hypothesis, with stronger effects in developing and high-emission economies. PHH is empirically confirmed exploiting M&A data in a different framework also by Carril-Caccia and Milgram-

Baleix (2024), who analyse how environmental regulation affects cross-border mergers and acquisitions using a structural gravity model with PPML estimation. Their specification includes rich fixed effects to control for time-varying bilateral and sector-specific factors. They find that stricter environmental policies significantly reduce cross-border M&As relative to domestic ones, especially for flows from developed countries to BRICS.

The development of global value chains (GVCs) has further complicated the interpretation and validity of the PHH. Firm relocation in response to strict environmental standards does not necessarily involve entire industries or complete production processes but may concern only the most pollution-intensive stages of the supply chain. This phenomenon is captured by the Pollution Offshoring Hypothesis (POH), which posits that firms tend to outsource the dirtiest segments of their production abroad rather than relocate entire business units. The POH leads, therefore, to trade outflows that are not directly motivated by the stringency of regulation but rather by carbon responsibility and the will to outsource highly polluting production tasks. In this context, Duan et al. (2021) estimate panel regressions for 40 economies for the period 1995–2009 linking the pollution intensity of value-added exports to income gaps between trading partners, controlling for country-pair and time fixed effects. They find that the larger is the income gap between countries that trade, significantly more pollution-intensive is the value-added exports, consistent with the Pollution Haven Effect. To address potential endogeneity, they instrument income gaps with their lagged values, and results remain robust. Their results indicate that high-income countries reduce their domestic emissions by relocating only the most pollution-intensive stages of production to low-income countries, rather than shifting entire production processes abroad. In this sense, global value chains can also be viewed as global pollution chains. Saussay and Zugravu-Soilita (2023) also test the POH using data on 63,000 industrial M&A deals across 41 countries in the period 2000-2015. They first estimate a probit model finding that stringency in environmental policy may have a significant impact in firms' decision to engage in cross-country M&A, identifying environmental taxation as main driver of these dynamics. They then exploit sectoral linkage measures to figure out that these effects are higher in acquisitions of firms in upstream sectors and in highly pollution-intensive industries.

Beyond direct measures of regulatory stringency, several studies exploit exogenous trade liberalization episodes to assess whether openness shifts the geography of pollution-intensive production. For instance, Kolcava et al. (2019) analyse a panel of 183 countries in the period 1987-2013 and find that participation in preferential trade agreements significantly increases the ecological footprint of exports from low-income countries, consistent with PHH predictions. Consistent results are found by Yao et al. (2019), who estimate a gravity model of bilateral CO_2 emissions for 39 countries and show that free trade agreements raise emissions especially in middle-income countries, consistent with PHH predictions, while agreements among high-income partners are associated with cleaner trade flows. Choi et al. (2025) also provide causal evidence in favour of the role of offshoring in the cleanup of U.S. manufacturing following the conferral of Permanent Normal Trade Relations (PNTR) status to China. Using establishment-level data from the Toxics Release Inventory matched with import and subsidiary information, they estimate a difference-in-differences model exploiting variation in exposure to the tariff uncertainty shock. Results show that establishments in industries more affected by PNTR experience significantly larger declines in emissions, consistent with the outsourcing of polluting tasks.

Despite these positive findings in favour of the existence of a pollution haven effect, not all studies

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employing more sophisticated econometric techniques support the PHH once endogeneity is accounted for, in different geographical contexts. For instance, Marconi (2012) analyses bilateral trade between 14 EU countries and China over 1996–2006, estimating panel regressions of changes in sectoral revealed comparative advantages on factor endowments, labour costs, and interactions between industry pollution intensities and country-level environmental stringency indices. Results reports that EU countries on average maintained or improved comparative advantage in polluting industries, suggesting that environmental regulation did not erode competitiveness in opposition to what the PHH posits. For the United States, Holladay (2016) uses plant-level panel data on several manufacturing establishments to examine the link between trade and pollution. He finds that exporters emit 10–13% fewer emissions than non-exporters, since import competition induces the exit of the dirtiest plants, lowering aggregate emissions. While his main focus is not on the existence of pollution haven motives, he digs deeper in his findings and shows that the domestic emission reductions are not driven by offshoring to lower regulated countries and subsequent re-imports, rejecting therefore a pollution haven explanation. Shao et al. (2019) re-examine the PHH for BRICS and MINT (Mexico, Indonesia, Nigeria and Turkey) countries using a panel VECM and co-integration tests over 1982–2014, treating FDI, carbon emissions, GDP, energy use, trade openness, and urbanization as endogenous. Their empirical results indicate that inward FDI has a negative long-run effect on carbon emissions for MINT countries and energy consumption for BRICS countries, rejecting the validity of PHH. In France, Dussaux et al. (2023) analyse firm-level data on emissions, imports, and energy prices for manufacturing firms using a Bartik-style IV strategy based on third-country supply shocks. They find that a 10% rise in imported emissions lowers domestic emission intensity by about 4%, particularly among energy-intensive and export-oriented firms but find no significant effect on total emissions, implying efficiency gains rather than pure offshoring, providing therefore evidence in contrast to pollution haven motives. More recently, Akerman et al. (2024) use detailed Swedish firm-level data for the period 2004-2016 and a shift–share IV exploiting foreign export supply shocks to identify the causal effect of importing intermediate inputs on carbon emission intensity. They find that a 10% increase in imports reduces firms' carbon intensity by 5.6%, explaining nearly one-third of the observed aggregate decline. The effect is strongest in energy-intensive industries and operates through productivity gains, abatement investments, and product mix rationalization. Importantly, the results show no evidence of a pollution haven channel, given that the effect is not guided by outsourcing towards countries with lower environmental standards.

A recurring theme in this second wave of studies is that identification strategy shapes results. Analyses that instrument environmental policy stringency (e.g., abatement costs or enforcement) generally find stronger evidence of a pollution haven effect. By contrast, studies that either rely on fixed effects without external instruments or use IV designs that instrument trade exposure or import competition rather than policy tend to report null or opposite effects, highlighting productivity and technique channels that lower emission intensity instead of relocation. This pattern suggests that whether the instrument targets policy or trade shocks may matter for what mechanism is identified, offering one potential explanation for the heterogeneity in findings.

A complementary body of literature uses environmentally extended input–output (EEIO) and multi-regional input–outpt (MRIO) models to measure emissions embodied in trade and test whether trade systematically shifts pollution toward less regulated countries. Unlike econometric studies, these approaches are descriptive rather than causal, but they provide a comprehensive accounting of carbon flows along global value chains. Indeed, they seek to integrate in the analyses a crucial dimension: the perspective from which emissions are measured. Distinguish between consumption-based and production-based emissions may help in disentangle the true net effect of firm delocalization toward pollution havens by looking at where dirty goods are finally consumed, opening the recent and important debate of countries carbon responsibility. A first strand focuses on country-level or bilateral balances of embodied emissions. For instance, Dietzenbacher & Mukhopadhyay (2007) compute the emissions intensity of Indian exports and imports for different type of air pollutants, finding that India's exports are relatively clean compared to domestic production. They claim that their results highlight a "green Leontief paradox", inconsistent with PHH. Brunel (2017) and Cai et al. (2018) extend this framework using input–output methodologies to examine whether trade liberalization and globalization patterns are consistent with PHH predictions. Brunel (2017) shows that the EU's manufacturing sector actually became more "brown" in its production mix while imports grew cleaner, providing little support for pollution offshoring and highlighting that technique improvements were the main driver of Europe's manufacturing cleanup. Similarly, Cai et al. (2018) employ a multi-regional input–output (MRIO) model for China, finding that China acts as a pollution haven for several developed countries, but also outsources pollution to lower-income partners.

Exploiting MRIO databases to capture global supply chain fragmentation, Zhang et al. (2017) embed the pollution haven hypothesis within global production fragmentation, distinguishing emissions from domestic activity, final goods trade, intermediate goods trade, and GVC-related trade. Using a Logarithmic Mean Divisia Index (LMDI) structural decomposition analysis, the study shows that trade-induced emissions have risen over time, peaking in 2008, with intermediate goods trade representing the largest share while GVC-related emissions are steadily increasing. Results indicate that declining carbon intensity mitigates emissions growth, whereas expanding trade volumes act as a positive driver, and cross-country differences reflect each nation's position in global value chains. Similarly, Duan et al. (2021) use a multi-country input–output model combined with a structural decomposition analysis to estimate emission intensities from bilateral value-added trade data, disentangling the impact of trade composition from that of technology. Their decomposition findings suggest a prevailing nature of the technique effects relatively to the composition one in explaining the observed decline in pollutant concentration in trade.

Moreover, some papers enrich the IO framework with spatial econometric techniques and counterfactual approaches, offering a more nuanced understanding of how trade structure and geography jointly shape embodied emissions patterns. For instance, Zhangqi et al. (2018) combine a MRIO model with spatial econometric regressions to analyse the transnational transfer of carbon emissions embodied in trade for 39 countries between 1995 and 2011. Their results highlight that emissions primarily flow from developing to developed countries, and that determinants such as energy and industrial structure exhibit significant spatial spillover effects, suggesting that policy interventions in one region can influence emissions outcomes elsewhere. Wu et al. (2021) also adopt an MRIO framework but introduce a novel no-trade scenario to reallocate global supply chain inputs domestically, allowing them to isolate the net effect of trade on greenhouse gas emissions; they find that current international trade, while boosting global economic growth, results in higher overall GHG emissions compared to a hypothetical world without trade. More recently, Dietzenbacher and Yan (2024) use WIOD-based GMRIO tables to test the Pollution Haven and Factor Endowment Hypotheses across 40 countries, showing that neither hypothesis alone satisfactorily explains observed bilateral trade-embodied emissions, and concluding that any ranking-based theory is at best only partially valid.

Taken together, these IO-based studies reinforce the mixed evidence from econometric analyses, revealing that while developed economies are net importers of embodied carbon, much of the variation in emission transfers is explained by structural factors such as income growth, consumption patterns, and energy efficiency rather than by policy-driven relocation. This suggests that the PHH mechanism, though present, accounts for only part of the observed carbon displacement and leaves space for alternative dynamics guiding carbon flows between countries, such as the Pollution Halo Hypothesis (PH).

4.4.2 Pollution Halo Hypothesis

In contrast to the PHH, the Pollution Halo Hypothesis (PH) posits that globalization can improve environmental outcomes by transferring cleaner technologies, better management practices, and stricter corporate environmental standards to host countries. Its theoretical foundation refers to the same scale–composition–technique framework as the PHH, but assuming that in case of trade liberalization the technique effect dominates the composition effect. The expected outcome is therefore a decline in emissions intensity despite an expansion in output. Both mechanisms can coexist with one of the two prevailing, and several of the studies reviewed above that reject PHH suggest that a halo-type mechanism may instead dominates (e.g., Duan et al., 2021; Hamaguchi, 2025; Dussaux et al., 2023). In the following, we review the most influencing studies that explicitly test the validity of the PH with models and data exploiting different methodologies.

The earliest formalization of the halo mechanism is offered by Eskeland and Harrison (2003), who analyse plant-level data from Mexico, Venezuela, Morocco, and Côte d'Ivoire. They find no evidence that foreign plants are more pollution intensive than domestic ones. On the contrary, foreign-owned firms tend to use cleaner inputs and adopt more energy-efficient production processes, offering some of the first empirical support for a halo rather than a haven effect. Building on this foundation, subsequent studies have sought to clarify the scope and conditions of the halo mechanism, often by exploiting increasingly rich FDI and trade datasets. Evidence from China provides early warnings that halo effects are not universal. Cole et al. (2011), using city-level data from 2001–2004, separate foreign investment originating from Hong Kong, Macao, and Taiwan from that of other economies. Their findings show that foreign firms frequently raise rather than reduce emissions, with outcomes driven by the sectoral composition of FDI rather than an intrinsic halo effect. By contrast, Zhu et al. (2016) adopt a distribution-sensitive panel quantile regression approach for the ASEAN-5 and show that FDI reduces carbon emissions only in high-emission countries. This indicates that halo effects are most evident where environmental pressures are strongest, suggesting a conditional, rather than general, relationship. Zugravu-Soilita (2017) adds a further perspective by showing that the environmental consequences of FDI vary with host-country characteristics, since in moderately regulated economies, FDI tends to reduce emissions (i.e., halo effect), while in capital-abundant or weakly regulated contexts, it increases them, more consistently with a pollution haven or factor endowment effects.

Beyond these cross-country comparisons, other studies highlight alternative dimensions of the halo effect. Wang et al. (2019), for instance, focus on Beijing's industrial relocation to neighbouring provinces. Their results show that domestic investment flows reduce most industrial emissions, indicating that halo effects can also operate within national boundaries, while foreign direct investment in the same regions produces more pollution-haven type outcomes. Similarly, Balsalobre-Lorente et al. (2019) identify an inverted-U pattern in MINT countries, where FDI initially worsens but eventually improves environmental performance once development thresholds are crossed. Their results confirm that halo and haven effects may coexist along different stages of growth. Methodological advances also play a role. Mert and Bölük (2020), by applying hidden co-integration and asymmetric causality to Turkish data, reveal halo effects in both the short and long run when accounting for asymmetric FDI shocks, in contrast to earlier studies that had suggested a haven dynamic.

More recent contributions expand the geographic scope and refine the conditions under which halo effects emerge. Abbass et al. (2022) examine Chinese outward FDI in seven Asian countries, finding long-run reductions in carbon emissions consistent with a halo effect, though short-run dynamics are mixed. Nejati and Taleghani (2022) show that in Iran, FDI alone worsens emissions, but when combined with energy efficiency improvements it yields halo outcomes, highlighting the importance of complementary domestic policies. Dauda et al. (2021) focus on African economies, showing that trade openness produces either haven or halo effects depending on absorptive capacity and spillover channels, with renewable energy use playing a crucial role in reducing emissions. At the global level, Duan and Jiang (2021) assess the role of multinational enterprises (MNEs), showing that while MNEs are less emission-intensive than domestic firms, their supply-chain activities raise indirect emissions. Their analysis points to the coexistence of halo and haven mechanisms depending on the stage of globalization.

Taken together, this body of literature shows that the halo effect is neither automatic nor universal. While trade and FDI can generate environmental benefits through cleaner technologies and better practices, these gains are highly contingent on host-country conditions, such as institutional quality, absorptive capacity, sectoral composition, and existing pollution intensity. Rather than uniformly offsetting the pollution haven mechanism, halo effects function as a conditional channel, emerging most strongly where complementary domestic policies and structural characteristics enable the transfer and adoption of cleaner practices, making highly uncertain the final climate consequences of trade.

4.4.3 Porter Hypothesis

While the pollution haven and the pollution halo views can be interpreted as two sides of the same coin, since they rely on the same theoretical framework and differ only in the prevailing balance of technique versus composition effects, the Porter Hypothesis (PH) introduces a different perspective. It challenges the traditional view of environmental regulation as a mere cost burden for firms. Originally formulated by Porter and van der Linde (1995), it argues that well-designed environmental regulations can stimulate innovation, yielding so-called innovation offsets that not only reduce compliance costs but also improve resource efficiency, product quality, and competitiveness. By reframing pollution as a sign of economic inefficiency, the Porter Hypothesis suggests that stringent but flexible regulations can spur firms to discover hidden opportunities for productivity gains and technological progress. This shifts the debate from a static trade-off between environmental protection and competitiveness toward a dynamic model in which efficiently tailored regulation may become a driver of innovation-led growth.

A growing body of empirical work has sought to test the validity and scope of this proposition. Costantini and Mazzanti (2008) provide one of the earliest systematic econometric validations, showing that environmental regulation can foster induced innovation in energy and environmental technologies, which in turn enhances export competitiveness in OECD countries. Their findings lend support to the weak version of the Porter Hypothesis that regulation spurs innovation, and provide partial evidence for the strong version, where regulation-induced innovation improves performance. Building on this innovation–regulation nexus, subsequent studies have expanded the analysis to new contexts. Liu et al. (2019), focusing on 29 Chinese

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provinces from 1996–2015, employ a fixed-effects partially linear additive panel model to capture nonlinearities in the growth–emissions–FDI relationship. They uncover an inverted U-shaped EKC for growth and an inverted N-shaped link between FDI and emissions. Initially they show reducing pollution through technology spillovers, consistent with Porter Hypothesis, later worsening it via scale effects, supporting pollution haven motives, and eventually improving environmental performance again as stricter regulations and industrial upgrading take hold. These results underline that the environmental consequences of growth and investment are stage-dependent and mediated by regulatory capacity. Attention has also turned to the role of policy design. Lodi and Bartarelli (2022) advance the discussion by distinguishing between different regulatory instruments and their effects on innovation. Using European firm-level data, they find that market-based tools such as carbon pricing are more likely to stimulate green innovation than command-and-control measures, confirming that the design of environmental policy is crucial to realizing Porter-type dynamics. Complementing this, Li et al. (2022) highlight the importance of trade in promoting regulatory-driven innovation. Analysing firm-level trade data on 142 green products across 30 Chinese provinces (2007–2016) with system-GMM, quantile regression, and mediation analysis, they show that green trade reduces sulfur emissions primarily through technological upgrading. Their results suggest that environmental regulations tied to green product standards can reinforce technological progress, thereby providing strong support for the Porter Hypothesis. More recent contributions extend the debate to developing country contexts. Bekoe and Jalloh (2023) examine the AfCFTA and its environmental implications for 41 African countries between 1995 and 2019. Applying system-GMM and quantile regression, they disentangle scale, composition, and technique effects of trade. Their results indicate that while liberalization tends to degrade environmental quality through scale and composition channels, improvements in regulatory quality substantially offset these effects by stimulating cleaner production. This lends further support to the Porter Hypothesis, showing that in settings of rapid trade expansion, robust regulatory institutions can convert environmental constraints into drivers of sustainable growth.

Taken together, this literature suggests that the Porter Hypothesis is not universally valid but conditional on regulatory design, technological opportunities, and firm capabilities. The common thread is that when regulations are stringent, predictable, and flexible, they can align environmental and competitive objectives by steering firms toward efficiency-enhancing innovation.

The evidence on the Pollution Haven, Pollution Halo, and Porter Hypotheses paints a nuanced picture of globalization's environmental impacts, where regulatory design, technological change, and firm behaviour interact in complex ways. Overall, recent comprehensive reviews indicate that most of the decline in emissions in high-income countries is attributable to technological improvements and cleaner production processes, implying that offshoring cannot account for the bulk of observed emission declines and that relocation effects, when present, are highly sector-specific and related to geographically mobile and energy-intensive industries (Levinson, 2023). However, the net environmental consequences of these trade flows remain highly uncertain, as they depend on a range of additional factors. For instance, the elasticity of environmental quality with respect to income plays a central role: if the Environmental Kuznets Curve (EKC) holds, rising incomes in emerging economies should eventually lead to tighter environmental regulations and enhance efficiency over time. The latter is the focus of the next section.

4.5 Environmental Kuznets Curve (EKC)

Using panel data for both developed and developing countries and several environmental indicators, Grossman and Krueger (1995) identified an inverted-U relationship between economic growth and environmental degradation, later popularized as the Environmental Kuznets Curve (EKC). Since then, a large body of empirical research has investigated the robustness of this pattern across pollutants, countries, and time periods using different empirical approaches. At the same time, Frankel and Romer (1999) find a positive relationship between trade and growth using an instrumental variable approach. Taken together, these findings suggested that trade, by influencing economic growth, can have very different environmental consequences depending on a country's position along the EKC.

The main economic mechanism underlying the EKC can be summarized as follows: during early stages of growth, scale effects dominate, leading to rising emissions as output expands. This dynamic is most prevalent in low- to middle-income economies, where production growth directly drives environmental degradation and emissions are roughly proportional to GDP. At higher income levels, however, composition and technique effects become more important. Economies begin to shift towards less resource-intensive sectors and adopt cleaner technologies, producing the EKC's characteristic turning point. This stage is more typical of advanced economies, where endogenous technological diffusion, structural change, and environmental regulation reinforce cleaner production.

Trade interacts with these EKC dynamics through the scale, composition, and technique (CST) mechanisms outlined in Section 2. It amplifies scale effects by expanding production and resource use, particularly in developing economies. It modifies composition effects by reshaping industrial specialization, as pollution-intensive sectors may relocate abroad (offshoring) while advanced economies increasingly shift toward cleaner sectors. Finally, trade influences technique effects through the international diffusion of cleaner technologies and harmonization of environmental standards. In this way, the CST framework provides the theoretical foundation for understanding how trade conditions the EKC trajectory – whether accelerating environmental degradation in early stages of growth or reinforcing cleaner production at higher income levels.

These trade–EKC interactions, however, are not neutral. As discussed in Section 2, CST effects evolve over time, and this evolution directly shapes the position and nature of EKC turning points. Scale dynamics may be prolonged in resource- and energy-intensive exporters, while composition effects are increasingly mediated by global value chains (GVCs), where production is fragmented and emissions outsourced. Similarly, technique effects can be uneven, with advanced economies adopting cleaner technologies while developing countries face barriers to diffusion. As a result, apparent environmental improvements in higher-income countries may partly reflect the relocation of environmental burdens rather than genuine decoupling. A further layer of complexity arises when linking the EKC to the competing hypotheses on regulation, technology, and trade which we discussed in Section 3. Indeed, according to the Porter Hypothesis, stricter environmental regulation can spur firms to innovate and adopt cleaner technologies, potentially reinforcing the EKC's downward slope at higher income levels. If these technologies diffuse internationally via DI, they may generate a Pollution Halo effect, reducing emissions even in host countries. Yet the opposite dynamic is also possible: if regulatory asymmetries dominate, firms may relocate polluting industries to countries with laxer standards, in line with the PHH. Taken together, these perspectives highlight that the global impact of growth and trade on the environment is theoretically ambiguous making the EKC outcome highly context-dependent. Understanding the EKC therefore requires embedding it within the CST framework, with trade acting as the transmission channel that redistributes – and potentially distorts – environmental outcomes across regions. In this section, we examine how our understanding of these trade–EKC linkages has evolved, from early cross-country regressions to more recent evidence using firm-level data, and multi-regional input–output (MRIO) approaches.

Muradian and Martinez-Alier (2001) provide an influential critique of the EKC theory. While EKC studies often emphasize the role of composition and technique effects at higher income levels, the authors contend that in practice developing countries may remain locked in scale-driven dynamics. Thus, Northern economies may appear to validate the EKC hypothesis by exhibiting declining local emissions, yet much of this improvement stems from environmental cost-shifting – that is, the relocation of ecologically intensive production to the South. Perhaps most importantly, they highlight a fundamental limitation of the EKC narrative. If one interprets the EKC literally, it suggests environmental problems will solve themselves as income grows. But this is not the case if there are irreversible ecological thresholds. For global problems such as biodiversity loss, carbon emissions, and natural resource depletion, export-oriented growth in resource- and pollution-intensive sectors may generate irreversible losses long before income levels rise enough to induce cleaner production. This makes their critique qualitatively different from the other studies, which mostly debate whether the EKC exists or how trade and FDI shape it. Their analysis is conducted using trade and material flow statistics, focusing on physical imports and exports of non-renewable resources between developed and developing countries. It is largely descriptive, but it anticipates later MRIO-based research by emphasizing the need to account for trade-embedded environmental costs. Indeed, much of the EKC literature relies on production-based emission accounts; when consumption-based measures are used instead, the apparent improvements at higher income levels often diminish, since part of the environmental burden is outsourced through trade. We return to this issue in Section 5 that will be entirely devoted to the concept of consumption vs production-based responsibility. Using a panel dataset spanning developed and developing countries, multiple pollution indicators, and a range of controls, Cole (2004) explores the links between the PHH, the CST framework, and the EKC. He tests whether differences in environmental regulation encourage the relocation of pollution-intensive industries from developed to developing economies. If this is the case, trade-driven composition effects can give rise to PHH dynamics and help explain why the EKC pattern is more likely to emerge in developed countries than in developing ones. He finds mixed evidence. Specifically, while he finds clear evidence of an inverted-U relationship for local pollutants, this is not the case for global pollutants like CO_2 where emissions continue to rise with income, thus supporting the finding of Muradian and Martinez-Alier (2001). He also finds little robust evidence that pollution-intensive industries systematically relocate from developed to developing countries purely because of weaker regulations. From his analysis it seems that: the EKC is more applicable to local air pollutants in advanced economies, but not to global pollutants or to developing countries; trade influences EKC dynamics, but mainly through subtle composition and technique channels rather than a clear-cut PHH. Aklin (2016) re-examines the EKC for CO_2 with panel data and spatial models, treating trade as a mechanism of diffusion. This diffusion can take two forms – either a relocation of pollution (outsourcing carbon-intensive industries) or a spread of cleaner technologies that reduces emissions across countries. Empirically, he finds the former dominates: once these spatial effects are accounted for, the EKC pattern vanishes and per-capita CO_2 emissions follow a linear trajectory. Aklin (2016) further identifies a "second mover disadvantage": developing countries emit 0.29–0.7 tons more CO_2 per capita than industrialized ones at similar income levels, showing they bear the burden of outsourced emissions. Shahbaz et al. (2017) analyze the relationship between trade openness, economic growth, and CO_2 emissions for a panel of 105 countries (1980–2014). Methodologically, they differ from earlier EKC studies since instead of quantile regressions, they employ panel Vector Error Correction Model (VECM) to identify both short- and long-run causal links. When looking at individual countries they find mixed results for the impact of both trade openness and economic growth on CO_2 emissions, although trade openness reduces CO_2 emissions in most of the countries. However, their results confirm the existence of an inverted U-shaped EKC-type relationship between trade openness and CO_2 emissions for the global sample and when countries are grouped into high-, middle-, and low-income categories. However, the turning points vary sharply: high-income countries reach them at relatively high trade openness levels, while middle-income countries experience the steepest environmental deterioration but also transition faster to improvements. Low-income countries show the longest path to the turning point and suffer the greatest relative environmental costs. Dong-Hyeon et al. (2019) test the EKC using a panel of 131 countries over 1960–2013 with an instrumental variable quantile regression approach. Their framework captures two sources of heterogeneity: first, the income–emissions relationship may differ across low- versus high-pollution contexts; second, trade flows may have distinct environmental effects depending on whether they occur between similar economies (North–North, South–South) or between heterogeneous partners (North–South, South–North). The results confirm a robust inverted-U shaped relationship between per-capita GDP and CO_2 emissions across most quantiles, consistent with the EKC. However, they find that while trade among similar countries (North–North and South–South) reduces emissions overall, North–South trade reduces emissions in the North and South–North trade is associated with higher emissions in the South. These findings suggest that the apparent EKC may partly reflect pollution haven dynamics, with developing (South) countries engaging in a "race to the bottom" as polluting industries relocate from the advanced economies (North). Yao et al. (2019) analyze the environmental effects of free trade agreements (FTAs) using a gravity model combined with a multi-regional input–output (MRIO) framework. The dataset covers 39 countries (32 of which are signatories of the Montreal Protocol and Kyoto Agreement) over the period 1995–2009. Countries are also grouped into high-, upper-middle-, and lower-middle-income categories to test for heterogeneous effects. Results show a pattern consistent with an inverted-U relationship between income and bilateral CO_2 emissions: high-income countries benefit from FTAs by reducing emissions, largely due to efficiency gains and stricter standards, while upper- and lower-middle income countries experience higher emissions as FTAs expand pollution-intensive production. This asymmetry suggests that while rich economies may appear to follow the EKC trajectory, environmental improvements are partly achieved by shifting pollution abroad, consistent with the Pollution Haven Hypothesis (PHH). Their findings resonate with Aklin (2016) and Cole (2004) in that EKC patterns in developed countries may mask outsourced emissions. A similar result is obtained in Yang et al. (2020). They adopt a footprint-based approach to examine the environmental consequences of consumption and trade in the Asia-Pacific (APAC) region over 1995–2015. Using the EXIOBASE 3.6 multi-regional input–output database, they trace six indicators – including GHG emissions, PM2.5 emissions, water use, and energy use – from final demand back through production across 49 regions and 200 sectors. Their results suggest patterns broadly consistent with a Pollution-Haven driven EKC: high-income APAC economies (e.g. Japan, South Korea, Australia) have reduced their domestic emissions intensity, appearing to move past the turning point, but largely by outsourcing pollution-intensive production to lower-income partners such as China, India, and Southeast Asia. In these developing economies, environmental footprints continue to rise (potentially surpassing sustainable thresholds), reflecting their position on the upward-sloping part of the EKC.

While the previous papers look at a broad set of countries, some concentrate their effort on specific subsets.

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Both Zhu et al. (2016) and Nasir et al. (2019) focus on ASEAN-5 economies (Indonesia, Malaysia, Philippines, Thailand, Singapore). Zhu et al. (2016) use panel quantile regression and find no evidence of an inverted-U relationship between income and CO_2 emissions for the ASEAN-5 over the sample 1981-2011. Their hypothesis is that for these emerging economies growth has not yet generated the composition or technique effects needed to offset scale-driven increases in emissions. Nasir et al. (2019) covers a similar period (1982–2014) but uses a different econometric approach, namely Fully Modified OLS (FMOLS) and Dynamic Ordinary Least Square (DOLS), which correct for autocorrelation and endogeneity. Nonetheless, they too find no robust support for the EKC in ASEAN-5. Similarly, Bekoe and Jalloh (2023) look at 36 African countries over 1990–2019 using a panel ARDL framework and they also reject the existence of an inverted U-shaped EKC.

Liu et al. (2019) use Chinese provincial data for 29 provinces over 1996–2015 in a semi-parametric additive panel model that captures nonlinearities and heterogeneity more flexibly than standard panel regressions. They find an inverted-U shaped relationship between per capita income and CO_2 emissions, consistent with the EKC. Interesting, a key contribution of the paper is to link the EKC with foreign direct investment (FDI). They find a nonlinear, inverted-N shaped effect of FDI on CO_2 emissions, with alternating phases of technology spillovers (supporting the Porter Hypothesis) and pollution relocation (supporting the Pollution Haven Hypothesis), before finally moving toward cleaner outcomes as environmental standards tighten. Similarly to Liu et al. (2019), Zafar et al. (2020) also focuses on the role of FDI but enlarge the analysis to a panel of 17 Asian economies over 1990–2018 using both DOLS and FMOLS. In their analysis FDI exerts a nonlinear effect – raising emissions in early development stages (supporting the PHH) but reducing them once cleaner technologies diffuse, consistent with the Pollution Halo effect. Education also follows an EKC pattern: early expansions are pollution-intensive, but higher levels foster efficiency and innovation, in line with the Porter Hypothesis. The main message is that EKC turning points in developing Asia depend not only on income growth but also on the quality of FDI inflows and the capacity of education systems to drive technological upgrading. Khan and Ozturk (2021) put the emphasis on the role played by financial development, a variable so far neglected. They use a large panel of 88 developing countries over the period 2000–2014, focusing on both the direct and indirect effects of financial development on environmental quality. Their empirical strategy relies on dynamic panel estimation and system GMM, which accounts for endogeneity and allows them to test financial development as both a direct determinant of emissions and as a moderating channel. They find strong evidence supporting the EKC hypothesis. More importantly, financial development plays a pollution-reducing role not only directly but also indirectly, by moderating the adverse effects of income, trade openness, and FDI on emissions. In weak financial systems, FDI and trade are associated with higher pollution, consistent with the PHH, but when financial development surpasses a threshold, the PHH ceases to hold. Taken together, Zafar et al. (2020) and Khan and Ozturk (2021) suggest that strong financial institutions can help channel foreign funds toward cleaner technologies thus mitigating the scale effects of growth. Support for the EKC is also found by Wang, Zhang, and Li (2023) using a global panel of 208 countries (1990–2018). Alongside CO_2 emissions per capita and per-capita GDP they also consider the role played by trade openness, human capital, renewable energy consumption, and natural resource rents. They use system GMM, AMG, FMOLS (and DOLS for checks). The estimations are done on the global sample as well as by classifying countries by decoupling status to study heterogeneity. The paper validates an inverted-U globally, with a turning point at about USD 19,203 (2017 international $). In 2018, 120 countries were still below the turning point; effects of the covariates differ pre- vs post-turning point (e.g., renewables have stronger mitigation before the turning point; human capital shows larger reductions after it). Trade openness only mitigates emissions in a subset of countries (notably those with weak decoupling after the turning point), while natural resource rents tend to raise emissions in most cases. Overall, the paper supports a global EKC with a concrete income threshold, but stresses that countries are in very different stages both in terms of income level and in terms of decoupling so that higher income or higher trade can have very different effects. Unlike the studies discussed so far, which either examined only developing countries (e.g., Liu et al. 2019; Zafar et al. 2020) or panels mixing developing and advanced economies (e.g., Zhu et al. 2016; Shahbaz et al. 2017), Frodyma (2022) focuses exclusively on 28 EU countries over the period 1970–2017. Using annual data on both production-based (PBA) and consumption-based (CBA) CO_2 emissions from the Eora MRIO database, the paper applies country-specific ARDL bounds cointegration tests to explore quadratic, cubic, and linear EKC specifications. Across most countries and specifications, there is no evidence of an EKC, neither for PBA nor for CBA emissions. Out of 168 estimated cases, only 11 showed any long-run relationship between income and emissions, and these were highly heterogeneous, lacking a common inverted-U pattern. In particular, the analysis of CBA emissions reveals a persistent positive link between income and emissions, undermining the idea that growth alone will eventually lead to decoupling. These findings stand in sharp contrast with earlier panel-based evidence (e.g., Zhu et al. 2016; Cole 2004), which reported at least partial EKC validation for certain pollutants or contexts. Instead, they resonate more with the critique by Muradian and Martinez-Alier (2001), highlighting how the EKC can disappear once consumption-based measures are used, exposing the limits of production-based environmental improvements in advanced economies (although in this case also PBA do not support the EKC). In a very recent paper Smith and Christopoulos (2025) investigate the link between income and CO_2 emissions in the context of global value chains (GVCs). Using data for 43 countries over 2000–2014 they apply a Temporal Network Autocorrelation Model (TNAM) to capture both the role of GDP per capita and a country's embeddedness in GVCs. In contrast with much of the earlier EKC literature, their results point to a U-shaped relationship between income and emissions. The authors argue that the divergence from previous findings is largely explained by their network-based methodology, which emphasizes the structural role of GVC participation, rather than relying on conventional panel data regressions.

While the bulk of the EKC literature relies on econometric tests using cross-country or panel data, there is a small fraction that consider structural approaches that explicitly model the mechanisms behind scale, composition, and technique effects. A prominent example is provided by Duan et al. (2021), who develop a general equilibrium trade framework to examine how trade liberalization and endogenous regulation shape emissions. Key features of the model are: a production sector with emission following Copeland and Taylor (2003); a multi-country multi-sector trade model as in Eaton and Kortum (2002); input-output linkages and trade in intermediate as in Caliendo and Parro (2015). Finally, following Grossman and Krueger (1993), they identify CST effects. Counterfactual simulations yield three key findings. First, while differences in environmental regulation constitute a source of comparative advantage, they play only a very marginal role in shaping trade patterns and specialization. Indeed, a reduction in trade costs does not systematically shift pollution-intensive production to weakly regulated economies: cross-country productivity differences and trade costs dominate environmental regulation in shaping specialization patterns, providing strong evidence against the PHH. Second, trade liberalization raises global emissions by around 8%, driven largely by scale and composition effects in developing economies. Finally, when environmental regulation is endogenous to the income level, higher incomes induce stricter emission taxes, reducing pollution intensities via a technique effect. This supports the view of an EKC which doesn't steam from the PHH i.e., the reduction in emissions after a certain level of income is due to the adoption of greener technology and not the simple artefact of relocating the environmental burdens. Compared to econometric EKC studies such as Cole (2004) and Zhu et al. (2016) which find mixed or context-specific EKC patterns that are mostly driven by PHH, Duan et al. (2021) provide evidence in support of the idea that the EKC materializes once environmental policy is endogenized as an income-driven choice, and it is the result of the adoption of greener technology.

Taken together, the large body of empirical research shows that evidence for the EKC remains highly mixed and context dependent. Results vary across regions, country groups, time periods, pollutants, and estimation strategies, indicating that the EKC should not be seen as a universal law but rather as an empirical regularity that may hold under specific conditions. A likely reason for this heterogeneity is that income growth alone does not automatically generate the EKC. In some contexts, rising income has spurred the development of crucial mediating factors – such as financial systems, green FDI, and education – that support investments in cleaner technologies, while in others these channels have been absent or not accounted for, leading to divergent empirical results. Moreover, even when an EKC pattern is identified, it may simply reflect the relocation of polluting activities abroad, consistent with the pollution haven hypothesis. This underscores the importance of distinguishing between production-based and consumption-based measures of emissions, since countries may appear to improve domestic environmental quality while continuing to drive pollution elsewhere through global value chains. Building on this insight, the next section moves beyond the income–emissions nexus and turns to the production-versus-consumption debate, where these issues can be more directly addressed.

4.6 Consumption vs Production Responsibility (and GVC)

The preceding section has shown that the evidence for the EKC is highly mixed and context-dependent, often shaped by mediating factors such as financial development, FDI, education, and global production patterns. A crucial aspect not considered there, however, is that the way emissions are measured strongly affects the conclusions drawn. Most of the EKC literature relies on *production-based accounting (PBA)*, which attributes emissions to the country where they are generated. This territorial perspective tends to penalize exporters of pollution-intensive goods – often developing economies – while portraying advanced economies as relatively "clean." By contrast, *consumption-based accounting (CBA)* allocates emissions to the country where goods are consumed, typically estimated through multi-regional input–output (MRIO) models that track carbon embodied in trade. This perspective shifts responsibility toward advanced economies to the extent that they outsource carbon-intensive production through global value chains (GVCs). In this way, the fragmentation of production across borders may enable richer countries to reduce their production-based emissions while continuing to drive pollution abroad – a mechanism consistent with the PHH. If so, the EKC patterns observed in some countries would not reflect genuine reductions in global emissions, but rather their displacement elsewhere. The distinction between PBA and CBA is also closely linked to the CST framework discussed in Section 3. For instance, if a country achieves large reductions in production-based emissions but its consumption-based emissions remain broadly stable, this suggests that trade is shaping environmental outcomes primarily through *composition effects* – that is, by relocating polluting activities/sectors abroad – rather than through genuine *technique effects* such as cleaner technologies at home.

Having outlined this conceptual shift, we now turn to the empirical evidence. The following section reviews studies that directly compare PBA and CBA to assess whether the apparent reductions in domestic emissions in advanced economies are matched by parallel declines in their carbon footprint, or whether instead consumption-based emissions have remained constant. We focus primarily on studies covering multiple countries, while drawing on country-specific analyses only where they offer insights of broader relevance. Interesting country-specific studies include Wiedmann (2009) for the UK, Yunfeng and Laike (2010), Liu et al. (2017), Mi et al. (2017), Lopez et al. (2020), and Liu et al. (2020) for China, Godar et al. (2015) for Brazil, and Chen (2023) for China-USA trade. Their findings are consistent with the global evidence reviewed in the main text and are therefore not discussed further here. Peters and Hertwich (2008) is widely regarded as the pioneering contribution that opened the production-versus-consumption debate in the climate–trade literature. It provides one of the first comprehensive assessments of CO_2 emissions (which at the time covered over 70% of global GHG emissions) embodied in international trade and their implications for global climate policy. Using data from the Global Trade Analysis Project (GTAP v6) covering 87 countries and 57 sectors for the year 2001, they apply an environmentally extended multi-regional input–output (MRIO) framework to estimate emissions embodied in exports, imports, and the balance of trade. Their results show that 5.3 Gt of CO_2 were embodied in trade flows in 2001, corresponding to about 21.5% of global CO_2 emissions (rising to 23% if international transport is included). Developed countries were found to be net importers of embodied emissions, while developing countries were net exporters, with large cross-country differences. Calculations of carbon leakage suggest that 10.8% of developing countries emissions were effectively displaced to developed countries through trade. The authors conclude that PBA, as under the Kyoto Protocol, systematically underestimates the responsibility of advanced economies, whereas a consumption-based perspective would provide a fairer picture of global responsibility. While the paper does not directly test the EKC, its findings are highly relevant: the apparent decoupling of emissions in developed economies may in part reflect outsourcing through trade, a mechanism consistent with the PHH and with the composition effect emphasized in the CST framework. In a subsequent contribution, Hertwich and Peters (2009) extend this analysis by moving beyond CO_2 to cover all major greenhouse gases, employing a fully coupled MRIO model for 73 countries and 14 aggregate regions. They further decompose national carbon footprints into detailed consumption categories (e.g., food, shelter, mobility), showing how patterns vary systematically with income. This shift from trade balances to household consumption provides a richer global picture of responsibility and highlights the role of lifestyles and demand structures in shaping cross-country emission disparities. Together, these two papers laid the foundation for the production-versus-consumption literature, and the following studies have built on this approach to explore how robust these findings are across countries, time periods, and methodological choices. Davis and Caldeira (2010) build on Hertwich and Peters (2008) by providing an updated global estimate for 2004, again finding that roughly one-quarter of global CO_2 emissions are embodied in trade (23%), a figure very much in line with Peters and Hertwich's earlier calculations. Their analysis goes further in emphasizing the distributional consequences: while countries such as China export nearly a quarter of their production emissions, many advanced economies – including Switzerland, Sweden, the United Kingdom, and France – import more than 30% of their consumption-based emissions. Davis and Caldeira highlight not only the accounting differences but also the ethical and policy implications, arguing that developed countries benefit disproportionately from outsourced emissions and should therefore assume greater responsibility in global mitigation efforts. Peters et al. (2011) expand the analysis of trade-related CO_2 transfers by developing an annual time–series database of production- and consumption–based emissions for 113 countries and 57 sectors from 1990 to 2008. Whereas the early contributions by Peters and Hertwich (2008, 2009) first established the methodological framework for the year 2001, and Davis and Caldeira (2010) provided a cross–sectional global snapshot for 2004, this study systematically tracks how emission transfers have evolved over nearly two decades. The results show that trade-related transfers have grown steadily, with most developed countries remaining net importers and most developing countries net exporters. This time–series perspective directly enriches the earlier findings showing that what Peters and Hertwich (2008 and 2009) and Davis and Caldeira (2010) had quantified for a specific year is in fact a persistent and deepening pattern. It also links to the broader debate on the EKC and the PHH. Indeed, the authors stress that these emission transfers are primarily induced by preexisting macroeconomic and structural differences across countries, and not by climate policy itself (i.e., they find no evidence of PHH). The time-series perspective is also crucial for evaluating the EKC framework since in many cases the transfer of emissions via trade exceeds the territorial emission reductions reported in developed economies, under-scoring that observed mitigation effort. Aichele and Felbermayr (2015) refine the analysis by Peters et al. (2011) by explicitly testing whether the Kyoto Protocol induced carbon leakage through trade flows. Using a gravity model applied to OECD input–output tables, bilateral trade data, and sectoral CO_2 emission coefficients over the period 1995–2007, they show that Kyoto-committed countries increased the carbon content of their imports from non-committed countries by about 5–8%, compared to the counterfactual of no commitments. This suggests that while Peters et al. (2011) are correct in showing that most of the production–consumption gap stems from structural trade dynamics unrelated to climate policy, a non-negligible share of the divide can be traced back to policy-induced leakage. Differently from the previous studies, Moran et al. (2013) extend the analysis beyond CO_2 by compiling a high-resolution MRIO database for 187 countries containing eight indicators of ecological pressure – greenhouse gas emissions, air pollution (PM_{10}), embodied water and scarcity-weighted water, threatened species, Human Appropriated Net Primary Productivity (HANPP), total material flow, and the ecological footprint – covering the period 1990–2010 for some indicators and around 2000 for others. Their objective is to test the hypothesis of ecologically unequal exchange (EUE), namely that developing countries bear a disproportionate share of ecological burdens through trade with wealthier economies. The results show that exports from low-income countries, particularly in Africa and Latin America, are indeed more ecologically intensive than those from high-income economies, confirming one dimension of EUE. However, in absolute terms high-income countries are found to be net exporters of natural resources because of the much larger volumes of trade they command, meaning that they do not exert a disproportionately large footprint abroad. In relative terms, though, the ecological intensity of developing country exports is much higher, implying that they sell natural resources more cheaply in biophysical terms. Over time, the intensity of exports has generally declined, but rising trade volumes have offset these efficiency gains. Xu and Dietzenbacher (2014) extend these earlier quantifications of emissions embodied in trade by focusing not only on the magnitude of emission transfers but also on the drivers behind their evolution. Using a global MRIO (GMRIO) model combined with structural decomposition analysis (SDA), they examine 40 countries from 1995 to 2007. Their results show that producers increasingly sourced intermediate goods from emerging rather than developed economies, which explains the divergence between high growth in developed countries' consumption-based emissions and the relatively modest growth of their territorial emissions. Tian, Sarkis & Geng (2020) extend the PBA–CBA debate by adopting a multi-dimensional footprint approach to the BRICS countries from 1995–2015. Using MRIO analysis, they calculate CO_2, SO_2, water, land, energy, and material footprints and show that BRICS economies bear greater environmental costs per unit of trade than they gain in economic returns. The study's key contribution is to highlight that the outsourcing of environmental pressure is not only about carbon, but also about multiple interlinked resource footprints. In contrast to most of the studies reviewed so far, Franzen and Mader (2018) take a critical stance toward CBA and argue in favor of retaining PBA as the standard. Using data for 110 countries over 1997–2011, they combine PBA data from the Emission Database for Global Atmospheric

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Research with CBA data from the Global Carbon Atlas derived through MRIO modeling. Their comparison shows that although numerical differences exist between the two measures – for instance, Switzerland's footprint is nearly three times larger when measured on a consumption basis – the correlation between PBA and CBA is extremely high (Pearson r = 0.89, Spearman r = 0.96). This implies that country rankings remain almost unchanged when switching from PBA to CBA, and large emitters like China and the United States retain their relative positions. On this basis, the authors conclude that the added complexity of CBA does not bring sufficient new insight to justify replacing PBA, a conclusion that stands in stark contrast to Peters et al. (2011), who emphasized the policy relevance of consumption-based metrics. Sanyé et al. (2019) apply the distinction PBA and CBA to the analysis of decoupling between GDP and environmental impacts in the EU-28 from 2005 to 2014. Using life-cycle assessment (LCA) indicators covering 16 impact categories, they construct both a Domestic Footprint (DF), reflecting territorial production-based impacts, and a Consumption Footprint (CF), which accounts for embodied impacts from trade. Results show absolute decoupling under the PBA perspective: GDP grew by 8% while DF declined by 19%. The CBA perspective gives a more ambiguous picture with CF ranging from –23% to +0.2% depending on the approached used to compute CF. The paper thus illustrates how conclusions about decoupling – and by extension about the Environmental Kuznets Curve – depend on the accounting perspective adopted. This stands in contrast to Franzen and Mader (2018), who argued that differences between PBA and CBA do not alter the overall picture of countries' environmental performance and responsibility. It also stands in contrast to the analysis of Frodyma (2022), which we discussed in the previous section, and that, using cointegration analysis, didn't find evidence of the EKC curve for EU 28 countries over the period 1970-2017.

An important step forward in the PBA vs CBA debate comes with Kander et al. (2015). They introduce a refinement of CBA called technology-adjusted CBA (TCBA), which corrects for differences in carbon efficiency between exporting and importing countries. Unlike standard CBA, which subtracts exports at the exporting country's domestic carbon intensity, TCBA uses the world-market average intensity for the relevant sector, thereby accounting for the counterfactual emissions that would have occurred if exports were produced elsewhere. Thus, while PBA assigns emissions to the country of production penalizing exporters of carbon-intensive goods and CBA shifts responsibility to consumers, but risks overlooking producer responsibility, TCBA corrects for differences in carbon efficiency thereby rewarding carbon-efficient exporters. This hybrid approach avoids free riding by either side and provides a more balanced assessment of responsibility. Using the World Input–Output Database (WIOD) covering 40 countries and 35 sectors for 1995–2010, the authors show that TCBA significantly alters the emissions map. For several European countries, often depicted as large net importers under conventional CBA, TCBA instead suggests smaller footprints – or even net exporter status – because their exports are relatively carbon-efficient. By contrast, the United States remains a net importer, and China's footprint falls between PBA and CBA, reflecting both its export role and its lower efficiency. The main contribution is methodological showing that not all the PBA-CBA gap reflects outsourcing or carbon leakage, but also efficiency differences that can lower global emissions. Lu et al. (2020) apply this approach to 62 Belt and Road Initiative (BRI) economies (1995-2015) and find that BRI countries as a whole are large net carbon exporters, with even higher footprints under TCBA due to lower-than-average efficiency. China and India emerge as the largest net exporters, while countries such as Singapore and Turkey are net importers. The study thus underscores the importance of TCBA in revealing the carbon responsibility of some emerging economies, where efficiency gaps are especially pronounced. Tang et al. (2024) build on this line of research by combining TCBA with a producer–consumer shared responsibility

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framework to assess the distributional consequences of international trade. Using EORA MRIO data for 189 countries over 2006–2016, they show that while global emissions rose, global carbon inequality decreased since the standard deviation of TCBA per capita across countries fell, meaning responsibilities converged. Developing economies benefited from trade-induced growth that aligned their per capita responsibilities with global averages, while developed countries saw convergence limited by carbon leakage through re-imports. Dietzenbacher et al. (2020) argue that neither PBA nor CBA adequately captures global emission responsibilities. Building on the Ricardian trade theory of comparative advantages but with a focus on how clean a country is in producing a certain good compared to the world average, the authors introduce the *Emission Responsibility Allotment (ERA)*, a hybrid approach that adjusts CBA by assigning credits or penalties depending on whether a country's trade reduces or increases global emissions compared to the world average. Using the WIOD for 41 countries (1995–2009), they show that ERA outcomes are generally close to CBA results, with credits and penalties. Rich countries tend to gain modest credits, while large emitters such as the USA and China incur significant penalties, reflecting trade patterns that worsen global emissions. ERA can serve a dual role: *ex post*, it can fairly evaluate past emission responsibilities, while *ex ante* it can guide trade policies towards cleaner specialization ("green Ricardian trade"). Importantly, the authors position ERA as a complement to PBA and CBA in the Paris Agreement framework, offering a robust accounting system for tracking national contributions and internationally transferred mitigation outcomes.

A relatively recent strand of the literature is focused on the role of trade in intermediate input for emission accounting. Xu (2017) analyse China's CO_2 emissions embodied in trade, with a focus on its exchanges with the US, EU, and Japan. Using the 2011 World Input–Output Database (WIOD), the paper applies a value-added input–output framework to show that conventional PBA not only shifts responsibility away from consumers but also suffers from double counting of emissions when intermediate goods cross borders multiple times. As a result, China's trade-embodied emissions were overstated by about 1.1 Gt in 2011 (roughly one-quarter of the emissions embodied in China's trade flows) compared to value-added measures. The study thus highlights another disadvantage of PBA and argues that value-added consumption accounting provides a fairer allocation of mitigation responsibility in global supply chains; see also Xion (2021) on China-USA trade and emission accounting. Meng et al. (2018) integrate global value chain (GVC) accounting with emissions analysis to consistently link production- and consumption-based perspectives. Using the WIOD over the period 1995–2009, they trace emissions along GVC routes and distinguish between "self-responsibility" (emissions for domestic demand) and "shared responsibility" (emissions tied to international trade). Importantly, the paper shows that major emission transfers now occur not only from developing to developed countries but increasingly among developing economies themselves, especially between China and other emerging markets. Indeed, the share of those emissions in total global trade related emissions went from 5% in 1995 to 20% in 2009. The paper thus complements the analysis of Xu (2017) as they both underline the importance of incorporating value-added and GVC perspectives to refine CBA5. Wang and Ang (2018), use essentially the same WIOD database (40 countries plus Rest of World, 35 sectors, 1995–2009) but apply a different methodology, introducing three interlinked index decomposition analysis (IDA) models to separate drivers of production-based, consumption-based, and net trade emissions. Their approach complements Meng et al. by focusing on decomposition of trends rather than value-added tracing along GVCs. Wang and Ang (2020) extend the analysis to a global scale using GTAP data for 140 countries and 57 sectors. Their focus is on intermediate product carbon emissions (IPCEs), which capture the emissions embodied in traded inputs along global production networks. They show that developed countries are overwhelmingly net importers of IPCEs (68%), while developing countries account for almost all net exports (98%). China emerges as the largest IPCE exporter but also a major net importer in bilateral trade with advanced economies, highlighting its dual role in global value chains. The paper argues that considering intermediate inputs is essential to avoid misallocating emission responsibilities under both PBA and CBA. Xiao et al. (2020) refine the GVC perspective by distinguishing between pure domestic demand, traditional trade, and simple versus complex GVC routes for 41 economies between 2010–2014. They find that international trade tends to reduce carbon intensities in high-carbon countries but increases them in low-carbon ones, with simple GVC routes often less efficient than complex ones. Xu et al. (2021) use gross export decomposition together with the WIOD to recalculate emissions at multiple levels of trade, production, and consumption, thereby eliminating the distortions caused by gross trade measures. Their results confirm that conventional PBA and even standard CBA systematically misstate countries' responsibilities because they ignore the value-added structure of global supply chains. Compared to earlier work, the paper's contribution lies in quantifying this gap systematically across countries and sectors and showing that value-added–based accounting provides a more consistent and fair allocation of global emissions responsibilities. Wang et al. (2022) use an MRIO framework combined with an optimized Regional Environmental Inequality (REI) index to evaluate the mismatch between carbon burdens and economic gains across six regions from 2010–2015. Their results show that major carbon exporters such as China, ASEAN, and other developing regions bear disproportionate emission burdens while capturing relatively little value added, whereas the USA, EU, and Japan are net importers of embodied emissions but retain most of the economic benefits. Sectoral analysis further reveals that carbon-intensive industries (electricity, petroleum, heavy manufacturing) underpin these imbalances. Xu (2020) complements this perspective by applying structural path analysis to MRIO data, tracing critical carbon transfer paths in global supply chains and highlighting the key sectors driving embodied emissions. A recent paper by Darwili & Schröder (2023) further refines the concept of TCBA by considering that, on top of technological differences, there are also substantial cross-country differences in input intensities in production. For example, according to their estimates, to produce 1 euro of gross output Chinese producers require on average 0.13 euros worth of additional inputs compared to German producers. This generates, ceteris paribus, a greater environmental impact. Using WIOD data for 40 countries + rest of world and 35 sectors, over the period 1995–2016, they construct a new index, the technology-adjusted balance of emissions embodied in trade (TBEET), which they interpret as a measure of "net weak carbon leakage". TBEET is meant to captures whether a country's trade structure helps avoid or induces additional emissions abroad once technology differences (including differences in the production structure) are neutralized. They find that EU countries are generally net avoiders of foreign emissions because of relatively clean production technologies while large emerging economies like China and India remain net exporters of emissions, though China still provides some avoided emissions for its trade partners. Importantly, they find that declining domestic emissions in developed countries were not offset by increases abroad via trade. Unlike earlier approaches that split responsibility along producer–consumer lines without considering trade frictions, Wang et al. (2024) further refine shared responsibility metrics by incorporating import and export tariffs/taxes and by estimating country- and sector-specific elasticities using a computable general equilibrium (CGE) model, showing how trade frictions alter the balance of emission responsibilities between producers and consumers. This allows them to more realistically capture how costs and benefits of trade are distributed between producers and consumers. Using a global dataset of 141 countries and regions in 2017, covering roughly 95% of world GDP, they estimate that trade-embodied carbon emissions amounted to 5,805 Mt CO_2. The largest responsibilities fall on China (939 Mt), the EU27 (761 Mt), and the USA (702 Mt), followed by India, Japan, Russia, Canada, Mexico, Australia, and Brazil. The methodological contribution is to show how tariffs and elasticities shift the producer–consumer balance of responsibility, providing a more nuanced picture than pure PBA or CBA.

Taken together, the literature shows that the choice of accounting perspective – PBA, CBA, or hybrid approaches – profoundly shapes our understanding of countries' climate responsibilities. While PBA remains the dominant standard in international agreements, it systematically underestimates the carbon footprint of advanced economies by overlooking the emissions embodied in imports. CBA corrects this asymmetry by reallocating responsibility to consumers, but risks obscuring producer-side incentives. Recent methodological advances such as technology-adjusted CBA (TCBA), value-added approaches, and shared responsibility metrics demonstrate that the PBA–CBA divide is not only about shifting blame but also about capturing how trade, technology, and production structures jointly affect global emissions. CBA based empirical evidence indicates that much of the apparent decoupling in developed countries reflects outsourcing rather than genuine mitigation, although efficiency improvements and structural shifts also play a role. Hybrid approaches like TCBA, ERA, or TBEET provide more balanced assessments, rewarding cleaner production and penalizing carbon-intensive trade, and are therefore promising candidates for complementing PBA in the design of fairer and more effective climate policy. Ultimately, the debate underscores that climate governance cannot rely on territorial accounting alone: understanding how global value chains redistribute both emissions and economic benefits is essential for attributing responsibility and aligning national policies with the collective goal of reducing global emission

4.7 International Transports

While much of the trade–environment literature has focused on production-based or relocation effects, an equally important yet often underexplored channel is the direct environmental impact of international transport. The movement of goods across borders requires extensive use of ships, aircraft, and trucks, and all these modes of transport collectively account for a consistent portion of global CO_2 emissions from the energy sector. As global value chains deepen and trade volumes expand, the carbon intensity of transport itself becomes a critical determinant of trade's overall climate footprint. Understanding this dimension is essential because even when trade induces cleaner production through technological spillovers or specialization, the gains can be offset by rising emissions from longer and more complex transport routes. Consequently, examining the transport channel provides a more complete assessment of the environmental consequences of global trade and of the trade-offs between economic efficiency and sustainability.

To this extent, recent research has increasingly examined how trade liberalization affects the environment through the international transports. Cristea et al. (2013) provide the first comprehensive quantification of greenhouse gas emissions from international freight transport using detailed global trade and transport-mode data. They show that transport accounts for roughly one-third of trade-related emissions, with air freight disproportionately contributing to global totals. Their simulations reveal that trade liberalization and growth in distant markets accelerate transport emissions faster than trade value, highlighting the need to integrate transport into climate policy frameworks. Building on this foundation, Shapiro (2016) incorporated transportation into a structural gravity model linking trade and the environment. He decomposed trade costs into fuel-related, regulatory, and residual components, finding that international trade increases global CO_2 emissions by around 5%, though welfare gains exceed environmental costs by a factor of 161. His framework enables counterfactual analysis of carbon taxes on shipping, bridging empirical evidence and theoretical modelling. Further advancing this line of research, Brancaccio et al. (2020) developed a spatial model of the shipping sector that endogenizes trade costs using vessel-level and contract data. They showed that shipping prices are asymmetric and shaped by trade imbalances and backhaul availability, revealing how geography and market structure jointly influence trade costs, emissions, and comparative advantage.

Extending the analysis to the global input–output structure, Klotz and Sharma (2023) integrated transportation into a multi-country general equilibrium framework. They demonstrated that trade liberalization lengthens value chains, increasing transport-related emissions through greater intermediate input use. While improved transport efficiency lowers direct emissions, it can amplify production emissions by encouraging input substitution. Khan et al. (2019) examined, instead, logistics performance and environmental sustainability at the macro level in SAARC countries. They found that poor transport infrastructure and fossil fuel dependence intensify emissions, whereas efficient customs and renewable energy use promote both trade and environmental outcomes, emphasizing the potential of green logistics policies.

Sun et al. (2022) analysed the transport sector's contribution to global emissions using an environmentally extended multi-regional input–output model. They showed that transport accounts for 4.2% of embodied global emissions, with land transport dominating demand-side impacts and air and maritime transport driving production-side emissions. Their findings highlight regional asymmetries and the importance of addressing emissions embodied in trade and consumption. Finally, Lin and Bai (2024) examined carbon emissions from transport sectors along global value chains using UNCTAD–Eora input–output data for 190 countries. Comparing production-based and consumption-based accounting, they identified significant cross-country differences in emission intensities and carbon-leakage patterns. Some countries' transport sectors produce high emissions with limited economic benefit, while others gain carbon-leakage credits by exporting transport intensive services. The study shows that once carbon costs are internalized, comparative advantage in trade can shift substantially.

Summing up, these studies show that international transport is a critical transmission channel linking trade and environmental outcomes. Trade liberalization and global value chain expansion tend to increase emissions by raising transport demand, while the magnitude of environmental impacts depends on transport modes, infrastructure quality, and geographic trade patterns. The literature thus underscores the need for policies that internalize transport-related externalities, through carbon pricing, technological improvements, and greener logistics, and to align trade expansion with climate objectives. As a direct consequence, transport is no longer treated as a passive conduit in trade-environment models; it is now recognised as a dynamic and policy-relevant channel through which trade liberalisation shapes global emissions and welfare outcomes.

4.8 Land, Water and Forest Usage & Biodiversity

So far, the analysis has focused on the impact of trade on emissions, whether carbon dioxide or other pollutants, emphasizing the spatial redistribution of environmental pressures through global production networks. However, greenhouse gases represent only one dimension of the broader environmental consequences of international trade. In many countries, land use, water extraction, deforestation, and biodiversity loss account for a substantial share of ecological pressures and are often closely intertwined with emission dynamics. Trade not only reallocates carbon-intensive production but also drives changes in land conversion, resource depletion, and ecosystem degradation. Extending the analysis beyond emissions, therefore, allows a more comprehensive assessment of how global trade reshapes environmental footprints across dimensions of sustainability. A landmark contribution in this direction is Lenzen et al. (2012), who provide the first global quantification of biodiversity loss embodied in international trade. By combining over 25,000 IUCN species threat records with an MRIO database covering 187 countries, they trace how consumption in developed economies indirectly drives habitat destruction and species endangerment in biodiversity-rich regions of the Global South. Their results show that around 30% of all recorded global species threats are linked to international trade, with the United States, the European Union, and Japan acting as major net importers of biodiversity loss. Conversely, countries such as Madagascar, Papua New Guinea, Sri Lanka, and Honduras are identified as net exporters, where up to 60% of species threats stem from the production of goods destined for foreign markets. The sectors most implicated are agriculture, forestry, and fisheries, with commodities such as coffee, cocoa, palm oil, timber, beef, and fish representing key vectors of habitat degradation. These findings highlight that international trade operates as a powerful transmission mechanism of ecological pressure, redistributing not only carbon emissions but also land conversion and biodiversity loss along global supply chains. The study introduces the concept of a "biodiversity footprint", conceptually analogous to carbon and water footprints, which attributes species threats to the final consumers of traded goods. This framework underscores that biodiversity loss is a global systemic outcome of consumption and production patterns, rather than a localized failure of environmental management. As in the climate domain, Lenzen et al. (2012) advocate for a shared responsibility between producers and consumers and for the development of policy tools – such as sustainability certification, trade regulation, and biodiversity labelling – to internalize the ecological costs embedded in trade. Chaudhary and Brooks (2019) combine a newly parameterized *countryside species–area relationship (SAR)* with an environmentally extended MRIO to capture the impacts of four main land-use types – agriculture, pasture, forestry, and urbanization – across 129 countries and 804 terrestrial ecoregions. Drawing on high-resolution global land-use data and habitat information for over 22,000 species of mammals, birds, and amphibians from the IUCN Red List, they estimate that 927 endemic species are projected to go extinct due to current global land use with agriculture, pasture, and forestry together accounting for more than 95% of the total impact. Importantly, about 25% of these projected global extinctions are embodied in international trade. The geography of these impacts reveals pronounced global asymmetries. Some countries like Brazil, China, India, and the USA have both a high production and a high consumption of biodiversity loss. Most EU production instead has a small impact on biodiversity loss while the same cannot be said about EU consumption. Methodologically, Chaudhary and Brooks introduce a significant refinement over earlier approaches by coupling ecological models with global economic accounts, thereby providing an explicit link between land-use dynamics, trade flows, and extinction risks. As previously noted in the EKC section, Yang et al. (2020) document an income-related turning point in environmental pressures within the Asia–Pacific region; in the present context, their results further highlight that this pattern is sustained by a spatial redistribution of land and water use, whereby higher-income economies increasingly outsource resource-intensive production and associated environmental externalities to lower-income regional partners through intra-APAC trade. Hong et al. (2022) provide the first comprehensive global assessment of land-use greenhouse gas (GHG) emissions embodied in international trade, integrating both agricultural and land-use change (LUC) emissions. Using an MRIO framework covering 141 regions between 2004 and 2017, the study attributes land-use emissions to final consumption and quantifies the net transfers of emissions through trade. Production-based estimates are derived from FAO agricultural data and the BLUE land-use bookkeeping model, while trade flows are drawn from the GTAP database. The findings reveal that Brazil, Argentina, Indonesia, Thailand, Russia, and Australia were the largest net exporters of land-use emissions in 2017 – together accounting for more than one gigaton of CO_2-equivalent emissions annually – whereas China, the United States, Japan, South Korea, Saudi Arabia, Germany, UK and Italy were major net importers. A similar pattern emerges for embodied land use: Australia, Brazil Mongolia, Argenina and Canada were the largest net exporters of agricultural land, while high-income, land-scarce regions such as Hong Kong, Singapore, and Kuwait relied overwhelmingly on imported land and emissions. For a country like Brazil net exports account for 40% of land-use emissions and 30% of land use. The study emphasizes that international trade acts as a key vector for the global redistribution of land-related emissions, often transferring environmental burdens from land-rich, developing exporters to land-scarce, high-income consumers. This structure mirrors patterns observed for biodiversity loss and water use, reinforcing the idea of ecological asymmetry in global trade. Hong et al. (2022) argue that recognizing land-use emissions as part of consumption-based carbon accounting is essential to avoid leakage in climate policy and to identify opportunities for cooperation – such as shifting sourcing toward regions with lower emission intensities or supporting sustainable land management in exporting countries. Wang et al. (2022) provide a detailed assessment of water use and virtual water trade in Central Asia, applying a multiregional input–output (MRIO) framework to trace production- and consumption-based blue water footprints across Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan between 1995 and 2015. Their results show a sharp rise in regional water footprints – driven almost entirely by irrigated agriculture, which dominates both domestic consumption and exports. More than 95% of exported virtual water originates from agriculture, with nearly 70% of exports directed to Europe. The study also highlights the post-Soviet fragmentation of transboundary water governance as a key driver of regional tension, with upstream states controlling most water resources and downstream economies depending heavily on irrigation. Among the socioeconomic determinants, urbanization is found to exert the strongest positive influence on water consumption, followed by population growth and income. Overall, the authors show that Central Asia is effectively exporting water while facing growing domestic scarcity, underscoring the need for coordinated basin-level management and policies to enhance water-use efficiency and resilience within the region's water–food–energy nexus.

Jia et al. (2023) introduce a novel perspective on land degradation embodied in global trade by focusing on soil salinization – a major threat to soil fertility, agricultural productivity, and ecosystem stability. Using the Eora MRIO database and complex network analysis, the authors map the global transfer of salinized irrigated land through trade flows, identifying how degradation pressures are redistributed across interconnected economies. The analysis focuses on irrigated lands, which – though more productive than drylands – are increasingly affected by salinity buildup due to poor irrigation practices.

The study estimates based on the year 2015 reveal a highly uneven spatial distribution: Central, South, and West Asia – particularly Pakistan, Afghanistan, Turkmenistan, Iran, and Iraq – constitute the global hotspot of salinization, together accounting for nearly 60% of all salt-affected land exports. Meanwhile, developed countries and large developing economies such as China and India are major net importers of embodied salinization. The authors argue that such "salinization transfers" exacerbate global disparities in land quality and food security. Policy recommendations include technological assistance from developed to developing economies, investment in irrigation efficiency, and the integration of environmental indicators into trade policy and agricultural planning. Ultimately, the study calls for international cooperation to address land degradation not merely by relocating production, but by improving land-use efficiency and irrigation management globally. Sun et al. (2023) extend the analysis of land and ecosystem pressures embodied in trade by introducing the concept of “embodied deforestation”, which captures the forest loss indirectly driven by international production and consumption. Using an environmentally extended input–output analysis (EEIOA) covering 189 regions and 26 sectors, the authors quantify the amount of deforestation embodied in imports and exports. The results reveal a pronounced asymmetry in global forest-use patterns: the top ten importing economies (among which the top 3 countries are USA, China and Germany) account for 60% of total embodied deforestation imports, while the top ten exporters (among which the top 3 are Canada, Brazil and Indonesia) account for 43% of exports. The authors argue that forest conservation should be understood as a shared international responsibility, requiring cooperative governance and supply-chain co-ordination rather than burdening heavily forested nations alone. Yue et al. (2023) quantify the global biodiversity loss embodied in trade by integrating an environmentally extended multiregional input–output (EE-MRIO) model with structural path and social network analysis to trace both the direct and indirect biodiversity footprints of production and consumption. Their framework distinguishes between internal, external, and overall biodiversity loss footprints, thereby capturing not only domestic impacts but also those transmitted through global supply chains. The results reveal pronounced cross-country differences: Indonesia, China, the United States, Mexico, and Brazil rank as the top five contributors to global biodiversity loss, with about 73% of impacts occurring domestically and 27% embodied in trade. High-income economies such as China, Japan, and the United States exert substantial external biodiversity pressures on other regions via their imports, while biodiversity-rich countries like India, Madagascar, and Indonesia bear the largest internal footprints, primarily through agriculture, food and beverage production, and construction. Agriculture emerges as the sector with the largest direct footprint, while the food and beverage industry contributes the most to indirect losses through downstream demand. Mapping the transmission pathways of biodiversity loss, Yue et al. (2023) show that final demand in the United States, Japan, China, and India drives species endangerment both domestically and abroad, underscoring the dual role of these economies as producers and consumers of biodiversity pressure. The authors conclude that embedding biodiversity accounting into global trade assessment is essential for clarifying shared conservation responsibilities and supporting evidence-based international policy on species protection. Finally, and unlike the preceding studies, which rely on empirical or accounting-based analyses of trade-related environmental pressures, Harstad (2024) offers a purely theoretical contribution, developing a dynamic game-theoretic model that captures the feedback between international trade and natural resource exploitation, using the case of tropical deforestation as a leading example. In his framework, the “South” exploits its forests to export goods such as timber and agricultural products, while the “North” values conservation but benefits from trade. Because deforestation generates negative externalities, the importing region may ultimately lose from trade, unless the resource is already depleted, in which case the marginal cost of additional depletion is less than the gain from trade. Thus, the North is interested in signing a Free Trade Agreement (FTA) only once there has already been substantial depletion. The opportunity for a future FTA motivates to accelerate exploitation. This dynamic produces a self-reinforcing cycle in which trade causes depletion, and depletion induces trade, leading to overexploitation even when the social damages exceed the gains from exchange. Harstad demonstrates that these adverse dynamics can be reversed through contingent trade agreements (CTAs) – trade deals in which tariffs are explicitly linked to the remaining stock of natural resources. By adjusting tariffs downward as conservation increases (and upward as depletion occurs), CTAs make restraint more profitable for exporters while keeping the agreement renegotiation-proof. When accompanied by export subsidies, such policies can achieve the first-best outcome of full conservation, but even without subsidies – given WTO restrictions – CTAs can still slow exploitation and yield a second-best solution that outperforms standard free trade agreements. The model thus offers a formal justification for linking trade preferences to environmental performance, echoing recent policy initiatives such as the EU proposal to condition tariff reductions on verified forest protection. Overall, Harstad's analysis provides a powerful theoretical foundation for using trade policy as an instrument of global forest governance, showing that well-designed, state-contingent trade mechanisms can transform trade from a driver of deforestation into a tool for conservation.

4.9 Discussion

Across three decades of research, the literature has moved from aggregate cross-country correlations toward firm-level, sectoral, and value-chain analyses that expose the heterogeneity of trade–environment linkages and the conditions under which they become mutually reinforcing or mutually damaging.

Early contributions identified the potential of trade to expand pollution through larger output (the scale effect) or to shift specialisation toward dirtier sectors (the composition effect). However, as regulatory capacity, innovation, and international technology transfer intensified, empirical work increasingly found that the technique effect – embodying cleaner processes, abatement, and efficiency gains – has outweighed the expansionary pressures of trade. Firm-level studies from the United States, Europe, China, and India demonstrate that export orientation and participation in global markets are often associated with lower emission intensities, primarily because openness exposes firms to competitive and regulatory pressures that reward technological upgrading. The environmental trajectory of open economies, therefore, depends less on the volume of trade than on the institutional and technological context in which that trade occurs. Trade and regulation are not inherently in conflict; rather, they are complementary drivers of technological change, provided that regulatory institutions are credible and firms have the absorptive capacity to learn from international partners.

The Environmental Kuznets Curve literature links these mechanisms along the development path. It shows that the same interplay between scale and technique effects that operates across countries also unfolds within countries over time. As economies grow, environmental pressures initially rise with industrial expansion but eventually decline when income-driven demand for environmental quality and policy stringency stimulate innovation. Yet this transition remains contingent: economies with weak governance or heavy dependence on resource-intensive exports often remain trapped on the upward segment of the curve. Thus, openness can accelerate or delay environmental improvement depending on whether it is accompanied by domestic policies that internalise environmental costs and foster innovation.

The rise of global value chains (GVCs) adds a spatial dimension to these dynamics. By fragmenting production across borders, GVCs redistribute emissions geographically, allowing advanced economies to exhibit declining territorial emissions while importing carbon embodied in intermediate goods. This phenomenon links directly to the composition and technique mechanisms: specialisation within GVCs determines where polluting stages of production occur, while technological spillovers across the same networks determine whether those stages become cleaner over time. Recent empirical work combining multi-regional input–output data with firm-level evidence suggests that trade has simultaneously externalised and mitigated environmental pressures – externalised, because pollution is often displaced; mitigated, because participation in global supply chains can catalyse technology transfer and efficiency gains. The challenge, therefore, is not to decouple trade from emissions geographically, but to align production responsibility, consumption responsibility, and innovation diffusion within coherent international governance frameworks.

Taken together, these findings indicate that the trade–environment nexus should be understood as a co-evolutionary process linking openness, regulation, and technological change. Trade liberalisation alters comparative advantages and production structures; environmental policy reshapes those advantages through regulation-induced innovation; and technology diffusion feeds back into both, redefining the environmental content of trade. Whether this feedback produces virtuous or vicious cycles depends on institutional quality and policy coordination. Where environmental governance is strong, trade contributes to decarbonisation; where it is weak, it reinforces path dependence in carbon-intensive sectors.

Going forward, the literature highlights several priorities. Empirically, the integration of CST decomposition, EKC dynamics, and GVC mapping requires micro-to-macro modelling frameworks capable of capturing endogenous technological change and cross-border spillovers. Conceptually, further progress depends on bridging the gap between production-based and consumption-based perspectives, recognising that responsibility for emissions and the capacity for innovation are jointly distributed across the global economy. From a policy standpoint, the evidence points toward the necessity of coordinated trade and climate strategies – trade agreements that embed environmental standards, mechanisms for technology transfer, and carbon border measures designed to prevent leakage while enabling equitable participation in low-carbon value chains.

In sum, the trajectory of the field reflects a decisive shift from viewing trade as a source of environmental degradation to viewing it as a potential vector of transformation. The cumulative findings of the reviewed literature suggest that globalisation neither inevitably harms nor automatically heals the environment; its ultimate effect is mediated by governance, innovation, and cooperation. The task ahead lies in shaping these mediating institutions so that the expanding web of international trade becomes a channel for global decarbonisation rather than its obstacle.

4.10 Summary

The environmental effects of global trade cannot be reduced to a simple trade-off between growth and degradation. What emerges from the literature is a dynamic system in which trade acts as both a source of pressure and a conduit for progress. Expansion in global exchange has undoubtedly increased the scale of economic activity and resource use, yet it has also accelerated technological diffusion, efficiency gains, and regulatory convergence. The decisive question is therefore not whether trade pollutes, but under which institutional and technological conditions it can foster cleaner growth. Evidence across decades and methodological approaches consistently shows that the technique effect – the ability of economies to innovate, regulate, and adopt cleaner production methods – plays a far greater role than the relocation of pollution-intensive industries. Where environmental policies are credible, and innovation systems robust, openness becomes a vector for sustainability rather than a threat to it. Conversely, in weakly regulated contexts, trade may reinforce asymmetries and externalize environmental costs through global value chains. The review thus calls for a reorientation of trade and climate policy: from managing emissions within borders to coordinating technological and regulatory standards across them. Sustainable globalization depends on this alignment – ensuring that the benefits of trade are harnessed to advance, rather than delay, the global ecological transition.

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5 Political Science

5.1 Introduction

This chapter summarizes the results of the systematic literature review regarding political science. The literature review was mainly guided by two research questions:

- How does environmental and climate policy affect trade (and possibly trade policy) and industrial competitiveness?
- How trade and/or trade policy (including international agreements and initiatives) enable or restrict our ability to implement environmental and climate policy making at national level?

As such, the literature on trade, climate, and industrial policy (TCI) examines how countries navigate the interplay between ambitious climate action and the imperatives of global trade and competitiveness. A central focus is the tension between climate policy leadership and carbon leakage which can undermine global emissions goals. Empirical evidence to date suggests that actual carbon leakage has been limited under frameworks like the EU Emissions Trading System. Nonetheless, competitiveness concerns remain prominent, as policymakers fear that unilateral decarbonization could erode industrial bases. This has spurred extensive debate on measures to reconcile climate ambition with fair competition, most notably carbon pricing strategies and their design in an open economy. Carbon taxes and emissions trading systems are analysed not only for their efficiency, but for how they affect trade flows and energy-intensive industries. Notably, studies show that careful policy design – for example, free emission allowance allocations or rebates for export sectors – can mitigate competitiveness impacts and leakage, albeit at the cost of complexity.

A closely related topic is the development of border carbon adjustments (BCAs). BCAs (or carbon tariffs) are proposed as a tool to level the playing field by applying a carbon cost to imports from countries with laxer climate policies. The literature evaluates BCAs' potential to reduce leakage and their legal and diplomatic implications. Research indicates that well-designed BCAs could significantly curtail direct leakage, but also warns they might shift adjustment burdens to developing countries and invite retaliation if implemented without sensitivity. Indeed, questions of WTO compatibility and international fairness are threaded throughout the discourse. Policymakers are urged to ensure that any trade-related climate measures do not constitute unjustifiable discrimination or "green protectionism" in the eyes of trading partners. This concern ties into long-standing North–South equity and fairness issues: developing countries, which have contributed least to historical emissions, worry that stringent climate trade measures by wealthier nations (like BCAs or generous green subsidies) could disadvantage their economies. The principle of "common but differentiated responsibilities" from the climate regime and analogous special-and-differential treatment in trade agreements are frequently invoked as norms to balance climate urgency with developmental fairness.

The literature also explores how green industrial policies and subsidies aimed at fostering low-carbon industries intersect with global trade rules. After decades of neoliberal trade norms, a resurgence of industrial policy (e.g. clean energy subsidies in the EU, US, and China) has raised complex questions about trade law. Analysts note that green industrial policy lies at the heart of many current trade–environment frictions, as nations strive to gain competitive advantage in emerging clean-tech sectors. There is active debate on reforming WTO disciplines to accommodate climate-motivated subsidies while preventing unfair protectionism. Some scholars argue for updated trade rules or plurilateral agreements that permit climate-friendly industrial policies in exchange for commitments to shared global goals. Alongside industrial policies, methods of emissions accounting are scrutinized: a production-based view versus a consumption-based view of emissions can shift perceptions of which nations bear responsibility for carbon emitted in making traded goods. Political scientists highlight that assigning accountability for embodied carbon in trade is critical for designing effective policies – for instance, whether importers or exporters should foot the carbon bill influences the viability of BCAs and the narrative of fairness between producers and consumers of high-carbon goods.

Another key theme is the integration of climate objectives into trade agreements and clubs. Environmental provisions in trade agreements have become more common, with many recent trade pacts including chapters on environmental cooperation and commitments. These range from clauses on wildlife protection and deforestation to emerging climate-specific measures. However, dedicated climate provisions (e.g. explicit allowance for carbon pricing measures or fossil fuel subsidy reforms) are still relatively rare. The effectiveness of green clauses is being assessed, with evidence that well-crafted provisions can help steer trade toward sustainable outcomes (for example, by reducing “dirty” exports and encouraging cleaner production standards). Finally, the concept of climate clubs has gained traction as a novel approach to foster international cooperation. In a climate club, a coalition of ambitious countries agree on stronger climate actions among themselves and use trade incentives or penalties to encourage broader participation. Economic modeling finds that without such incentives, global climate agreements face free-rider problems, whereas even modest trade penalties on non-participants can stabilize large coalitions with high levels of abatement. Scholars discuss how initiatives like carbon clubs or alliances (such as the idea of an EU-led climate club or G7 climate coalition) could complement multilateral efforts by creating “minilateral” frameworks where members benefit (for example, through preferential market access or shared technology) while non-members are nudged to increase their ambition.

In summary, the political science literature on TCI illuminates the governance challenges and opportunities at the intersection of global trade and climate change mitigation. Across issues of carbon leakage, trade measures, industrial policy, legal compatibility, equity, and international cooperation, this body of research underscores the importance of aligning trade policy with climate objectives. The core finding is that trade policies can be designed to support decarbonization – through smart adjustments, supportive rules, and cooperative agreements – but doing so requires careful attention to fairness, legitimacy, and the avoidance of unintended consequences. By examining these debates, the chapter provides insight into how climate and trade policies can be jointly crafted to reinforce each other: mitigating emissions without provoking economic dislocation, and advancing sustainable development in an open global trading system. Such insights are increasingly policy-relevant as governments worldwide strive to achieve climate targets while safeguarding economic prosperity and international collaboration.

The systematic literature review regarding political science is structured as follows: Chapter 5.2 entails a research report and explains the specificities of the political science review. Chapter 5.3 shows some quantitative statistics on the analysed articles, mainly regarding citations and development of the literature over time. In chapter 5.4 the results are summarized and chapter 5.5. discusses them. Chapter 5.6 concludes.

5.2 Research Report

Identification of Search Strings

While the main methodological process was explained already in chapter 2, there are some deviations from the other two sub-groups that requires additional reporting. Those deviations are mainly related to thematic search strings and a specific procedure in the analysis step. To identify the final search string the research group had intense discussions and try outs with different options. The final search string was in the end used in Web of Science and Scopus to extract the articles for the next stage of the systematic literature review. The export of the articles was conducted on 27.03.2025:

("global trade" OR "global value chain" OR "international trade" OR "Trade Poli?" *OR "Trade Governance" OR "world trade" OR "cross-border trade" OR "export flows" OR "import flows" OR "commodity trade" OR "merchandise trade" OR "trade flows" OR "world trade organisation" OR "trade agreement" OR "north-south trade")*

AND

("Climate Change" OR "Climate Governance" OR "Climate Poli?" OR decarboni?ation OR "low-carbon" OR "net-zero" OR "environmental pollution" OR "air pollution" OR "water pollution" OR "industrial pollution" OR ecosystem OR biodiversity OR "land use" OR deforestation OR "carbon leakage")

AND

(Poli? OR Governance OR "International Relation")

(Topic) and All (Document Types) and English (Languages)

Narrowing down the number of articles for analysis

The first export resulted in 3608 articles identified in WoS and SCOPUS. We then decided to apply a citation cut-off to filter out articles which were deemed less relevant in the past. The citation cut-off was applied to articles with less than 20 citations (<20) and only to articles which were published before the year 2020 (<2020) to allow for more recent articles which have a lower chance for citations. 2791 articles remained at this stage.

In the next stage, we narrowed down the process further by manually examining the titles of each article. Through this step we reached the number of 1220 articles. We then continued by looking at the abstracts which brought us down to 390 articles. After another extensive review of the abstracts we reached the final number for analysis of 157 articles.

Coding Process

In this stage it was decided to rely on the coding software Taguette for the coding process. While offering only the very basics of qualitative coding the software has the advantage that it is free to use and easy to navigate with the availability of multiple people working online simultaneously. The political science sub-group decided to define 6 major codes for the coding stage:

- AFOLU: Biodiversity, land use, agriculture, forestry, water etc.
- Economic Theory: EKC, Porter hypothesis, technique, composition (carbon leakage), scale effect etc.
- Industrial commodities: raw materials (minerals etc.); basic materials (steel, cement etc.); products (green, grey: EVs, buildings etc.)
- Politics: Policies (CBAM, cap and trade, tariffs, subsidies etc.); Governance, Institutions (WTO etc.),

Trade Agreements
- Climate and environmental impacts: Emission accounting, pollution etc.
- Rest and Undefined: Used as a reserve category to be discussed within the research group

Analysis

In this step the research group decided to follow a three-stage process. First, the coded material was fed into Gemini to identify the key topics that appear in the coded material. The prompt used for this step was as follows:

You are a Researcher at the Wuppertal Institute for Climate, Environment and Energy engaged in the EU Horizon research project called ENTICE (ENhanced understanding of Trade Impacts on Climate, industries, and the Environment). The task is to conduct a systematic literature review on trade, climate and industrial policies (TCI). The attached Excel file shows the results of the coding process of this review with the software Taguette. In the document column you see author_year, in the tag column you see the tags that were used for highlighting and in the content column you see the highlighted passages from each article. Now, make a ranking of the most important topics that appear in this file in terms TCI in your perspective. Do not rely on the topics in the tag column, instead read the content column. In the ranking adjust for the number of documents a topic appears in so if a topic appears in a large amont of documents then the ranking should be higher. Thanks, any Questions?

Gemini identified nine topics which are shown in the prompt below. Based on the identified topics, Gemini and Co-Pilot were then asked for summaries on each of the topics based on the coded material. The prompt used for this step was as follows:

You are a researcher working on a systematic literature review on trade, climate and industrial policies (TCI) for the EU Horizon research project called ENTICE (ENhanced understanding of Trade Impacts on Climate, industries, and the Environment). The attached Excel file shows the results of the coding process of this review with the software Taguette. Now, based on the coding results, please write summaries for the following 9 identified key topics, namely:

1. Carbon Leakage and Competitiveness Concerns

2. North–South Equity and Fairness Issues

3. Green Industrial Policies and Subsidies

4. Border Carbon Adjustments (Carbon Tariffs)

5. WTO Rules and Trade Law Compatibility

6. Carbon Pricing Mechanisms (ETS/Carbon Taxes) and Trade

7. Environmental Provisions in Trade Agreements

8. Climate Clubs and International Cooperation Initiatives

9. Emission Accounting and Embodied Carbon in Trade

In the final step, the summaries from Gemini and Co-Pilot for each chapter were merged and manually reviewed. The research group found that some were better suited than others to reflect the coded material. Hence, some chapters were either changed extensively or entirely overhauled.

5.3 Results: Quantitative Analysis

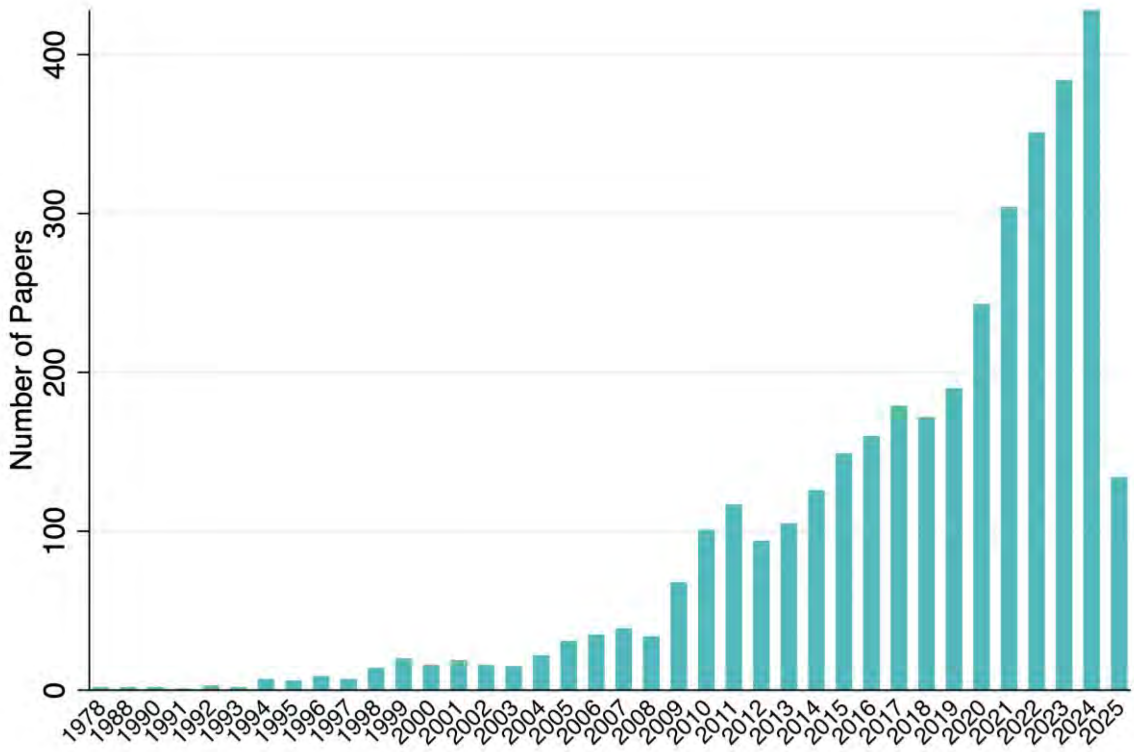

Figure 6: Number of papers for year of publication.

Figure 6 shows the number of papers for each year of publication in the original sample that were derived from Web of Science and Scopus. In the 1990s, foundational work focused mainly on theoretical models of carbon leakage and competitiveness with only a few articles published on the Trade, Industry and Climate nexus. The 2000s saw growing interest in trade law and emission accounting, as global climate negotiations matured. However, publications still remained on a relatively low level compared to today. This might be connected to the dominance of neoliberal theory, especially in the 1990s and the early 2000s. The financial crisis 2007/2008 and the following EU debt crisis marked a first turning point in thinking about trade, competitiveness and climate. From the mid-2010s onward, attention shifted toward policy implementation, especially around CBAM, industrial policy, and international cooperation. The surge in CBAM-related literature in the 2020s corresponds with the EU's Green Deal and the global reactions to it, especially CBAM.

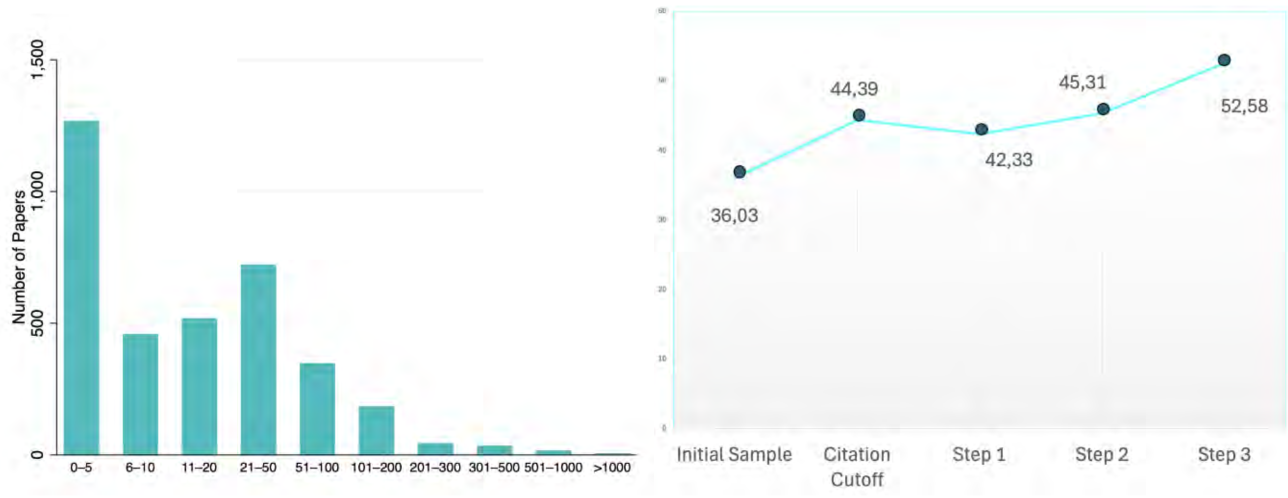

Figure 7: (a) Number of papers for range of citations. (b) Average number of citations after each step.

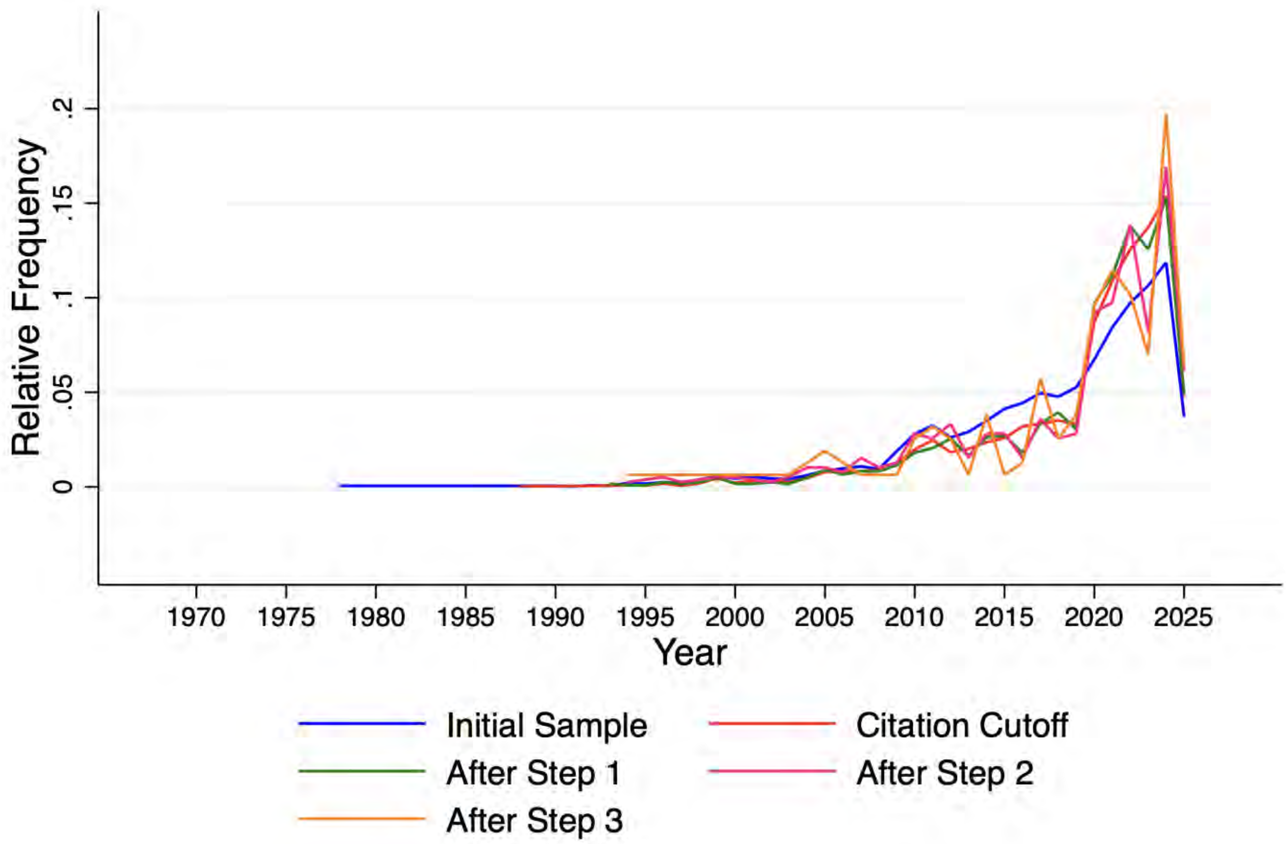

Figure 8: Average number of citations after each step.

In terms of citations Figure 7a shows that the largest number of articles only received 0-5 citations in the original sample. This can be partially explained by the large increase of articles around the TCI nexus in the last 5 obviously had lesser chance to receive a high number of citations which is why we exempted them from the citation cut. Correspondingly, Figure 7b shows the average citation per article which was significantly increased through the citation cut-off and again when the final list of articles was selected.

Finally, Figure 8 shows that the original sample had a relatively more even distribution of articles over time compared to the selection steps. This resulted in a shift towards more recent articles which is not surprising since most articles around the TCI nexus were published after the announcement of the EU Green Deal or the Paris Agreement. Also, other related events had their impact, such as the first Trump administration which introduced a shift in the global trade order away from a WTO based world converging towards free trade, to an order where tariffs between geoeconomic power blocs dominate. Therefore, industrial policy and competitiveness concerns moved up on the agenda of policymakers.

5.4 Results: Qualitative Analysis

5.4.1 Implementing Climate Policy in a Globalized World – Carbon Leakage and Competitiveness Concerns

In a globalized world, our economies and societies are no longer isolated but closely tied to each other through a dense network of trade relations. Hence, climate policy needs to consider the fact that a given country is part of a complex global trading system and consider that any climate policy measure can have cross-national spillovers and unintended or unanticipated feedback effects. Part of that reality is that climate change has been frequently described as a collective action problem and climate stability a global common pool resource that is prone to free riding (Jakob, 2022; Keohane & Victor, 2016; Ostrom, 2014). Climate change is described as a collective action problem because the global benefits of reducing emissions are shared by all countries, while the costs are borne individually, which incentivizes free riding, where some countries benefit from the actions of others without contributing their fair share to emission reductions.4 This strategic dimension helps explain why without coordination, even well-intended climate actions can be partially offset by behaviour abroad.

Perhaps the most salient concern in this regard is the risk of carbon leakage. Carbon leakage refers to the relocation of emissions from a region with strict climate policies to regions with laxer or no policies (De Cian et al., 2017; Grubb et al., 2022; King & van den Bergh, 2021). Considering carbon leakage in the design of climate policies is essential because the effect may undermine the competitiveness of domestic regulated industries vis-à-vis their international counterparts and at the same time limit the effectiveness of the climate policies when reductions in one place led to an increase of emissions elsewhere. The analysed literature identifies several channels through which carbon leakage and competitiveness effects can arise:

- **Competitiveness (Trade) Channel:** Climate policy raises production costs for carbon-intensive industries in regulated regions, weakening their comparative advantage. Firms in these regions may lose market share to foreign competitors or relocate production to lower-cost jurisdictions. This change in relative costs can reduce exports and increase imports of emissions-intensive goods, causing emissions to “leak” abroad (Branger & Quirion, 2014). In the short run, such leakage may occur via reduced utilization of domestic capacity and increased output from foreign plants (“operational leakage”), while in the long run it may involve investment shifting to countries without carbon constraints (“investment leakage”) (Branger & Quirion, 2014).
- **Energy Market (Fuel Price) Channel:** When one region reduces its fossil fuel demand through climate measures, global fossil fuel prices can decline. Lower world energy prices make fuel cheaper

[4] Note that recently this perception has been challenged by scholars that argue that the main impediment towards climate action is not the international free ride problem but strong intranational distributive conflicts that inhibit more ambitious policies (Aklin & Mildenberger, 2020; Colgan et al., 2020).

Funded by the European Union

in unregulated markets, which encourages higher consumption of coal, oil, and gas elsewhere. The result is an emissions increase abroad offsetting some of the original region's reductions (Jakob, 2021). This fuel price channel implies that even without any relocation of industries, global emissions may partly rebound due to market price effects. Additionally, the anticipation of future climate policy can prompt fossil resource owners to accelerate extraction – a phenomenon known as the inter-temporal leakage or "green paradox" – thereby increasing near-term emissions outside the regulated region (Jakob, 2021).

- **Strategic Behaviour:** In imperfectly competitive markets, firms may respond strategically to climate policies in ways that amplify leakage. For example, producers might adjust output or prices to capture market share from regulated competitors, exacerbating the shift of emissions-intensive production abroad. Modelling studies have shown that accounting for oligopolistic competition can lead to much larger losses of competitiveness and higher leakage rates than those predicted under pure competition (Alistair, 1995).

Importantly, theoretical models indicate that carbon leakage rates can vary widely depending on which channels dominate and on policy design. General equilibrium simulations (which capture both trade and energy market effects) often predict higher leakage than partial equilibrium models that include only the competitiveness channel (Felbermayr et al., 2024). For instance, if both the trade and fuel-price channels are active, leakage rates in model scenarios have ranged from moderate levels (e.g. 5–20% of the emission reduction leaks away) up to cases of over 100% leakage where global emissions actually increase when a subset of regions act (as in some early models with OPEC responses) (Bellelli & Xu, 2024). However, theory also suggests that these models may overstate leakage if they ignore mitigating factors such as technological innovation and diffusion. Climate policies can induce clean technology development and efficiency improvements that spill over internationally, thereby reducing emissions in other countries and counteracting some leakage. Studies note that without accounting for such technology spillovers, model projections tend to exaggerate leakage outcomes (Felbermayr et al., 2024). In summary, the theoretical expectation is that unilateral or uneven climate action creates competitive cost disparities and global market adjustments that can drive significant carbon leakage – but the magnitude is highly sensitive to economic channels and strategic responses.

Empirical findings on carbon leakage and competitiveness impacts are mixed and generally reveal a gap between dire theoretical predictions and observed outcomes to date. Results differ across policy instruments, sectors, and phases of implementation. Overall, real-world experience has so far shown modest leakage effects, especially compared to early theoretical concerns. As reviewed in detail by Felbermayr et al. (2024) observed carbon leakage has been relatively small in practice both under the Kyoto Protocol as well as under the European Emissions Trading Scheme (EU ETS). The latter can, in part, be explained with policy design (free allowances, limited initial stringency, and now prospective border measures – see discussion on border carbon adjustments below). But also market responses differed from worst-case theoretical assumptions. Ongoing research highlights that innovation and technology transfer can play a role in mitigating leakage, turning the challenge of competitiveness into an opportunity for low-carbon leadership. The literature thus increasingly emphasizes balancing robust climate action with smart policy measures to address legitimate leakage and competitiveness concerns – ensuring environmental goals are met without simply shifting emissions across borders. (Alistair, 1995; Felbermayr et al., 2024).

5.4.2 Carbon Pricing and Trade

Carbon pricing – whether implemented as a carbon tax or an emissions trading system – has long been considered the first best option in terms of efficiency by most economists. Yet, in recent years a consensus seems to have emerged that in the real world carbon pricing is a central component of the policy mix but should be accompanied by other policies (Bergh et al., 2021; Gawel et al., 2014; Kivimaa & Kern, 2014; Rogge et al., 2020; Rogge & Reichardt, 2013; Skjærseth et al., 2021). But given the central nature of carbon pricing and its profound impacts it deserves special treatment here. The literature explores the economic and trade-related effects of different carbon pricing mechanisms, most notably the EU's Emission Trading System (ETS) and carbon taxes. These mechanisms, while sharing the goal of putting a price on emissions, can have distinct impacts on trade and competitiveness. In an interconnected world, implementation of a carbon tax or a cap-and-trade system in one country can have profound consequences for others.

Some studies examine impact of carbon pricing policies on trade in different commodities. For instance, food products can be impacted by carbon pricing by increased costs of production (Anderson, 2022). Impact of carbon pricing is often discussed for energy-intensive and trade exposed goods, such as iron and steel, cement or aluminium. These goods are potentially most exposed to competitiveness loss, however they are also often treated more favourably by policy instruments, as a result of political debate and industrial lobbying (Branger & Quirion, 2014). The favourable treatment is justified by carbon leakage risk, literature on which is described in more detail in a separate section.

The EU ETS is a cap-and-trade system that sets a cap on total emissions, with a resulting carbon price determined by the market. Being the first major emission trading system globally, an extensive body of ex-post literature has assessed its effects on trade and competitiveness during its first 15+ years of operation. These studies generally found little to no significant carbon leakage (Fontagné & Schubert, 2023, Grubb et al., 2022). Sector-level analyses focusing on energy-intensive trade-exposed (EITE) industries (like cement and steel) failed to detect increases in imports or production shifts attributable to carbon costs under the EU ETS. For example, an econometric study of EU cement and steel sectors (2005–2012) using output and price data found no evidence that the EU carbon price led to increased net imports or output losses in these sectors (Felbermayr et al., 2024). Similarly, a gravity-model analysis of the CO_2 content of trade between EU and non-EU countries concluded that the EU ETS did not cause measurable carbon leakage through trade flows (Felbermayr et al., 2024). In other words, despite the EU's relatively high carbon prices in later phases, there has been no statistically significant sign of domestic production moving abroad or imports rising in response. Consistent with this, studies have not observed competitiveness losses such as job cuts or output contractions that can be attributed to carbon pricing in regulated European industries.

This outcome is largely attributed to the policy design. The EU ETS and other regional schemes incorporated anti-leakage measures from the start. Chief among these was the free allocation of emission allowances to vulnerable EITE industries. By granting a large share of permits for free based on past output or benchmarks, regulators effectively shielded domestic firms from the full cost of carbon, preventing a deterioration of their international cost-competitiveness (Jakob & Mehling, 2025). This policy design choice appears to have been successful in limiting carbon leakage at the expense of some economic efficiency: recent reviews find that free allocation indeed curtailed leakage under the EU ETS (as also reported by Joltreau & Sommerfeld, 2019 and Verde, 2020), although it arguably dampened the incentive for firms to reduce emissions and innovate because their effective carbon costs were reduced (Jakob & Mehling, 2025).

Moreover, the overly generous allocation of allowances in the early phases of the EU ETS, resulting in relatively low carbon prices, minimized the financial burden on these industries, thereby preventing production from relocating but also dampening the full environmental effectiveness of the policy (Fontagné & Schubert, 2023). These conditions likely kept compliance costs manageable, and many firms could abate emissions or improve efficiency at low cost, negating the need to relocate. Indeed, rather than mass offshoring of industry, what has been documented is a stimulus to innovation: firms subject to EU carbon pricing increased investments in emissions-reducing technologies. For instance, the EU ETS is credited with significantly spurring low-carbon innovation at regulated companies (as evidenced by patent data) without causing widespread plant closures (Bellelli & Xu, 2024). This aligns with the hypothesis that well-designed environmental regulation can induce innovations that partially offset compliance costs and may even enhance competitiveness in the long run ("Porter Hypothesis" see also (Bellelli & Xu, 2024).

However, an unintended consequence of overcompensating certain industries has been the creation of an "intra-regional pollution haven effect," where firms relocate to less stringent countries within the EU ETS jurisdiction itself (De Beule et al., 2022). This analysis demonstrates that the effectiveness of carbon pricing mechanisms is a function of not only the price signal itself but also the design and interaction of complementary policies.

5.4.3 Border Carbon Adjustments as an Anti-leakage Measure

Levying a carbon tariff on carbon-intensive imports to emulate the effects of domestic carbon pricing has been part of the academic debate from the outset (Grubb, 2011; Kuik & Hofkes, 2010; Van Asselt & Biermann, 2007) but have recently received renewed academic and political interest, not least due to the adoption of the EU's Carbon Border Adjustment Mechanism (CBAM). Border carbon adjustments (BCA) impose a carbon price on imports to a jurisdiction to ensure that they have paid an equivalent price for their embedded emissions as domestic producers. This aims to apply the same level of stringency of environmental regulation to imports than domestically produced goods and prevent the relocation of production to countries with less stringent climate policies. The EU's CBAM, which to date is the most advanced and most salient instrument in the literature reviewed for this report - complements the EU ETS by targeting a narrow scope of energy-intensive and highly traded commodities including cement, iron and steel, aluminium, fertilizers, hydrogen, and electricity. Beyond its defensive role – protecting domestic producers from competition with low cost but high emission imports – CBAM is also intended to be a proactive tool for global climate governance. By imposing a tariff, it creates a strategic incentive for non-regulating countries to adopt their own carbon pricing systems. From this perspective, a CBAM acts as a credible threat to promote wider participation in climate cooperation and reduce free riding (Chen et al., 2025; Erdogdu, 2025; Mehling et al., 2019; Otto, 2025; Smith et al., 2024).

Ex-ante studies generally predict that a well-implemented CBAM will reduce leakage compared to a scenario with unilateral carbon pricing alone, by neutralizing the competitiveness channel. However, model projections also indicate that leakage will not be completely eliminated. One reason is that a border tariff on carbon does not mitigate the fuel price channel – if EU demand for fossil fuels falls, world prices drop and incentivize extra consumption elsewhere, a leakage effect that CBAM cannot directly counter. Indeed, recent modelling of EU climate policy scenarios finds that even with an extensive CBAM in place, a significant portion of the EU's emissions reduction could still be offset by increases in the rest of the world (Bassi et al. 2024). In a global simulation for 2030, the introduction of EU-wide carbon pricing plus a comprehensive import tariff on carbon was projected to yield leakage rates on the order of 50–60%, as opposed to slightly higher leakage in the absence of the border measure (Bassi et al. 2024). This suggests that while CBAM can dampen the trade-related component of leakage, it may only partly address the total leakage risk, especially if other countries do not also strengthen their climate efforts.

One open question that has proved particularly difficult to address is the role of regulated exporters. The CBAM of the EU addresses competition on domestic markets by targeting carbon-intensive imports. But to date there is no compensation available for domestic producers that export their product to international markets on which they compete with foreign produces that are not subject to the same kind of environmental regulations. The issue has been identified as a particularly thorny issue already several years ago (Mehling et al., 2019) but yet has to be fully resolved as most of the available options are hard to reconcile with international trade law (Jakob & Mehling, 2025) (see discussion below).

Finally, the literature discusses the practical challenges of implementing border carbon adjustments in general and the CBAM in particular. A primary challenge is the accurate and consistent accounting of embedded emissions in traded products, especially across global supply chains. While environmentally extended input-output models are commonly used for this, a lack of standardized methodologies remains a concern. This is particularly challenging for developing countries, particularly those with carbon-intensive exports and limited regulatory capacity, as they face disproportionately high costs and administrative burdens (Chen et al., 2025; Erdogdu, 2025).

5.4.4 Green Industrial Policies and Subsidies

Historically, climate policy instruments have been categorised into three categories: carrots, sticks, and sermons (Bemelmans-Videc et al., 1998). Carbon pricing instruments including the EU ETS fall into the sticks category of punitive instruments that sanction environmentally malign behaviour. Sermons refers to information instruments and political signalling which is less of an issue in the context of international trade (also see section on emissions accounting below). But the category of carrots remains an important one. It is particularly important because constitutional and political economy constraints have made it impossible for the United States to adopt any meaningful carbon pricing or emissions trading at the federal level (Stavins, 2020). Instead, the US has adopted the Inflation Reduction Act (IRA) which provided massive financial incentives and subsidies for investment in clean tech industries. The was supposed to achieve deep emission reductions with generous green industrial policy instead of carbon pricing instruments (Bistline et al., 2023). As we shall discuss in this section, this also has major implications for international trade (Kleimann et al., 2023; Suárez-Cuesta & Latorre, 2024).

Industrial policy in general and green industrial policy in particular has recently seen a significant uptake both in terms of academic attention (Juhász et al., 2024) and policy practice (Evenett et al., 2024; Fang, 2025). Juhász et al. (2024) define industrial policy as "those government policies that explicitly target the transformation of the structure of economic activity in pursuit of some public goal" (p. 216). As the authors note, the goal of industrial policy was typically to stimulate innovation and economic growth. Due to the urgency of climate action, advancing climate change mitigation and other environmental purposes has also become a goal (Veugelers et al., 2024, Chang & Andreoni, 2021).

Industrial policy interventions are warranted due to several well-established economic rationales that are particularly relevant for addressing climate change challenges. Market failures provide the primary justification, including externalities where economic activities generate benefits not captured in private revenues, coordination failures where profitability depends on related activities by others, and the need for specialized public inputs tailored to specific sectors (Juhász et al., 2024). In the climate context, these rationales become especially compelling as green industrial policy can address the fundamental problem that private returns to green technological development are well below their social value due to the public good nature of emissions reductions (Allan et al., 2021). Moreover, green industrial policy can create national security externalities by reducing dependence on foreign energy sources and good-jobs externalities by creating middle-class employment that promotes social cohesion (Juhász et al., 2024). Furthermore, green industrial policies can help overcome the commitment under uncertainty problem that characterizes modern industrial economies, where firms must make irreversible investments in green technologies despite uncertain future conditions (Chang & Andreoni, 2021).

Historically, however, industrial policy has had a bad reputation for being largely ineffective due to information asymmetries and prone to corporate capture and rent seeking, but more recent research reviewed by Juhász et al. (2024) suggests that industrial policy can be effective under certain circumstances. Specifically, industrial policy has proved to be effective if governments target new export-oriented industries that are subsidised to enhance their competitiveness on global markets. Protecting declining incumbent industries from growing international competition to conserve the structure of economic activity has a less successful track record (Cherif & Hasanov, 2024).

Green industrial policy serves as a crucial mechanism for advancing climate change mitigation by strategically directing government interventions to support domestic industries that provide environmental benefits while simultaneously pursuing economic development goals (Fischer, 2016). Unlike traditional environmental policy that focuses primarily on reducing emissions through pricing mechanisms, green industrial policy combines public investment with standards to create concentrated benefits for clean technology industries, thereby mobilizing political support from economic groups that might otherwise oppose costly climate policies. This approach facilitates environmental goals by reducing technology costs for achieving emission reduction targets and nourishing economic beneficiaries that form advocacy coalitions for climate objectives (Meckling, 2021). By addressing market failures specific to green technologies - which face higher externalities, greater uncertainty, and competition from subsidized fossil fuel alternatives - green industrial policy provides the directed support necessary to overcome carbon lock-in and accelerate the transition to zero emissions across energy-intensive industries (Veugelers et al., 2024, Nilsson et al., 2021).

Green industrial policy has emerged as a significant force reshaping global trade patterns, creating both opportunities and tensions in the international trading system (Fang, 2025; Pak, 2024; Evenett 2024, Suárez-Cuesta et al., 2024; Wu & Salzmann, 2014; Green, 2006). Renewable energy subsidies have been frequently challenged at the WTO (see also section below). The challenges have targeted various forms of support including China's subsidies to solar panel manufacturers that led to US countervailing duties, the EU's anti-dumping measures on Chinese solar imports, and domestic content requirements in programs like India's solar mission and Canada's feed-in tariff program that were found to accord less favourable treatment to imported equipment (Hajdukiewicz, 2020). Similarly, the US Inflation Reduction Act (IRA) has been criticized for including trade-distortive local content requirements that enable vehicle tax credits only to electric cars with 'final assembly' in North America (Kleimann, 2023, Pak, 2024). Consequently, the proliferation of green industrial policies has triggered defensive responses. Countries facing discriminatory measures have frequently adopted similar measures fostering a "race to the bottom competition" (Fang, 2025, p. 167). Meanwhile, subsidies for fossil fuels and high-carbon activities dwarf clean technology subsidies but have received much less scrutiny and contestation under the WTO (Meyer, 2017, Cima & Esty, 2024).

5.4.5 North–South Equity and Fairness

A fundamental equity issue is the uneven distribution of emissions and responsibilities between the Global North and South. Developed economies historically industrialized with high emissions, while many developing countries have contributed relatively little to climate change yet face pressure to curb emissions. Scholars note that globalization and trade have reinforced historical hierarchies, allowing rich countries to outsource carbon-intensive production to poorer ones. This results in an uneven geographical spread of emissions: goods consumed in wealthier nations often generate pollution in less developed countries. Such "ecologically unequal exchange" means the environmental burdens of production fall on the South while the North enjoys the consumption benefits. Consequently, debates persist on whether emissions should be counted by production or consumption, with developing countries arguing for recognition of their lower per-capita emissions and historically smaller carbon footprint (Wang et al., 2019; Jorgenson, 2009).

The previous sections have addressed competitiveness concerns related to stringent climate policies implemented in the context of a complex global trade network. Since competitiveness is a matter of relative costs, climate policies that may compromise the competitiveness of developed countries with ambitious climate policies should boost the competitiveness of developing countries without such policies. But the flipside of this relationship is that not only production may be relocated but also pollution. In this regard, the literature explores the profound asymmetry in responsibilities for climate change and the capacity for its mitigation between developed and developing countries. Trade liberalization has exacerbated a divide that leads to a pattern of unequal environmental pollution and degradation that disproportionately burdens the Global South while benefiting the North (Schmitz et al., 2012). Furthermore, countries with the highest CO2 emissions often benefit most from free trade, using their economic influence in negotiations for trade agreements (Balogh, 2022). This creates an inherently unjust relationship in which those most responsible for the climate crisis are less severely affected than those who suffer most from its consequences (Oladipupo & Ajide, 2024; Erdogdu, 2025).

In recognition of the historical contributions of industrialized nations to global emissions and their greater capacity for climate action, international agreements from Rio to Paris have enshrined the principle of Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC). This framework has traditionally imposed emissions reduction obligations on a limited group of developed countries, while exempting a significant number of emerging economies (Davidson Ladly, 2012; Grubb et al., 2022; Erdogdu, 2025). Moreover, there is an inherent tension between CBDR-RC principle and the uniform application of trade rules. International climate agreements recognize that wealthy countries should take the lead and allow developing nations more leeway in mitigation commitments, reflecting differences in historical emissions and capabilities. In contrast, trade law emphasizes equal treatment (non-discrimination) for all trading partners. This clash raises equity questions when designing climate-related trade policies. For instance, applying the same carbon requirements or tariffs to all countries – regardless of their development status – is seen as inconsistent with CBDR's call for greater burdens on rich nations. Developing countries thus call for flexibilities that account for their lower capacities and development needs. If climate–trade policies do not accommodate these disparities, they risk being perceived as unfair (Ahmad & Brand-Imeli, 2025; Marceau &

George, 2025).

Another equity concern is the potential for pollution haven effects. Critics long feared that stringent environmental regulations in advanced economies would drive heavy industries to nations with lax standards, shifting pollution to the developing world. This dynamic could not only increase pollution in poorer countries but also force a "race to the bottom" in environmental standards as countries compete for industrial investment. While empirical evidence for widespread pollution havens has been limited, recent studies do find some North–South shifting of dirty industries. The very fear of such outcomes has made developing nations wary of aggressive climate measures that might undermine their industrial base. It underscores the need for global cooperation so that poorer countries are not unfairly disadvantaged or turned into pollution refuges as the world pursues decarbonization (Gallagher, 2009).

Developing countries have also been highly concerned about "green protectionism." They worry that environmental requirements in trade policies might serve as disguised trade barriers against their exports. For example, if rich nations impose strict low-carbon standards or subsidies favoring their own industries, poorer exporters could struggle to compete. Trade negotiators from the Global South warn that environmental provisions in trade agreements may become "veiled protectionism," limiting developing countries' market access under the pretext of sustainability. This sentiment reflects a broader demand for fairness: climate-related trade measures should not simply advance the economic interests of wealthier nations at the expense of poorer ones. Some scholars argue that equity requires incorporating special accommodations for developing economies – such as technology transfer, financial support, or longer adjustment periods – so that green trade rules do not reinforce global inequalities (Gallagher, 2009).

On that basis, critics of the EU CBAM have argued that what looks like establishing a "level playing field" for domestic producers and importers from an EU perspective may be perceived as an act of extraterritorial overreach to developing countries that is in violation to the CBDR principle because it imposes an identical level stringency of regulation to producers that have much less (historical) responsibility and more importantly economic and administrative capacity to mitigate climate change (Corvino, 2025; Erdogdu, 2025). Developing countries often lack the financial and technological resources to comply with stringent standards. Emerging and developing countries, whose production technologies are often carbon-intensive – a situation exacerbated by carbon leakage as developed nations outsource polluting industries – are particularly vulnerable due to their reliance on exporting these goods. The EU's CBAM, for instance, is expected to have a greater direct impact on countries like China, India, Turkey, and Russia. Studies project that while the EU and other developed nations may experience welfare gains, these developing countries could face substantial declines in welfare and GDP, with one analysis estimating a potential GDP reduction of 2.7–3.6% for Turkey by 2030 (Erdogdu, 2025).

To mitigate the aforementioned issues of justice and fairness, the literature advocates for a more inclusive approach to global climate governance. This includes implementing exemptions, transitional arrangements, and robust support mechanisms to ensure equitable participation (Buser, 2025; Erdogdu, 2025). Moreover, instruments like border carbon adjustments policies should be complemented by international cooperation and support to be fully effective and fair. Proposed solutions involve recycling CBAM revenues to fund industrial transformation in vulnerable nations (Grubb, 2011), providing financial and technical assistance for least-developed countries (LDCs) to adopt green technologies, and engaging in bilateral agreements to harmonize policies with key trading partners (Branger & Quirion, 2014; Grubb, et al., 2022).

5.4.6 Emission Accounting and Embodied Carbon in Trade

A central question of fairness relates to how emissions are accounted for. The official GHG emissions inventory of the United Nations Framework Convention on Climate Change (UNFCCC) has been set up in the early 1990s has focused on territorial or production-based accounting (PBA), which attributes emissions to where they are physically produced. Since then, PBA has become the de facto global default. Yet, scholars have proposed accounting methods that attribute emissions embedded in final products to the country in which they are consumed instead of the country in which a given product was produced. The choice between different accounting methodologies is not merely a technical one; it is a critical policy decision that shapes the allocation of responsibility for global emissions and determines the effectiveness of climate policies (Reeve & Aisbett, 2022). Consumption-based accounting (CBA) is supposed to better inform mitigation policies and assign responsibility based on consumption patterns, especially since developed countries have outsourced their "dirty production" to others (Karakaya et al., 2019; Grubb et al., 2022; Safi et al., 2023). They argue that the apparent separation of growth and environmental harm in most developing countries (Environmental Kuznets Curve) is largely due to the outsourcing of polluting industries rather than a genuine, clean transition (Karakaya et al., 2019). And in fact, the literature shows that the difference between production-based and consumption-based accounting is significant and growing. Studies show that industrialized and rich countries have typically reduced their production-based emissions while their consumption-based emissions have either remained stable or increased due to the "outsourcing" of emissions. This trend is primarily driven by importing emissions-intensive goods from emerging and developing economies, such as China. For example, UK emissions (production) fell 14% between 1990 and 2008, but emissions associated with UK consumption increased by almost 20% in the same period. This gap between territorial emissions and carbon footprints in rich countries hints at an increased outsourcing of emissions to the Global South (Grubb, 2011; Reeve & Aisbett, 2022).

However, accurately accounting for embodied emissions is a complex technical challenge. Most studies use multi-regional input-output (MRIO) models to estimate the aggregate emissions embodied in trade flows. However, several authors note concerns about a lack of standardization and consistency in these methodologies (Grubb, 2011; Reeve & Aisbett, 2022). Furthermore, a large portion of the emissions associated with trade comes from shipping and other transportation, which are often captured in a very stylized way in models. More sophisticated models are needed to differentiate these emissions on a product and destination level to accurately assess the total carbon footprint of trade. The very concept of "emissions embodied in trade" can be problematic, as countries import goods and services, not emissions directly. This highlights the need for a more nuanced understanding of the complex links between production processes, trade flows, and environmental outcomes.

The choice of emission accounting framework has profound implications for global climate governance. The focus on a production-based approach in agreements like the Paris Agreement's NDCs creates a significant "real risk of carbon leakage," Reeve & Aisbett (2022) and Grubb (2011) suggest that for climate policies to be truly effective, they must move beyond the rigid confines of national borders and explicitly consider the carbon flows within the global trade network. According to the traditional production-based emissions inventories fail to capture the complexity of modern consumption patterns, leading to the carbon loophole that undermines national and global mitigation efforts. Instead, they propose to use policy levers that can influence emission intensity in exports and a shift toward global, collective governance rather than fragmented, national policies. Instruments like a BCAs and policies addressing directly the extraction of fossil fuels (supply side policies) are proposed as ways to address this by incorporating consumption-based considerations into the policy framework. Such a shift from a purely production-based to a more comprehensive accounting system would not merely be a technical adjustment; it would be a fundamental re-evaluation of how responsibility for global emissions is allocated.

5.4.7 WTO Rules and Trade Law

The conventional view often positions trade law as a constraint on environmental policy. As such, existing trade rules, while somewhat flexible, may still hinder ambitious climate policies. The World Trade Organization (WTO) provides the legal framework for international trade, and its rules are a significant factor in the design and implementation of climate policies that have trade-related implications. Its key foundational documents, notably the Global Agreement on Tariffs and Trade (GATT), significantly predate the UNFCCC and were established in a period when concerns over anthropogenic climate change were not yet widely acknowledged. The compatibility of measures like border carbon adjustments and subsidies with WTO law is a central point of academic and political debate (Davidson Ladley, 2012; Branger & Quirion, 2014; Cima & Esty, 2024).

The fundamental legal principles of the WTO are non-discrimination and transparency. The principle of non-discrimination is embodied in two key provisions: the National Treatment principle, which prohibits a country from discriminating against imported products in favour of its own, and the Most-Favoured Nation (MFN) principle, which requires equal treatment for all trading partners (van Asselt & Biermann, 2007). The legal challenges for trade-related climate policies often arise when government measures are perceived as discriminatory, particularly if they target products based on their production processes rather than their final characteristics. A border tax on an imported product, for example, could be challenged if it is not levied on a domestic "like product"[5] (Biermann and Brohm, 2004; Smith et al., 2024).

While a policy might initially appear to violate a core WTO principle, it may still be permissible under the General Agreement on Tariffs and Trade (GATT) if it can be justified under its exception clauses, specifically Article XX. This article allows for measures that are "necessary to protect human, animal or plant life or health" or "relating to the conservation of exhaustible natural resources," provided they do not constitute "arbitrary or unjustifiable discrimination" or a "disguised restriction on international trade" (van Asselt & Biermann, 2007). The distinction between direct and indirect taxes is crucial for border adjustments. Under current interpretations of WTO law, indirect taxes (e.g., value-added taxes) are eligible for border adjustments, while direct taxes (e.g., taxes on wages or profits) are not. This distinction presents a legal hurdle for instruments like the EU ETS, which the European Court of Justice has ruled cannot be considered a customs duty, tax, or charge (Biermann and Brohm, 2004).

CBAM sits on several fault lines when it comes to the WTO-law perspective. First, it risks breaching the core non-discrimination disciplines – Most-Favoured-Nation (GATT Art. I) and National Treatment (Art. III) – because it conditions charges on the carbon intensity of imported “like products,” an area where differentiation by production processes (PPMs) remains unsettled in WTO jurisprudence (Davidson Ladly, 2012). Relatedly,

[5] In the context of the WTO, "like products" are defined very narrowly as products that are identical or closely resemble each other in all essential respects, including their physical characteristics, nature, and end-use.

while GATT Art. II:2(a) permits border adjustments for internal taxes, the legal fit is far less certain where the domestic instrument is an emissions trading scheme rather than a straightforward tax, which weakens reliance on Art. II:2(a) for an ETS-linked CBAM (Davidson Ladly, 2012). Even if CBAM's objective could be provisionally justified under GATT Art. XX(b) or (g), the chapeau imposes demanding constraints: application must be flexible, account for different national conditions and comparable policies, and avoid rigid design or administrative burdens that yield "arbitrary or unjustifiable discrimination" or a "disguised restriction on trade" (Davidson Ladly, 2012). A further structural tension arises from the climate regime's principle of CBDR: a uniform EU-determined carbon price for imports sits uneasily with CBDR expectations of differentiated burdens, while MFN's insistence on origin-neutral treatment constrains across-the-board leniency for developing countries (Davidson Ladly, 2012; Cima & Esty, 2024; Corvino, 2025). In practice, compliance and reporting costs may fall disproportionately on low-income exporters, creating de facto discrimination risks that could be scrutinized under the Art. XX chapeau as well as broader WTO principles (Erdogdu, 2025). Sector-specific analyses also caution that CBAM-type measures can penalize environmentally friendly production methods in third countries or generate welfare losses for developing, agriculture-reliant economies. These outcomes have the potential to increase equity- and discrimination-based challenges [Bassi et al., 2025]. Taken together, CBAM's WTO vulnerabilities cluster around MFN/NT parity, the uncertain tax-adjustment hook for ETS-linked charges, stringent Art. XX chapeau requirements, and the unresolved WTO–CBDR equity gap.

Subsidies are another area of potential conflict. The WTO Agreement on Subsidies and Countervailing Measures (ASCM) prohibits subsidies that are contingent on export performance. This means that direct financial support tied to the volume of exports from a regulating country would likely be considered a prohibited export subsidy. To avoid a violation, support for innovation and industrial transformation should be made available regardless of whether the produced goods are for domestic or foreign markets (Jakob & Mehling, 2025; Cima & Esty, 2024). Consequently, the literature discusses specific WTO reforms or reinterpretations might be necessary. For instance, clearer allowances for carbon pricing measures, a "climate waiver" or amendments to subsidy rules to favour green support over fossil-fuel subsidies have been proposed (Wu & Salzman, 2014; Cima & Esty, 2024). So far, negotiations on green goods and related trade disputes under the WTO have not substantially progressed despite efforts to come to an agreement (Meckling, 2021).

5.4.8 Environmental Provisions in Trade Agreements

While the WTO is frequently regarded as constraining climate policy options, a different perspective suggests that preferential free trade agreements beyond the WTO can be a powerful instrument for global climate governance. By incorporating environmental provisions, these agreements can serve as a framework for coordination and accountability, potentially increasing cooperation and fostering a convergence of standards.

Gutsch et al. (2024), following previous scholarship, define the term "environmental provisions" as encompassing "all forms of provisions with a broad range of environmental issues, including deforestation, biodiversity, water, fisheries, and forests and air pollution and climate change with different levels of enforcement from aspirational to enforceable". Cesar de Oliveira et al. (2024), following George and Yamaguchi (2018), indicate four different channels through which environmental provisions in FTAs can contribute to environmental protection: (1) strengthening environmental regulations (new environmental laws or impact access frameworks); (2) introducing new institutional arrangements (i.e. establishing relevant governing and monitoring bodies); (3) enabling cooperation on environmental law and enforcement; and (4) improving environmental awareness and public participation processes (see also Gutsch et al., 2024).

According to Abman and Lundberg (2020), prior to the 1990s, the issue of environmental protection was largely absent from regional trade agreements, unless as exception clauses, allowing to limit trade commitments when necessitated by protection of natural areas. This changes throughout the 90s and 2000s, when environmental provisions, in particular regarding biodiversity and deforestation were introduced into trade policies and trade agreements with increased frequency (Abman and Lundberg, 2020), as the debate over the environmental consequences of liberalized trade, intensified by negotiations like those for NAFTA, spurred efforts to integrate environmental protection into trade policy. The inclusion of an environmental regime in NAFTA, for example, was a necessary condition for its political passage in the United States (Gallagher, 2009). USA and the EU in particular led the charge, with USA binding itself to include such provisions into every preferential free trade agreement under the US Trade Promotion Act of 2002 and the EU including "Trade and Sustainable Development" Chapters into its FTAs (Gutsch et al., 2024).

A primary motivation for these provisions is the potential to "export environmental standards" from countries with more ambitious regulations to their trading partners. This is viewed as a way to leverage trade relationships to raise global environmental standards. Besides, Abman and Lundberg (2020) highlight three reasons for the inclusion of environmental provisions in trade agreements:

- Interdependency – environmental provisions mitigate negative environmental outcomes generally stemming from opening trade;
- Enforcement – environmental provisions allow for the use of trade retaliation as possibly the only effective means of enforcing international environmental commitments;
- Incentive – an exchange of trade concessions on one side for more stringent commitments on the other.

They further point out that the inclusion of environmental provisions can result either from mutual agreement of the parties, or from unilateral pressure of the party with stronger bargaining power. Non-compliance can result in retaliatory tariffs or other dispute resolution mechanisms entailed in the breached agreement (Abman and Lundberg, 2020). Therefore, environmental provisions are seen as a viable tool for developed states to compensate for their comparative disadvantages resulting from their more stringent domestic regulations (Gutsch et al., 2024). On the other hand, representatives of developing countries have been wary of environmental provisions as a possible invitation to a "veiled protectionism" (Gallagher, 2009). The use of environmental provisions as leverage can thus reach unproductive levels. Also, FTA negotiations could theoretically also undermine environmental regulations. For example, during the ultimately failed negotiations of the Transatlantic Trade and Investment Partnership (TTIP) between the US and the EU in the early 2010s, many observers and civil society organisations voiced concerns that the US would use its bargaining power to force the EU to water down its environmental regulations. The (in)famous symbol of their campaign was the TTIP would allow the American meat industry to export chlorine-treated chicken – a pathogen reduction treatment prohibited in the EU – to Europe (Eliasson & Huet, 2018).

Despite the promise of environmental provisions, their effectiveness and robustness are a subject of ongoing debate Gutsch et al. highlight the challenges of analysing the general effectiveness of environmental provisions given the multitude of contexts in which they appear. While some studies - e.g. Baghdadi et al.

(2013), Saucier and Rana (2017) - find evidence of their positive impact both on the emissions and pollution (Felbermayr et al., 2024) and the transboundary flow of goods (Gutsch et al., 2024), others suggest the opposite (e.g. Muller, 2023). It follows that there is no clear consensus in the current academic literature regarding the impact of such provisions (Gutsch et al., 2024). However, while such provisions can lower emissions and foster green exports, especially when agreements are between countries with similar development levels, this is not necessarily the case when there are income and development disparities between the parties (Felbermayr et al., 2024). One such example is NAFTA, which led to an increase in Mexico's emissions (e.g. through car retirements rates in Mexico) and deforestation rates (Abman and Lundberg, 2020) while not having much impact – positive or negative - on emissions of the US and Canada (Felbermayr et al., 2024). Enforcement and institutional capacity are key to the success of agreements which include environmental provisions. The impact of environmental provisions is also not uniform across all sectors and all types of agreements. Balogh (2022) observes that, while studies have linked EFTA, ASEAN, and MERCOSUR to a reduction in CO2 emissions, NAFTA was found to encourage emission growth.

Besides climate, Abman and Lundberg (2020) note that NAFTA allegedly accelerated deforestation in Mexico through stimulation of agricultural expansion rather than timber exports. Their study indicates that, to prevent environmental harm, it is often insufficient for environmental provisions to focus solely on the sector covered by a given agreement. A lack of corresponding environmental provisions may lead to increased deforestation because of an increase in agricultural production and agricultural exports, as well as the increased governmental intervention in these sectors (measured in expenditures) following the agreement's entry into force.

To conclude, trade agreements with environmental provisions can be a powerful tool for promoting sustainable practices. They can serve as a mechanism to lower pollution-intensive exports from developing countries and foster trade in "green" goods and services. In some cases, these provisions have been found to offset the negative environmental effects of trade liberalization, such as deforestation. The existence of a legal framework and an adjudication process can encourage countries to ground their measures in agreed-upon parameters, reducing the likelihood of a scenario characterized by unilateral measures followed by retaliatory actions (Jakob & Mehling, 2025). This demonstrates that trade law is not simply a constrain to effective environmental governance but can also serve as a useful coordination instrument for the construction of effective and fair global environmental policy.

5.4.9 Climate Clubs and International Cooperation Initiatives

Climate change mitigation is widely recognized as a collective-action problem, with countries incentivized to free-ride on others' efforts (Bassi et al., 2024; Barrett, 2011). In this context, *climate clubs* – voluntary coalitions of countries with common climate commitments – have been proposed to overcome cooperation failures. Drawing on the literature, some scholars argue that breaking the global problem into smaller multilateral agreements supported by trade sanctions can improve enforcement and reduce free-riding (Barrett, 2011; Bassi et al., 2024). For example, Barrett (2011) suggests that linking trade measures (such as tariffs on polluting imports) to climate commitments can incentivize wider participation: countries that do not join would face trade penalties, making non-participation more costly. Similarly, Bassi et al. (2024) emphasize that unilateral climate efforts alone risk carbon leakage and "tragedy of the commons," and propose either cooperative clubs or border adjustments as alternative solutions (Jakob, 2021). In other words, when the gains from club membership (market access and tariff exemptions) exceed abatement costs, stable coalitions can form (Barrett, 2011; Bassi et al., 2024). However, some scholars caution that club design must balance ambition with inclusivity. Jakob (2021) and Bassi et al. (2024) note that climate urgency demands supranational coordination, yet unilateral policies without support can distort trade. The consensus is that *climate clubs* should complement multilateral frameworks, embedding enforcement in trade instruments and meeting concerns about equity and competitiveness (Barrett, 2011; Bassi et al., 2024).

Central to club proposals is the use of trade-related measures. Many authors highlight *border carbon adjustments* (BCAs) as "game changers" for club stability. Al Khourdajie and Finus (2020) demonstrate theoretically that BCAs can greatly enlarge the gains from cooperation by mitigating leakage. Banks and Fitzgerald (2020) similarly argue that BCAs implemented cooperatively – such as through their proposed Carbon Sectoral Tariff Reduction (CSTR) – provide dynamic incentives for abatement and reduce the risk of protectionism. In their framework, cleaner producers in club countries earn tariff discounts, encouraging broad participation. By contrast, these authors warn that unilateral BCAs risk trade retaliation and fragmentation (Banks & Fitzgerald, 2020). They note that if major emitters like the EU and US impose carbon tariffs non-cooperatively, other countries may "retreat behind walls of protectionism," undermining green supply chains (Banks & Fitzgerald, 2020). Thus, a key message is that climate clubs relying on BCAs must be carefully negotiated.

As such, BCAs must be applied in ways that avoid geopolitical backlash (Jakob, 2021; Mehling & Jakob, 2024). In practice, this means combining trade sanctions with incentives. Leonard et al. (2021) for instance recommend that the EU coordinate with the US on a common carbon border tax so as to eventually bring large emitters like China into the club. They also suggest that the EU leverage its role in standard-setting – e.g. by mandating clean-technology norms – to become a climate governance leader (Leonard et al., 2021). In short, the literature sees BCAs as a potentially powerful tool, but one that must be embedded in a broader cooperative strategy (including technology transfer and finance) to be politically viable (Mehling & Jakob, 2024; Cui et al., 2024).

Despite these opportunities, several authors emphasize that climate clubs face significant challenges, especially for developing countries. Jakob (2022) and Zhao (2025) note that African and South Asian economies often have limited incentive to join coalitions led by rich countries. In their modelling of EU–Africa trade, Bassi et al. (2024) find that developing partners benefit only if clubs include technology transfers or CBAM exemptions; otherwise, leakage and competitiveness losses deter participation. Similarly, Zhao (2025) argues that smaller, plurilateral trade forums like WTO's Trade and Environmental Sustainability Structured Discussions (TESSD) may provide a more flexible path than rigid WTO negotiations, reflecting the diverse interests of developing members. Rowan (2024) also shows that effective club members must have both high climate ambition and economic openness, traits that do not coincide in all countries. In practice, governments in emerging economies often view carbon tariffs as protectionist measures, not as incentives. Vidigal and Venzke (2022) warn that many developing states fear WTO-legal challenges to climate measures and thus may resist exclusion or punitive trade rules. One consequence could be the formation of counter-coalitions: Leonard et al. (2021) envisions "fossil fuel" producer alliances lobbying against advanced economy tariffs (Vidigal & Venzke, 2022). The literature therefore stresses that clubs must offer positive side-payments – such as development aid, climate finance or capacity-building – to be attractive and equitable (Bassi et al., 2024; Zhao, 2025). In other words, a purely punitive club strategy risks backlash; multiple authors, e.g. Grubb et al. (2022) and Jakob (2021) recommend embedding climate clubs in trade agreements with built-in transfers and green investment provisions.

The debate on climate clubs also intersects with broader trade and governance issues. Many contributions place clubs within evolving international institutions. Vidigal and Venzke (2022) argue that longstanding WTO jurisprudence now accommodates legitimate environmental measures, so the legal “conflict” between trade and climate can be managed. In this view, WTO rules may even help formalize climate clubs: border measures could be crafted as allowable under Article XX exceptions (Vidigal & Venzke, 2022). Likewise, Buser (2025) refers to the idea of *planetary jurisdiction* – the notion that states can impose laws extraterritorially to protect global commons. He notes that countries are already enacting extraterritorial climate laws (e.g. national CBAMs or supply-chain due diligence requirements) that project domestic standards abroad. This suggests climate clubs may not always require new treaties but could evolve from unilateral laws gradually accepted by peers (Buser, 2025).

At the same time, many scholars see trade agreements as vehicles for club-like cooperation. Grubb et al. (2011) document how environmental provisions are increasingly built into preferential trade agreements. Rowan (2024) finds that linking climate commitments to trade liberalization expands the bargaining space – for example, offering tariff preferences on green goods in exchange for emission cuts. In Asia, Cui et al. (2024) and Zhong & Pei (2024) note that RCEP members with differing climate policies could use club-style accords to harmonize standards and finance digital infrastructure for green trade. Overall, the literature frames clubs as complementing multilateral forums: they are seen as “fast-moving, flexible” initiatives that reinforce UNFCCC goals and may prefigure future WTO reforms.

In sum, climate clubs are treated as a promising but contested pathway for aligning trade and climate objectives. Many scholars agree they have the potential to reduce leakage and raise ambition if major economies take part. However, success hinges on careful design: trade measures must be tailored to avoid retaliation and must be paired with development support to win broader buy-in (Jakob, 2021; Bassi et al., 2024). As Banks and Fitzgerald (2020) note, initial club efforts may best focus on specific sectors (e.g. steel, cement) where cooperation yields clear gains. Moving forward, the literature calls for more empirical and political economy analysis of clubs, including how innovation, digital governance and institutional trust shape outcomes (Vidigal & Venzke, 2022; Zhao, 2025). In any case, ongoing work suggests that by merging trade policy with climate objectives – through carbon tariffs, preferential trade in green goods, and plurilateral accords – climate clubs and related initiatives could help accelerate global decarbonization while navigating the pitfalls of unilateralism.

5.5 Discussion

In today’s globalized economy, trade and climate policy are inextricably linked. Many new environmental regulations carry implications for trade flows and industrial competitiveness, just as shifts in trade policy can influence carbon emissions and environmental outcomes. The findings of this systematic literature review reflect this mutual interdependence. In our research questions we asked first, “how does environmental and climate policy affect trade (and possibly trade policy) and industrial competitiveness?” (RQ1), and second “how trade and/or trade policy (including international agreements and initiatives) enable or restrict our ability to implement environmental and climate policy making at national level?” (RQ2). This discussion synthesizes the findings from the results, highlighting key mechanisms, trade-offs, and possible implications for policy.

One recurring theme is that stringent environmental policies, while crucial for sustainability, can put domestic industries at a competitive disadvantage internationally. Strong climate measures often raise costs for carbon-intensive sectors, weakening their comparative advantage and creating incentives for production to shift toward countries with laxer standards. This phenomenon, called carbon leakage, means emissions are not eliminated so much as relocated via trade; indeed, evidence shows that when countries adopted ambitious emissions targets (such as under the Kyoto Protocol), their carbon-intensive imports rose even as domestic emissions fell, indicating that a portion of their carbon footprint was effectively outsourced (Branger & Quirion 2014). Additionally, climate policies can indirectly influence global energy markets in ways that undermine their effectiveness: if a major economy curbs its fossil fuel consumption, the drop in demand may depress world fuel prices and in turn encourage other countries to burn more, a feedback known as the "fuel price channel" that can lead to a rebound in emissions without any industry relocation (Jakob 2021). These dynamics highlight a critical trade-off, namely that unilateral climate action can achieve local environmental benefits but may be partially offset by global market responses and competitive adjustments.

Despite these risks, well-designed climate policies can limit adverse trade impacts and even yield competitive advantages over time. Environmental regulations often stimulate innovation in cleaner technologies and processes. Such innovations help regulated firms offset compliance costs through efficiency gains and can spill over internationally as other countries adopt the new technologies, partially counteracting leakage and global emissions rebound. Empirical evidence supports the idea that carefully designed climate policy need not undermine industrial competitiveness. For instance, the European Union's emissions trading system imposed a price on carbon but did not trigger significant production flight or a surge in carbon-intensive imports from abroad. Policy design choices such as granting free emission allowances to vulnerable industries and keeping carbon prices at moderate levels shielded domestic manufacturers from abrupt cost shocks while still incentivizing emissions cuts (Felbermayr 2024). This experience aligns with the Porter Hypothesis, which suggests that well-calibrated environmental regulation can spur innovation that offsets its costs, turning a potential competitive handicap into improved efficiency and technological leadership.

To address the trade-related challenges of asymmetric climate action, policymakers are also exploring instruments that directly link trade and climate objectives. One prominent example is the carbon border adjustment mechanism (CBAM), which imposes a carbon cost on imported goods to ensure that domestic and foreign producers face similar emissions constraints. By levelling the playing field in this way, a border adjustment is intended to reduce the incentive for firms to offshore production and to prevent carbon-intensive imports from undercutting domestic climate efforts. However, a unilateral carbon border tax is no panacea: it cannot fully eliminate leakage if other countries do not follow suit, since cheaper fossil fuels on the global market can still spur higher consumption elsewhere, offsetting the leading region's emissions reductions. Moreover, such measures carry significant diplomatic and legal risks, raising concerns about compatibility with World Trade Organization rules because they can be perceived as violating the non-discrimination principle by favouring domestic producers (Boehringer et al. 2018). Another concern revolves around the question of equity for developing countries that depend on carbon-intensive exports. Nations with fewer resources to decarbonize could be disproportionately affected by border adjustments, as they struggle to meet the higher standards demanded by importers (Erdogdu 2025). These considerations underscore that, while carbon border measures may help industrialized countries press ahead with climate policies, their design must carefully balance effectiveness with fairness and international obligations.

Parallel to these trade-focused measures, governments are reorienting domestic industrial policy to align economic development with climate goals. Rather than treating emissions reduction as a pure cost to be shouldered by industry, policymakers are using industrial strategies to turn decarbonization into an opportunity for innovation and growth. Modern industrial policy in this context aims to simultaneously stimulate technological innovation, economic competitiveness, and emissions cuts. It addresses market failures (for example, the failure to price carbon externalities or the underinvestment in early-stage clean technologies) and coordination problems (such as the need for new infrastructure, skills, and supply chains for green industries) that markets alone may not solve. By investing in areas like renewable energy, energy-efficient manufacturing, and electric mobility, such policies can reduce reliance on imported fossil fuels and create jobs in emerging clean-tech sectors, building a domestic workforce and industrial base geared toward sustainability (Meckling 2021). Notably, industrial policy tends to be most effective when it supports new, export-oriented green industries rather than subsidizing declining high-emission sectors; the former approach is more likely to yield lasting competitive advantages. Furthermore, well-designed initiatives de-risk private investment in clean technologies and help form innovation clusters, while also cultivating political support for ambitious climate action – industries and workers that benefit from the green transition become stakeholders advocating for its continuation. In these ways, an integrated industrial policy can help overcome "carbon lock-in" (the inertia of existing high-carbon systems) by driving structural change toward a low-carbon economy without sacrificing long-term competitiveness.

Conversely, regarding research question 2, the influence of trade on climate policy is evident in how emissions are accounted for and in the constraints imposed by international economic rules. Countries have traditionally measured their progress on climate goals using production-based emissions accounting. This means counting the CO_2 emitted within their own borders which has been the standard practice since the 1990s. This method, however, can distort both the perceived responsibilities and the effectiveness of climate actions. Wealthier economies often appear to make emission gains partly by importing carbon-intensive goods instead of producing them at home, while the associated emissions are recorded in the exporting countries (frequently emerging economies). Such an arrangement shifts the apparent burden of mitigation to producers and benefits importing nations, raising questions of fairness. A developing country might justifiably argue that it is carrying the emissions cost of manufacturing goods for foreign consumers. Moreover, because only domestic emissions count under production-based accounting, there is an implicit incentive for nations to outsource their dirtiest industries to meet climate targets, which reinforces carbon leakage (Reeve & Aisbett 2022). Alternatives like consumption-based accounting – where emissions are attributed to the country that ultimately consumes the goods – have been discussed as more equitable, but no universal standard has been adopted. The lack of an agreed method to account for carbon embodied in trade means that current climate policies often overlook or struggle to address a significant portion of global emissions that are essentially traded across borders.

Beyond accounting, the international trade regime itself influences the space for national climate policy. Trade agreements and rules can both restrict and enable environmental action. On one hand, World Trade Organization (WTO) principles demand that countries not discriminate against foreign products, which complicates policies that favour domestic green industries. For example, a subsidy or public procurement rule designed to boost local renewable energy technology might run afoul of trade commitments if it is seen as excluding foreign competitors. Governments thus must design support for clean technology carefully, to avoid violating rules against protectionism. On the other hand, trade law does provide avenues for climate measures: GATT Article XX, for instance, allows exceptions to trade obligations for policies aimed at protecting human, animal, or plant life or conserving exhaustible natural resources (van Asselt & Biermann 2007). In principle, this means a well-justified climate policy such as a carbon regulation applied equally to domestic and imported goods could be deemed permissible even if it departs from normal free-trade disciplines, so long as it meets the criteria of necessity and avoids arbitrary discrimination. The ongoing development of the EU's carbon border adjustment illustrates this careful navigation. Designers of that policy have been careful to frame it as aligned with existing trade law (for example, treating the carbon charge similarly to an indirect tax adjustment on imports, which is a recognized practice), yet it remains untested how such a climate-trade measure will be received in practice. In sum, the interplay between trade rules and climate action requires delicate balancing: countries seek to uphold an open trading system while also advancing aggressive climate policies, and this often necessitates innovative policy design or even reinterpretation of trade norms to accommodate the urgency of climate change.

In addition to working within multilateral trade rules, countries are leveraging trade agreements and new coalitions to advance climate objectives. Many bilateral and regional trade agreements now incorporate environmental provisions such as obligations to enforce pollution controls, protect biodiversity, promote sustainable resource use, and so forth. This development effectively turns trade partnerships into vehicles for strengthening environmental standards. These provisions encourage governments to maintain robust environmental regulations and provide a framework for cooperation on issues like deforestation, renewable energy, or pollution reduction as part of trade relations (Gutsch et al. 2024). Beyond formal agreements, the concept of "climate clubs" has gained traction as a way to align trade incentives with climate action. A climate club involves a coalition of countries committing to more ambitious emissions cuts among themselves and agreeing on collective measures to deter free-riding. For example, club members might coordinate carbon pricing or grant each other preferential trade benefits (such as lower tariffs or mutual recognition of green product standards), while imposing tariffs or fees on imports from non-members that do not meet similar climate efforts. By combining the incentive of market access with the imperative of emissions reduction, such clubs aim to minimize competitive disadvantages among participants and put pressure on outside countries to elevate their climate commitments. Both the inclusion of environmental provisions in trade agreements and the formation of climate clubs illustrate how trade policy tools can be repurposed to support, rather than hinder, the implementation of climate policies at the national and international levels.

Despite the growing understanding of trade–climate interactions, the literature still exhibits notable blind spots in this fast-changing context. One emerging issue is the shift toward a new geoeconomic paradigm in which some countries prioritize domestic industrial growth and even expand fossil fuel production, potentially at the expense of international climate cooperation. This trend, most evident in recent policy shifts in the United States raises questions about how a retreat from multilateral climate governance by major economies might alter trade and competitiveness dynamics, yet it remains underexplored in existing studies. A related uncertainty is the assumption of stable international institutions that underpins much of the current research. Many analyses implicitly rely on the continuity of a rules-based trading system and effective global governance. In reality, key institutions are showing signs of strain: for example, the WTO's traditional mechanisms for dispute resolution have been weakening in recent years. If the multilateral trade regime continues to erode, strategies for integrating trade and climate policy may confront new obstacles, as countries could be less bound by common rules or more prone to unilateral measures. These blind spots suggest that future research should examine how a more fragmented and less cooperative global landscape would affect the viability of ambitious climate policies. In particular, understanding the implications of a retreat from globalization or a weakening of trade institutions is crucial for anticipating whether climate initiatives can endure and succeed under shifting geopolitical priorities.

Finally, it is important to acknowledge the limitations of this literature review. Although the systematic literature review underwent a rigorous process of excluding articles based on the SCOPUS and Web of Science results, analysis drew on a limited number of sources. This constrains the breadth of perspectives and case studies captured. Important work in this expansive field of trade, climate, and industry policy may have been omitted due to the scope of the review, and as a result the conclusions should not be over-generalized. The selection of literature, while systematic, cannot fully encompass the diverse regional and disciplinary viewpoints that exist on these topics, especially in different national circumstances. Moreover, the policy landscape in this area is evolving rapidly, and some recent developments might not be reflected in the reviewed studies. These limitations mean that the insights presented here should be interpreted with an understanding of the review's scope, and they highlight the need for continual research. Future studies that incorporate a broader array of sources and keep pace with ongoing changes will be valuable to further test and refine the findings on the trade–climate–industry nexus.

5.6 Conclusion

A systematic literature review was conducted in this report with the goal to identify the key topics around the trade climate and industry nexus (TCI) from a political science perspective. The literature review shows that trade, climate, and industrial policies are tightly linked in ways that produce both opportunities and tensions for global sustainability. Uncoordinated climate action in a globalized economy can trigger carbon leakage and competitiveness challenges, as firms and emissions may shift to jurisdictions with weaker constraints. At the same time, trade can serve as a conduit for climate solutions – for example, by diffusing low-carbon technologies and creating incentives for broader participation in emissions reduction. A recurring theme is the need for policy coherence: aligning international trade rules and climate objectives to ensure that measures like carbon pricing, border carbon adjustments, and green subsidies can be deployed effectively without provoking counterproductive trade disputes or unwanted effects. The review also highlights questions of equity and fairness. Developing countries often perceive new climate-related trade measures (such as carbon tariffs or stringent environmental standards) as potential barriers to their economic development, underscoring the importance of inclusive approaches. Several scholars argue that supporting poorer nations through climate finance, technology transfer, or preferential terms is essential to legitimise and spread robust climate action worldwide. Furthermore, the resurgence of industrial policy in major economies (e.g. large-scale clean energy subsidies) introduces a new dimension to the trade-climate nexus. These policies can accelerate decarbonisation but risk fragmenting global markets if not internationally coordinated. Overall, the literature suggests that stronger integration between climate policy and trade policy is imperative: well-designed cooperation can mitigate trade-offs, whereas a lack of coordination risks a scenario where climate policies are undermined by trade frictions and geopolitical competition.

For global climate governance, these findings underscore the urgency of forging an integrated framework that bridges the traditionally separate regimes of trade and climate. Policymakers should work toward mutual reinforcement between trade agreements and climate commitments, for instance, updating World Trade Organization rules or negotiating new plurilateral agreements so that legitimate climate measures (such as carbon border adjustments or clean tech subsidies) are accommodated and encouraged rather than challenged as protectionist. Institutions and coalitions have begun to adapt: the inclusion of environmental provisions in trade agreements and the emergence of climate clubs and alliances show viable paths to align trade incentives with climate goals. Going forward, ensuring the credibility and fairness of these initiatives in the light of geopolitical challenges and changing global environments will be key. This means providing transition periods or assistance for low-income countries and engaging them in rule-making, so that global decarbonisation efforts are seen as a shared endeavour rather than a new basis for trade discrimination.

Despite growing academic attention to the trade-climate-industrial policy nexus, there are still important knowledge gaps. The rapid evolution of real-world policies – from new carbon tariffs to competitive green industrial subsidies – calls for continual research to assess their long-term impacts on both emissions and international relations. One emerging concern is how a more fragmented geopolitical landscape could affect TCI integration. If multilateral institutions weaken or major emitters retreat from global cooperation, future research must explore how climate initiatives can adapt (or endure) under such conditions. There is also a need for more interdisciplinary analysis that combines political science with economics and law to design innovative solutions at this nexus. This review has provided a foundation by mapping existing literature and debates, but further studies should expand on under-explored areas (such as the effects of trade policy in a world of divergent national climate strategies, or the governance of supply chains critical for the clean economy). In conclusion, aligning trade, climate, and industrial policies emerges as both a pressing governance challenge and a frontier for research. Bridging these domains will require not only political will and diplomatic creativity but also improved evidence: continued academic research will be crucial to guide policy innovations that achieve climate objectives while maintaining a fair and open global trading system.

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6 Economic Modelling

6.1 Introduction

In this section, we describe the methodology to be followed for the conduction of the third part of literature review of Task 1.1.1, aiming to reveal the limitations of current-generation modelling tools in support of climate policymaking, with regard to exploring the trade policy – climate policy nexus. On the one hand, we envisage to explore how trade policy has already been treated through the adoption of various types of economic models, focusing especially on the most recent studies. On the other hand, we aim at capturing all the capabilities that state-of-the-art may offer, focusing especially on the underlying trade theories, the integration of technological change, the potential interlinkage with international transportation, material flow schemes, as well as the AFOLU effects.

To deliver on these objectives, a step-by-step methodology has been adopted in order to document the modelling capabilities and the potential gaps, by focusing especially on integrated assessment and macro-economic modelling research, thus aligning our targets with the core modelling pursuits of the ENTICE project. The outcome of this economic modelling literature review will offer additional insights into research capacity needs, intended to feed into the project's model update and upgrade work (WP3), towards ultimately enhancing the project's model ensemble's capacity to assess the complex TCI interactions.

6.2 Methodology

To achieve both literature review targets – trade policy representation and state-of-the-art capabilities and gaps, the workflow of this sub-task is broken down into four *Research Objectives* (ROs), as outlined below:

- RO_1: Systematic literature review
- RO_2: Review of model documentations
- RO_3: Assessment of ongoing model developments
- RO_4: Identification of ENTICE ensemble gaps

The first research objective (RO_1) takes aim at the published literature and thus both explores the capabilities of the state-of-the-art models and critically scopes their implementation, with the aim to respond to the following guiding research question: *How has trade policy, and its interaction with climate policy, been addressed by economic modelling?* The remaining research objectives (RO_2-RO_4), instead, focus explicitly on the capabilities and limitations of the models as operational tools, without considering their application in scenario studies and policy analyses. This is carried out in three steps: first, capturing model capabilities and weaknesses based on publicly available documentations found online or referred to as part of established model documentation wikis (RO_2); second, exchanging with scientific consortia tasked with relevant model developments in currently running projects (RO_3); and, third, taking a more nuanced approach and doing a deep dive into the models in the ENTICE model ensemble, in dedicated exchanges with the project's modelling teams (RO_4). The timeline of this substantial, multi-layered activity is illustrated in Figure 9**Error! Reference source not found.**. By M10 (October 2025), our literature review has focused on RO_1, while the fully-fledged review, including the technical aspects of models, will be completed by M14 (February 2025).

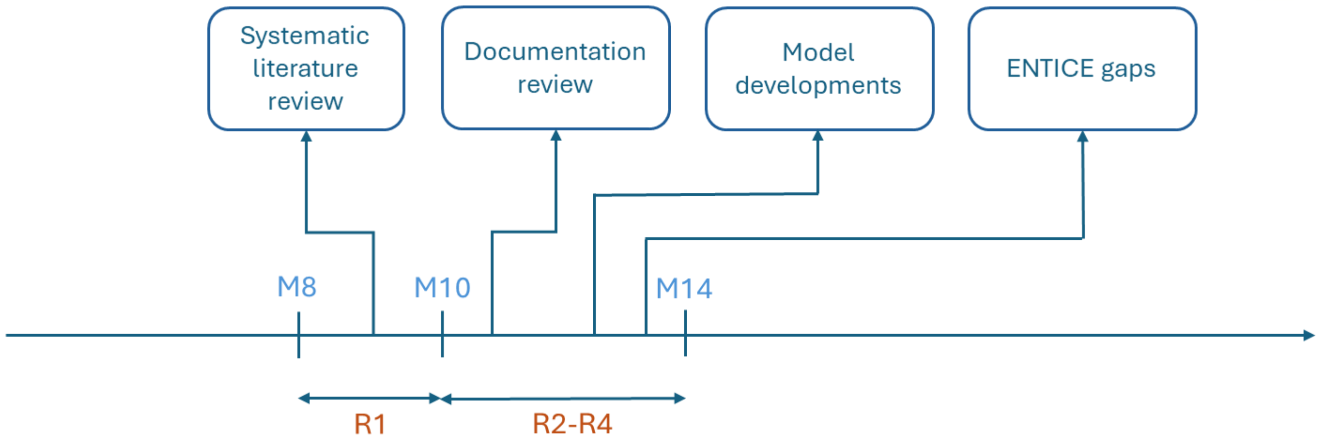

Figure 9. Research objectives' span.

6.2.1 RO$_1$: Systematic literature review

In research objective RO$_1$, the aim has been to capture how trade policy has hitherto been explored through economic modelling. In particular, a dedicated literature research and review protocol was followed, in line with the established PRISMA framework (Moher et al., 2015), drawing on the Scopus database. To this end, a search query was adopted, involving three search categories, defined as follows:

"integrated assessment model" OR "climate-economy model" OR "climate-economic model" OR "energy system model" OR "energy model" OR "energy system optimisation model" OR "macroeconomic model" OR "macroeconometric model" OR "equilibrium model" OR "CGE model" OR "DSGE model" OR "input-output model"

AND

"trade policy" OR "international trade" OR "world trade" OR "open trade" OR "free trade" OR "trade liberalisation" OR protectionism OR "trade nationalism" OR tariff OR CBAM OR "rules of origin" OR "content requirements" OR "non-tariff"

AND

"climate policy" OR "climate change" OR "climate mitigation" OR "greenhouse gas" OR emissions

AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND LIMIT-TO (SRCTYPE,"j")

AND

LIMIT-TO (DOCTYPE,"ar") AND LIMIT-TO (LANGUAGE,"English")

The query was applied in the Scopus database, restricting results to the last decade. The review period was deliberately confined to the past decade to ensure that the analysis captures the most recent methodological advancements and evolving policy contexts within the trade-climate nexus. During this timeframe, significant progress has been made in both climate policy – particularly in the aftermath of the Paris Agreement – and in the refinement of global modelling databases such as the GTAP Data Base. Accordingly, this temporal restriction enables a more precise and policy-relevant evaluation of current modelling capacities and their applicability to contemporary trade and climate policy analysis. Subsequently, following PRISMA rules, an exclusion protocol was applied to exclude out-of-scope papers. Finally, the outcomes of this literature review part were collected in table form, allowing for comparison analysis and capturing features as follows:

- *Model type*: specifying the analytical/mathematical framework (CGE, IAM, recursive dynamic, etc.)
- *Geographic scale*: specifying the level of spatial aggregation or disaggregation at which a model represents economies.
- *Sectoral coverage*: specifying the level of detail with which a model represents different economic sectors and activities.
- *Trade policy*: specifying which trade-related instruments or mechanisms are evaluated by the study.
- *Climate policy*: specifying which climate instruments or mechanisms are evaluated in conjunction with the relevant trade policy.
- *Trade theory*: specifying the underlying theoretical framework used to represent international trade.
- *Technological change mechanism*: specifying how a model represents the diffusion of new technologies, and how these changes affect productivity and cost structure.
- *Material flows*: specifying whether and how a model explicitly tracks the movement of physical resources through the economy.
- *International transport modelling*: specifying whether and how international transport is considered as a distinct sector (shipping, aviation).
- *Limitations in terms of trade theory / policy*: specifying aspects of international trade theory and/or policy that the model cannot fully capture.

6.2.2 RO_2: Review of model documentations

The aim of research objective RO_2 is to provide a structured review of how different classes of economic models could potentially be used to conduct trade policy analysis, as well as which are the capabilities and/or limitations of modelling tools. The review does not only focus on the models identified under objective RO_1, but instead covers as many general equilibrium models, Integrated Assessment models, and other relevant frameworks identified that could potentially evaluate the nexus of trade policy and climate policy, via well-established model wikis, repositories, etc.

This sub-task consists of a systematic literature and documentation review of models that are available on well-known repositories, including:

- IAMC documentation wiki (Integrated Assessment Modelling Consortium)[6]
- IAM PARIS detailed model documentation[7]
- GTAP-related models and extensions[8]

While research objective RO_2 is not "study-driven", thereby not designed to capture how trade policies are evaluated through models, the analysis is conducted by means of a near-identical template to that of RO_1, enabling comparability. Thus, in the adopted comparison table, each model is assessed with respect to the following dimensions: treatment of technical change, underlying trade theory, geographic scale, explicit representation of international transport, explicit representation of material flows, and other additional aspects such as sectoral representation detail and mathematical formulation.

The workflow in response to this research objective proceeds in the following steps:

[6] https://www.iamconsortium.org/resources/models-documentation/
[7] https://iamparis.eu/detailed_model_doc
[8] https://www.gtap.agecon.purdue.edu/about/data_models.asp

Step 1. Identification of relevant models from the targeted repositories.

Step 2. Collection and review of technical documentation associated with each model.

Step 3. Systematic coding of model features according to the defined dimensions.

Step 4. Comparative analysis to identify commonalities, divergences, and limitations across models.

Step 5. Synthesis and reporting, including the development of summary tables and a narrative analysis of key insights.

6.2.3 RO_3: Assessment of ongoing model developments

The aim of research objective RO_3 is to complement the systematic literature review by incorporating insights from ongoing Horizon Europe projects and the broader modelling community efforts. This activity ensures that recent and forthcoming model developments on trade representation are adequately captured in the review process. To this end, work in response to RO_3 is broken down into two main sub-activities:

1. Engagement with Horizon Europe projects:
   - Reaching out to targeted Horizon Europe projects focusing on energy-climate-economy and integrated assessment modelling (DIAMOND[9], PRISMA[10], WorldTrans[11], CHOICE[12], TRANSIENCE[13], AMIGDALA[14], DECIPHER[15], CAPABLE[16], PATTERN[17]).
   - Requesting a short interview or written feedback from project representatives based on a structured questionnaire and addressing the following dimensions:
     a. What models are used/developed in the project (including link to documentation or publication)?
     b. Are there any model developments, either completed or planned within the project, regarding representation of trade, technological change, international transportation, material flows, or AFOLU impacts?
     c. Have the project's modelling teams addressed, or is the consortium planning to address, research questions explicitly related to trade? If so, which questions?
   - Synthesis of responses to identify recent innovations, gaps, and directions in the representation of trade, technological change, international transportation, material flows, and AFOLU impacts.
2. Complementary scoping of broader modelling community efforts
   - Reviewing and ensuring that notable inter-comparison studies (e.g., (Böhringer et al. 2012) on CBAM and unilateral policy) have been captured/represented in the literature review as part of RO_1.
   - Conducting targeted discussions with key experts within the consortium (e.g. GTAP team) and the Scientific Advisory Board (SAB) to validate findings and identify additional relevant insights.

[9] https://climate-diamond.eu/
[10] https://www.net0prisma.eu/
[11] https://worldtrans-horizon.eu/
[12] https://www.climatechoice.eu/
[13] https://www.transience.eu/
[14] https://amigdalaproject.eu/
[15] https://decipher-horizon.eu/
[16] https://capableclimate.eu/
[17] https://pattern-heu.eu/

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6.2.4 RO$_4$: ENTICE gaps

To ensure that the project's own ensemble of models is thoroughly represented in our review and offer nuanced and more detailed insights into the models to be upgraded in the context of the ENTICE project, research objective RO$_4$ (a) systematically reviews the documentation of the models available within the consortium, and (b) directly engages with the corresponding modelling teams to capture ongoing or planned developments. This activity focuses on the ensemble of models used within the project – namely, GEM-E3, ICES, NEMESIS, GEMINI-E3, ENVISAGE, FIDELIO, and ZEW (with the possibility of adding more models that are not necessarily part of ENTICE but are nonetheless used by the consortium, such as GCAM, E3ME, WITCH, IMAGE, and OPEN-PROM); as well as the LBAM trade model and the GLOBIOM biosphere management model. To this, the work will consist of two main components:

- Systematic inclusion:
    - Ensuring that the documentation of each model is reviewed and coded according to the framework defined under research objective RO$_2$.
    - Where documentation is missing or incomplete, complementing it with material or references provided by the corresponding modelling teams.
- Engagement with model teams:
    - Organising short discussions with each model team to address targeted questions in the same spirit of research objective RO$_3$.
    - Using these discussions to identify improvements not yet published and to capture future research and modelling directions for the models.

6.3 Results

6.3.1 A systematic literature review of state-of-the-art economic modelling

This section presents some preliminary findings of the systematic literature review conducted in the context of the first research objective (RO$_1$). The final results alongside a comprehensive analysis of the identified data and model development needs will be included in deliverable D1.4 ('Modelling research needs').

By applying the research query defined in Section 6.2.1, our search in the Scopus database yielded 328 papers in total (as of August 2025). Subsequently, a hierarchical exclusion process was applied to remove papers outside the scope of the research. This process was broken down into four sequential steps: (i) exclusion by title, (ii) exclusion by abstract, (iii) exclusion by Introduction and Conclusions, and (iv) exclusion by examining the whole paper. The first three steps were done centrally (by ICCS), while the fourth step was completed by all contributors (ICCS, CMCC, ORDECSYS, E3M). The final list of within-scope papers included 147 papers in total. Then, detailed review and data extraction were allocated in consideration of each contributing team's availability, towards filling out the table-format template (extraction protocol) with the features defined in Section 6.2.1.

To synthesise the results and extract useful takeaways and patterns that can guide WPs 2-3, a post-analysis was conducted exploring research questions such the following:

- Which model types dominate efforts to assess the trade-climate nexus?
- What trade mechanisms are explored the most?
- How has technological change been incorporated and applied in models?
- Can international transportation, and the relevant embodied emissions, be explicitly treated in state-

of-the-art economic and integrated assessment models?
- To what extent is standard modelling dependent on the GTAP data structure?

Considering that the research objective RO_1 is trade policy-driven (given the features explored and papers extracted), it is valuable to clarify the trade policies captured (and classified) in the employed literature review extraction protocol. The following classes were identified:

- *Carbon border policies:* policies adjusting the price of traded goods at the border to reflect the carbon content (e.g., CBAM, carbon tariffs, etc.).
- *Carbon pricing – trade interaction:* policies reshaping competitiveness and embodied emissions, beyond carbon border mechanisms.
- *Trade liberalisation policies:* policies aimed at removing the barriers to international trade (e.g., trade agreements, WTO accession, etc.).
- *Agricultural trade policies:* policies focusing in the agricultural and food sectors (e.g., food security policies).
- *Trade restriction policies:* policies imposed for geopolitical reasons (e.g., sanctions).
- *Sector-specific policies:* policies targeting specific commodities and/or infrastructure relevant to trade and climate interaction (e.g., hydrogen, ores).
- *Indirect policies:* policies not primarily designed as trade ones that, however, influence trade and climate.

Before delving into the mapping of trade policies across model types, it is also useful to clarify the model classification employed in this literature review analysis. In particular, the extraction protocol featured the following classes of models:

- *Computable general equilibrium (CGE) models:* representing the entire economy as a system of highly interrelated markets in equilibrium.
- *Partial equilibrium (PE) models:* focusing on one sector or a subset of sectors, while assuming the rest of the economy fixed (and the propagation of equilibrium effects from said sector(s) to the rest of the economy negligible).
- *Dynamic stochastic general equilibrium (DSGE) models:* general equilibrium models, where economic agents "decide" in the light of uncertainty.
- *Integrated Assessment Models (IAMs):* representing economy-energy-society-climate interactions (typically involving the AFOLU sector in detail and/or a simple climate module).
- *Energy system models[18]:* bottom-up, technology-detailed models that represent the whole energy chain, from production to use.
- *Sectoral models[19]:* models tailored to a single industry (e.g., iron and steel, chemicals, etc.).
- *Other quantitative trade models:* a heterogeneous group of models that do not fall into any of the above categories but are used to analyse the trade-climate nexus (e.g., game-theoretic, network equilibrium, agent-based, and other analytical trade models).

Trade policies across model classes

As shown in Figure 10, general equilibrium models dominate trade policy assessment efforts in the literature – expectedly, as any change in the trade status quo (tariff adjustments, border measures, carbon pricing, etc.) tends to propagate across multiple economic sectors (Ivus & Strong, 2007). Among these, the Global

[18] Obviously, they are not necessarily designed for trade-driven policies; however, there are studies evaluating the trade-climate interaction through energy system models.
[19] There is an overlap with energy system models. Therefore, energy sectors are excluded from this category.

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Trade Analysis Project (GTAP) and its numerous extensions (e.g. GTAP-E, GTAP-AEZ, GTAP-BIO) are by far the most frequently used. In addition, there exist several GTAP-based recursive-dynamic CGE models, such as MIRAGE, GEM-E3, GEMINI-E3, GDyn-E, and ENVISAGE, relying heavily on the same data inputs (GTAP Data Base) among those frequently adopted to assess various trade-related policies in the trade-climate nexus. Focusing on the most recent decade may have resulted in a concentration of studies related to recent policy developments, particularly the "Fit for 55" package and the CBAM. This trend indeed reflects the growing academic and policy interest in these initiatives in the considered period. However, the choice of timeframe was motivated by the intention to capture the most up-to-date modelling practices and policy-relevant analyses within the evolving climate–trade nexus.

An important exception to CGE application concerns agricultural trade policies, which typically target a narrow set of commodities rather than the entire economy. For such cases, PE approaches are often more suitable, as they provide a more detailed representation of crop and livestock production systems, as well as of land use effects (Ciaian & Swinnen, 2006). Models such as CAPRI and CARD capture an adequate level of detail for the agricultural sector, which is typically simplified in a wide-economy CGE. As a result, for policies focused on land use, food security, and biofuel use, modelling literature shows an almost balanced share of CGE and PE applications. The PE approach enables more detailed treatment of yields, land heterogeneity, and agricultural intermediates (e.g., fertilisers and feedstock), which is challenging in economy-wide CGE models.

In contrast, trade liberalisation is almost exclusively analysed through general equilibrium models. Liberalisation shocks, such as the removal of tariffs or the formation of a Free Trade Agreement (FTA), propagate through industries and factor markets, impacting prices and the production structure across the entire economy (involving both direct and third parties). Therefore, CGE models are preferred for capturing these complex impacts among sectors and countries (Ackerman & Gallagher, 2008). Although few alternative approaches have emerged, such as network equilibrium models representing global supply chain interdependencies (Hassani et al., 2025), their application remains limited.

Trade restrictions (e.g., sanctions) represent another category of policies that are increasingly explored in the literature. Such measures are often bilateral or regional (e.g., EU bans on imports from specific countries). Their economic impacts depend strongly on third-country adjustments, including trade diversion and re-routing effects. Since CGE models are de facto economy-wide and typically multi-country, they are better suited for analysing both direct and indirect effects of trade restrictions.

Finally, our review of the modelling literature highlights that trade policy impacts are closely related to technology, resources, and infrastructure – and thus the economic-engineering trade-offs in model types. For instance, policies affecting carbon border adjustments hinge on the availability and cost of low-carbon technologies. Since CGE models often represent technology in aggregated forms, they may not adequately capture the engineering constraints of specific sectors. In such cases, sector-specific models (e.g., AIM for aviation) provide complementary insights by representing the available technologies in more detail. Linking such sectoral frameworks with CGEs allows a better understanding of the macroeconomic impacts, without weakening the presence of any specific technology (Keppo et al., n.d.).

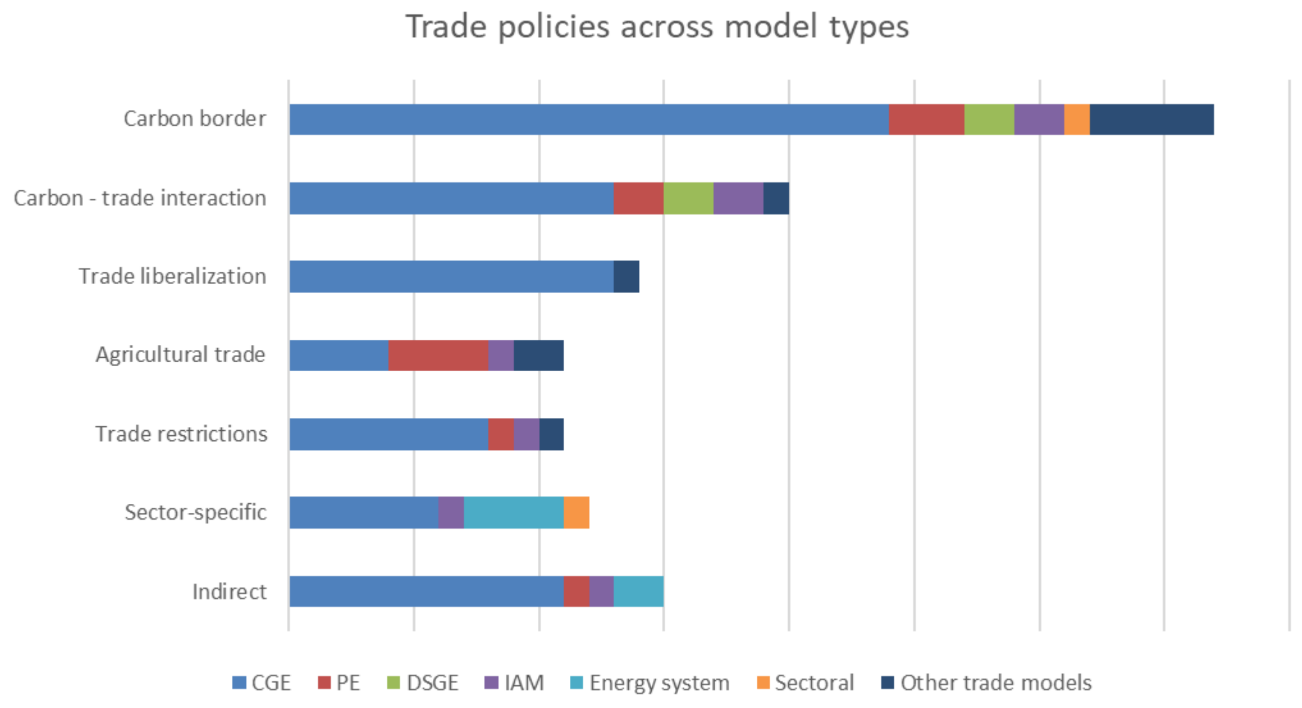

Figure 10. Trade policies across model types.

A detailed account of the models employed in the literature

Most of the models identified in the scope of this systematic literature review are global in scope, both in geographic and sectoral coverage, thereby allowing to capture the interdependences of economies and sectors. A significant share of these models rely on the well-known GTAP Data Base as their primary input. Covering approximately 99.1% of world GDP (GTAP, 2023), the GTAP Data Base provides a harmonised representation of national accounts, bilateral trade, energy flows, and emissions. This consistency makes the database a cornerstone for large-scale global economic models (GDyn-E, GEMINI-E3, ENVISAGE, etc.), as well as for hybrid frameworks that integrate trade and climate dimensions. This reliance on GTAP data allows data integrity and modelling comparability; however, it also "hampers pluralism", due to the high degree of aggregation20 in specific sectors.

As illustrated in Table 2, the Armington assumption remains the dominant trade-theoretic scheme across the reviewed models. Under the Armington elasticity model, commodities are differentiated by origin, and substitution elasticities determine how easily imports and domestically produced commodities replace one another (Armington, 1969). While this specification offers computational simplicity, it limits the capacity to represent firm heterogeneity and other structural trade dynamics represented by modern trade theories. Regarding the technological evolution, most models treat it exogenously, introduced via assumed trends in productivity and efficiency. Another recurring limitation is the absence of the explicit representation of international transportation services. In particular, GTAP-based models – which constitute the bulk of assessment tools in the reviewed literature – aggregate international transportation services into a global "transportation margin" sector, which renders them unable to assess high-interest policies such as the maritime

[20] Most studies of the literature review rely on the "65-sectors" version of the GTAP Data Base, not on the specific extensions.

decarbonisation under the 'Fit For 55' package (FuelEU Maritime, 2025).

Overall, the models identified are characterised by strong consistency and broad coverage but remain limited in trade micro-level diversification, technological progress, and transportation systems.

Table 2. List of models identified in the systematic literature review (RO_1).

CGE	Global	Armington	GTAP Data Base
CGE (energy-environmental version)	Global	Armington	GTAP Data Base
CGE extensions (biofuels, land, water)	Global	Armington	GTAP Data Base
recursive dynamic CGE	Global	Armington	GTAP Data Base
CGE variants	Global	Armington	GTAP Data Base
Recursive dynamic CGE (energy)	Global	Armington	GTAP Data Base
Recursive dynamic CGE	Global	Armington	GTAP Data Base
Dynamic intertemporal CGE	Global	Armington	GTAP-style SAM + IMF data
Recursive-dynamic CGE	Global	Armington	GTAP Power Data Base
Recursive-dynamic CGE	Global	Armington	GTAP Data Base
Dynamic CGE	Global	Armington	GTAP Data Base, FAO
Recursive-dynamic CGE	Global	Armington	GTAP Data Base
Dynamic CGE	National	Armington	National SAMs
CGE	National	Armington	National SAMs

[21] https://www.gtap.agecon.purdue.edu/models/current.asp
[22] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2959
[23] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5172
[24] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2605
[25] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4346
[26] Calzadilla et al. (2011), The GTAP-W model: Accounting for water use in agriculture, Kiel Working Paper, No. 1745, Kiel Institute for the World Economy.
[27] https://www.gtap.agecon.purdue.edu/models/Dynamic/model.asp
[28] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=4292
[29] Corradini et al. (2018). A dynamic assessment of instrument interaction and timing alternatives in the EU low-carbon policy mix design. Energy Policy, 120, 73-84.
[30] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=409
[31] https://www.european-calculator.eu/
[32] Corong, E., & Strutt, A. (2020). Exploring the Impacts of Changing Energy Costs on New Zealand Agriculture to 2030: A GTAP-E-RD Application.
[33] https://www.gtap.agecon.purdue.edu/models/envisage.aspx
[34] https://www.gcubed.com/
[35] https://2025.ordecsys.com/page/gemini-e3
[36] https://dart.omp.eu/#/
[37] https://www.cepii.fr/cepii/en/bdd_modele/bdd_modele_item.asp?id=14
[38] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=6452
[39] https://www.pep-net.org/research-resources/cge-models
[40] https://www.copsmodels.com/oranig.htm

Partial equilibrium (agriculture)	International	Armington-like	Eurostat, FAO
Recursive-dynamic CGE	Global	Armington	GTAP Data Base, FAO
CGE	National	Armington	China SAM
CGE	national	Armington	GTAP Data Base, China data
CGE	Global	Armington	GTAP Data Base
IAM	Global	Armington-like	IEA, UN, national data
Energy system model	Global	No trade theory	IEA, technology data
Energy system model	National, regional	No trade theory	IEA, energy balances
IAM	Global	Armington	GTAP Data Base, IEA, FAO
IAM	Global	Mixed (perfect substitution for MESSAGEix, imperfect substitution for GLOBIOM)	IEA, FAO
CGE	Global	Armington	GTAP Data Base
Partial Equilibrium	Global	Armington-like	Eurostat, CAP data

Underlying trade theory

Despite its rather weak theoretical foundation, the Armington hypothesis has remained the dominant trade scheme. Practically, Armington-based models require a small set of elasticity parameters per sector, allowing calibration from input such as the GTAP Data Base. In recent years, however, a debate has sparked on the limitations of the Armington trade theory (Dixon et al., 2018). Approaches distinguishing goods by firms rather than countries, drawing on trade theories of (Krugman, 1980) and (Melitz, 2023), are being advocated. Such models introduce firm heterogeneity and endogenous market entry/exit, while allowing product diversification, meaning they are better equipped to explain intra-industry trade and welfare gains from trade liberalisation (Dixon et al., 2016; Bekkers & Francois, 2016).

Nevertheless, there are attempts to bridge the gap and embed modern trade theories into CGE models.

[41] https://www.capri-model.org/
[42] https://cgspace.cgiar.org/items/c2e8c11b-ffd8-4e8f-aff7-774404769234
[43] Liang at al. (2014). Platform for China Energy & Environmental Policy Analysis: A general design and its application. Environmental modelling & software, 51, 195-206.
[44] https://www.3e.tsinghua.edu.cn/en/category/evaluation-models
[45] https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-eu-ems/
[46] https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model
[47] https://www.i2am-paris.eu/detailed_model_doc/tiam
[48] https://iea-etsap.org/index.php/etsap-tools/model-generators/times
[49] https://www.iamcdocumentation.eu/Model_Documentation_-_REMIND-MAgPIE
[50] https://docs.messageix.org/projects/global/en/latest/overview/index.html
[51] https://www.wto.org/english/res_e/reser_e/ersd201910_e.htm
[52] https://biooekonomie-bw.uni-hohenheim.de/en/tp117

Zhai (2008) integrated a Melitz-style firm heterogeneity mechanism into a CGE model, improving the ability to capture the trade expansion and welfare effects of trade liberalisation. In the same context, Roson & Oyamada (2014) showed how to build a CGE model with Melitz "characteristics", gradually moving from a single-industry partial equilibrium model to a multi-industry general equilibrium one. Bekkers & Francois (2016) proposed a unified approach to incorporating Krugman, Melitz, and Eaton-Kortum trade frameworks into the GEMPACK implementation of the GTAP model, while providing coding and parameterisation guidelines. Firm Melitz-type heterogeneity was also introduced in a GTAP model by Akgul et al. (2016), calibrated to version 8 of the GTAP Data Base.

GTAP data dependence

As shown in Table 1, most large-scale economic models rely on the GTAP Data Base for their core input. This database and its many extensions, including GTAP-E (energy, environment), GTAP-AEZ (land use), GTAP-BIO (biofuels), and GTAP-W (water), have greatly expanded their policy scope. Also, the database's modular structure facilitates its "plug-and-play" adaptation into various economic models. However, the widespread dependence on the GTAP data structure introduces limitations. In particular, its sectoral aggregation limits the capacity to capture evolving industries; for instance, energy-intensive industries relevant to policies like CBAM (e.g., aluminium, steel, cement, hydrogen) are often grouped withing broader sectors (e.g. "cement" under the broader "non-metallic minerals")[53]. Aggregations of this type constrain a more detailed assessment of embodied carbon.

International transportation modelling

In most, if not all, CGE frameworks, and especially those that are based on the GTAP Data Base, international transportation is typically represented as an aggregated "global transportation services sector". This sector links exporters and importers via trade margins, reflecting the difference of cost, insurance, and freight (CIF) and free on board (FOB) value (Gehlhar & McDougall, 2016). While this approach ensures some consistency and facilitates the calibration process, it cannot represent modal, geographic, or technological diversity of transport systems beyond domestic limits. This limitation has significant implications for the climate-trade nexus, since policies such as the ReFuelEU Aviation Regulation of the EU's 'Fit-for-55' package (European Parliament, 2023) cannot be assessed in sufficient detail.

To address this gap, modelling studies such as those retrieved in our literature review have been based on the linkage of CGE models with dedicated transportation models. One such recent application concerned the aviation sector. To evaluate decarbonisation policies under the ReFuelEU Aviation regulation, Wei & Kallbekken (2024) linked the AIM aviation model with the GRACE CGE model, where the setup was based on linking information such as fuel consumption and substitution. Other attempts have focused on the maritime sector, such as the study of Ferrari et al. (2023), where a maritime cost database was linked to the MAGNET model, or that of Key et al. (2024), which combined MAGNET with the Chatham House Maritime Analysis Tool to assess disruptions in critical maritime passages.

[53] GTAP-CE was launched in 2025, thus, there are no studies using this version, at least in the context of the current literature review.

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Technological change

Across the literature, a clear finding emerges regarding technological change: it is predominantly treated as exogenous. In most economic modelling frameworks, improvements in productivity and efficiency are pre-determined through external assumptions, rather than arising endogenously from innovation or market dynamics. This limitation is especially pronounced in CGE models, where technological progress is typically represented as exogenous shifts in productivity parameters. Agricultural models, such as CAPRI, incorporate exogenous yield growth derived from external projections (e.g., FAO data). However, certain PE models allow for endogenous technological progress through cost-yield relationships that respond to market signals. These endogenous mechanisms, while providing meaningful impact, remain confined to specific sectors.

In contrast, sectoral models generally offer more realistic treatments of technological change, embedding learning mechanisms, cost reductions, and substitution capabilities. Models such as TIMES and TIAM describe an energy system as a network of technologies that compete to meet the energy demand at the least cost. In such frameworks, the adoption of various technologies emerges endogenously. Similarly, global IAMs and/or IAM frameworks, such as REMIND-MAgPIE, embed feedbacks between technological investment, innovation, and emission trajectories. Nevertheless, even in IAMs and sectoral models, the representation of technical progress remains stylised. Learning rates are usually pre-calibrated from historical data rather than derived from endogenous research and development (R&D) decisions. Furthermore, the interaction between international trade and technological diffusion – a crucial mechanism for analysing the trade–climate policy nexus – is often simplified or absent (Sun & Duan, 2024).

Limitations

Our literature review on modelling capabilities allowing for trade policy assessment, in the context of this research objective (RO_1), revealed various limitations in current-generation modelling tools. Key weaknesses arise from the operationalisation of the predominantly Armington-based trade theory, the high level of sectoral aggregation, the static and short-term nature of simulations, the exogenously defined technological improvement, and the lack of explicit representation of international transport. Moreover, data constraints – especially the dependence on the GTAP Data Base, which additionally is not open access – prevent a more detailed representation of critical industrial value chains and technology-specific emissions. A more comprehensive description of the modelling limitations identified is presented in Table 3.

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Table 3. Identified modelling limitations.

	Dominance of the Armington framework: absence of firm heterogeneity and limited product differentiation in large-scale CGE models.
	Absence of bilateral trade structures: IAMs often fail to explicitly represent region-to-region trade flows.
	No modelling of international transportation: International water, air, and land transportation systems are treated as a global service represented through the difference of CIF and FOB values.
	High aggregation of energy-intensive sectors: CBAM-relevant industries (cement, steel, aluminium, fertilisers, hydrogen) are parts of broader sectors[54] (e.g. non-metallic minerals, chemical products).
	Limited presence of endogenous technological change: Efficiency improvements are usually imposed exogenously.
	Static frameworks: many studies rely on static models, thus providing only short-term insights.
	Limited policy sequencing: policies such as CBAM and retaliation are rarely analysed jointly.
	Simplified representation of carbon pricing: carbon taxes or BCAs are treated as fixed shocks rather than dynamic policy instruments.
	Narrow regional focus: many studies focus on a single country, ignoring international/global spillovers.
	Partial policy scope: analyses often ignore concurrent policies such as non-EU climate actions in the case of CBAM.
	Simplified trade policy mechanisms: border carbon adjustments are often implemented as uniform taxes, without accounting for WTO rules, or retaliatory behaviour.
	Outdated data: emerging technologies are often absent.
	No explicit emissions data: narrow representation of international transportation allows missing information on embodied carbon for international water, land, and air transportation.

6.4 Conclusions

This literature review conducted under research objective RO$_1$ provides a comprehensive overview of how different classes of economic models can treat trade policy within the climate-trade nexus. Our findings suggest that (computable) general equilibrium models dominate the field, particularly those calibrated to the GTAP Data Base. However, the majority of models do not consider firm heterogeneity, instead treating international trade through the conventional mechanism of Armington.

Partial equilibrium models play a strong role in assessing agricultural and food security policies, where sector-specific focus and detailed commodity representation are critical, though they omit economy-wide feedback. Integrated assessment models and sector-specific models incorporate technology-richer structures and often endogenise productivity and efficiency but tend to simplify bilateral trade.

Across all model types, technological change remains primarily exogenous, represented through assumptions in productivity, rather than endogenous R&D responses. Moreover, international transportation is

[54] The GTAP Circular Economy Data Base was launched within 2025, thus, the search protocol of RO$_1$ didn't capture any study using this expanded database, which allows for improved representation of critical sectors.

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usually modelled as a global service sector, meaning that non-domestic water, air, and land embodied carbon cannot be explicitly captured. This simplification limits the ability of current frameworks to evaluate the transportation-related leakage effects.

A recurring limitation also lies in the high level of sectoral aggregation, especially for energy-intensive and trade-expose industries that are relevant to carbon border policies, such as cement, steel, aluminium, fertilisers, and hydrogen. These commodities are usually parts of broader GTAP sectors (e.g., non-metallic minerals), thus preventing the analysis of competitiveness at individual commodity level.

Expectedly, our literature review reported in this section does not reflect all available models, nor the overall available modelling capabilities in this domain, as the literature review search query (see Section 6.2.1) cannot capture studies falling outside the search strings or models not applied (yet) in relevant research questions. This is why RO_1 will be complemented by RO_2 (i.e., looking into model documentations – see Section 6.2.2) as well as RO_3-RO_4 (i.e., looking into ongoing model developments and more targeted gaps within the ENTICE model ensemble).

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7 Synthesis and Research Priorities

The preceding chapters presented dedicated reviews of the economic theory, political science, and computational modelling literatures pertaining to the trade-climate-industry (TCI) nexus. This final analytical section synthesizes these disparate findings. The primary goal of this synthesis is twofold: first, to identify cross-cutting findings and shared challenges across all three fields; and second, to extract overarching insights and complementarities that can inform integrated policy design and guide future research, particularly within the ENTICE project's scope. By moving beyond siloed disciplinary perspectives, we aim to build a coherent framework for understanding the mechanisms and constraints that define the global trade and climate policy landscape.

Cross-Cutting Gaps and Challenges

Pollution represents a negative externality that distorts market efficiency and can, in principle, be corrected through a coordinated tax on emissions applied by all countries. The absence of such coordination is the defining issue at the intersection of trade and climate policy. Early studies focused on the consequences of **unilateral climate action**, particularly the risk of carbon leakage and the Pollution Haven Hypothesis (PHH), prompting empirical research on how non-harmonized carbon taxes induce a "pollution haven" effect.

However, the policy challenge has evolved from simply identifying leakage to managing the *distribution of carbon responsibility* in a way that is both environmentally effective and politically acceptable. The availability of disaggregated data and Multi-Regional Input–Output (MRIO) models has enabled the measurement of consumption-based emissions, fundamentally shifting attention toward the principle of common but differentiated responsibilities. This conceptual evolution – from solely addressing **leakage (the economic channel)** to resolving **fair responsibility (the political channel)** and then requiring **detailed quantification (the modelling channel)** – has driven a constant reassessment of appropriate policy instruments for an interconnected global economy.

Set against this backdrop, the three chapters approach the trade–climate–industry nexus from complementary angles. Chapter 4 (Economics) catalogues mechanisms and magnitudes. It structures empirical evidence around scale, composition and technique effects, showing that output expansion tends to raise emissions, sectoral reallocation effects are heterogeneous and often modest, and technique effects – driven by regulation, innovation and diffusion – are central to the medium-run decline in emission intensities. The PHH literature has evolved from early aggregate tests riddled with endogeneity concerns to more credible designs and to MRIO-based accounting that connects production and consumption footprints along global value chains. Across this evidence, findings on leakage and "pollution havens" remain context-dependent; robust cases exist, but many sectors – especially in advanced economies with strong policy frameworks – show limited relocation. The economics review also ties these results to EKC dynamics, underlining that any inverted-U relationships depend on technology change and policy, and that consumption-based emissions temper optimistic readings based solely on domestic production data.

Chapter 5 (Political science) examines the institutional design space that conditions those very mechanisms. It analyses how climate and trade policies can be crafted to reinforce each other – via carbon pricing, border carbon adjustments, green industrial policy, and environmental provisions in trade agreements – while preserving legitimacy, fairness and legal robustness. A recurring theme is that responsibility metrics (production vs. consumption accounting) shape distributive politics, North–South equity debates and the acceptability of measures such as BCAs. The chapter synthesizes ex-post evidence on the EU ETS and competitiveness, noting little observed leakage to date in regulated energy-intensive, trade-exposed sectors, and then links this to instrument design choices (e.g., free allocation, rebates, cooperation) and to WTO compatibility. It highlights the tightrope between non-discrimination rules and environmental exceptions, and how careful policy design – transparent objectives, equal treatment of imports and domestic goods, and avoidance of arbitrary discrimination – can keep measures defensible. It also situates emerging climate-club ideas and green subsidies within broader questions of international cooperation, side-payments and development impacts.

Chapter 6 (Modelling) assesses how far current quantitative tools can operationalize these questions. The review finds that most global models rely on the GTAP Data Base and adopt Armington trade structures, with limited representation of firm heterogeneity and entry–exit dynamics. Technological progress is often imposed exogenously; simulations are frequently static or short-run; sectoral aggregation remains high, especially for EITE and CBAM-relevant commodities; and international transport is typically treated as an aggregate margin rather than an explicit sector with technology and policy levers. These features facilitate tractability and comparability but constrain the ability to evaluate border measures, green-industrial subsidies, responsibility shifts along GVCs, and transport-specific policies with the granularity highlighted by the other chapters.

Taken together, convergences and tensions are clear. All three chapters foreground the importance of responsibility accounting: economics documents the empirical salience of consumption-based emissions; political science translates this into fairness and coalition-building concerns; modelling, however, rarely embeds consumer-side instruments or club-style accounting rules in a way that captures their distributional and strategic implications. Likewise on leakage and competitiveness, economics provides mixed but bounded magnitudes; political science shows how design choices can mitigate risks and retain legitimacy; modelling can quantify counterfactuals but tends to stylize complex instruments (e.g., BCAs) as simple taxes, abstracting from administrative frictions and legal constraints that matter for real-world outcomes. On innovation, economics attributes much of the emissions-intensity decline to technique effects, and political debates revolve around subsidy design and diffusion; yet most models still treat technology as exogenous, limiting assessment of R&D, learning and trade-mediated spillovers that are central to policy. Finally, both economics and governance analyses emphasize GVC fragmentation and the role of aviation and maritime transport in embodied emissions, while modelling often collapses transport into a generic margin, making it hard to test route-, mode- or technology-specific measures.

Each strand nonetheless contributes distinct value to a coherent narrative. Economics delineates plausible channels and orders of magnitude, warning against over-interpreting PHH or EKC results without attention to technology and accounting boundaries. Political science maps the feasible policy space – how rules, norms and coalitions can align trade with decarbonization without triggering illegality or backlash – and identifies equity conditions for durable cooperation. Modelling offers a laboratory for policy packages and scenario exploration; its main gaps are not conceptual but representational: trade structures that miss firm-level margins, sectoral aggregation that blurs technology pathways, exogenous innovation that mutes policy-induced change, and thin treatment of bilateral flows and transport.

Implications for the ENTICE Project

For ENTICE, the synthesis implies three priorities.

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Priority 1: Aligning Modelling Capabilities. Align modelling capabilities with the empirical and governance questions: introduce richer trade structures (e.g., heterogeneity or hybrid approaches beyond pure Armington), increase disaggregation for EITE/CBAM-relevant sectors, represent international transport explicitly, and move toward more endogenous technology (learning, diffusion, and R&D).

Priority 2: Evaluating Realistic Policy Packages. Evaluate realistic policy packages rather than isolated instruments, combining BCAs with export-rebate rules, subsidy designs attentive to trade law, environmental provisions in trade agreements, and club-style incentives and finance, including revenue recycling that addresses distributional concerns for developing exporters.

Priority 3: Tracking Indicators and Dynamics. Track both production- and consumption-based indicators in scenarios and analyze policy sequencing and dynamics – such as the phase-out of free allocation alongside CBAM ramp-up, subsidy sunsets and potential retaliation – so that the quantitative analysis speaks directly to the mechanisms and constraints identified in the economics and political-science literatures.

This alignment will enable the project to stress-test governance designs against empirically grounded channels and produce policy-relevant insights on the trade–climate–industry interface.

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