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L'étrange cas du Dr. Compétitivité et de M. Climat

Une évaluation de la compatibilité entre décarbonation et compétitivité industrielles au sein de l'UE

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***

Abstract

English

DECARBONIZING heavy industry is essential for the EU to meet its climate goals yet concerns over competitiveness and carbon leakage have hindered the adoption of more ambitious policy measures. This thesis explores whether decarbonization and competitiveness can coexist in the EU's heavy industry. Using sector- and firm-level data, it employs econometric analysis, deterministic programming, economic modeling, and a systematic literature review. The findings show that carbon leakage risks during Phase 3 of the EU Emissions Trading Scheme were minimal, and that standard *ex ante* assessments often overestimate leakage by ignoring market structure. Additionally, the analysis reveals that neither green patenting nor efficiency gains alone are sufficient for firms to meet climate targets given current technological trends. Together, these results suggest that a balanced and targeted policy approach is needed to drive deep decarbonization without sacrificing industrial competitiveness.

Français

L'UE doit rapidement décarboner son industrie lourde pour atteindre ses objectifs climatiques. A ce jour, les craintes de fuites de carbone ont freiné l'adoption de politiques climatiques assez ambitieuses. Cette thèse s'interroge sur la possibilité de concilier décarbonation et compétitivité industrielle. Elle s'appuie sur des données sectorielles et d'entreprise, et mobilise des méthodes variées : analyse économétrique, programmation déterministe, modélisation économique et revue systématique de la littérature. Les résultats indiquent un risque faible de fuites de carbone durant la Phase 3 du marché du carbone européen, et que les évaluations *ex ante* surestiment souvent ce risque en négligeant la structure des marchés. L'analyse montre aussi que les brevets verts et les gains d'efficacité technique ne suffisent actuellement pas aux objectifs climatiques de l'UE. Ces résultats plaident pour une politique ciblée capable de concilier ambition climatique et compétitivité industrielle.

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Thesis summary

DECARBONIZING heavy industry is both essential and urgent for the European Union (EU) to meet its climate objectives. However, concerns about industrial competitiveness and carbon leakage have hindered the adoption of more ambitious policy measures. This thesis examines this apparent contradiction and assesses whether decarbonization and competitiveness can go hand-in-hand in the EU's heavy industry.

Chapter 1 systematically reviews the literature on carbon leakage and border adjustments to identify areas of consensus and gaps in existing research. It highlights three key gaps addressed in the subsequent chapters of the thesis: (1) explaining the divergence between *ex ante* and *ex post* estimates of carbon leakage; (2) evaluating the impacts of the EU ETS on heavy industry firms beyond Phase II; and (3) understanding the role of green innovation in shaping production and emissions dynamics within EU ETS-covered firms.

Chapter 2 addresses research gap (1) by developing a novel *ex ante* measure of carbon leakage risk that incorporates market structure—an element often overlooked in previous studies. Using the hypothetical monopolist test, the analysis demonstrates that leakage risks in the steel and cement sectors have likely been overstated in earlier assessments due to their failure to account for market structure.

To address research gap (2), Chapter 3 investigates the impact of decarbonization on firm-level economic and financial outcomes during Phase III of the EU ETS. Drawing on a micro-level panel econometric approach, the chapter finds that even during this period—when carbon allowance prices began to rise meaningfully—decarbonization did not adversely affect corporate performance in heavy industry sectors.

Chapter 4 adopts a dynamic perspective to examine the technological frontier of heavy industry firms regulated under the EU ETS during Phase III. The analysis highlights that green patenting and efficiency improvements will not be sufficient for industrial firms to achieve their climate objectives. Deeper technological and structural changes are necessary for meaningful decarbonization.

Taken together, this thesis advances the literature on EU climate policy and industrial competitiveness through four main contributions: (1) a comprehensive synthesis of the existing research, (2) novel static analyses of carbon leakage mechanisms in recent years, (3) a dynamic exploration of technological change and its implications for long-term competitiveness, and (4) a new and open-source method to match micro-level databases that do not have a common identifier.

Résumé de thèse court

L'Union européenne (UE) doit rapidement décarboner son industrie lourde pour atteindre ses objectifs climatiques. Toutefois, les craintes liées à une perte de compétitivité et aux fuites de carbone ont freiné l'adoption de politiques climatiques suffisamment ambitieuses. Cette thèse examine cette contradiction apparente et évalue si décarbonation et compétitivité peuvent aller de pair dans l'industrie lourde européenne.

Le Chapitre 1 propose une revue systématique de la littérature sur les fuites de carbone et les ajustements carbone aux frontières. Il fait le point sur les connaissances existantes et met en évidence trois principales questions auxquelles la littérature actuelle ne répond pas : (1) comment expliquer les divergences entre les estimations *ex ante* et *ex post* des risques de fuite de carbone ; (2) quels ont été les effets de la troisième phase (2013–2020) du marché du carbone européen (EU ETS pour l'anglais *EU Emissions Trading Scheme*) sur les firmes industrielles ; et (3) quel est le rôle de l'innovation verte dans les dynamiques de production et d'émissions des entreprises couvertes par l'EU ETS.

Le Chapitre 2 traite la question (1) en développant une mesure *ex ante* des risques de fuites de carbone intégrant la structure de marché des producteurs industriels - un facteur souvent négligé dans les études existantes. En s'appuyant sur le test du monopoleur hypothétique, cette nouvelle mesure est appliquée à quatre produits issus des secteurs du ciment et de l'acier, et montre que les risques ont probablement été surestimés dans la littérature existante.

Pour répondre à la question (2), le Chapitre 3 étudie l'impact de la décarbonation sur les performances économiques et financières des firmes industrielles régulées pendant la troisième phase de l'EU ETS. À partir d'une analyse économétrique de panel au niveau microéconomique, il montre que, malgré la hausse marquée du prix des quotas, la décarbonation n'a pas eu d'effet négatif sur les résultats des entreprises concernées.

Le Chapitre 4 adopte une perspective dynamique en analysant la frontière technologique des firmes industrielles régulées par l'EU ETS durant la phase III. L'analyse met en évidence que les brevets verts et les améliorations en termes d'efficacité technique ne sont pas suffisants pour que l'industrie lourde européenne atteigne ses objectifs cli-

matiques. Des changements structurels et technologiques plus profonds sont nécessaires pour cela.

Dans l'ensemble, cette thèse contribue à la littérature sur les liens entre politique climatique et compétitivité industrielle en Europe à travers quatre apports majeurs : premièrement, une synthèse systématique de la littérature existante pour identifier ses lacunes et contradictions ; deuxièmement, une analyse statique des mécanismes de fuites de carbone dans la troisième phase de l'EU ETS ; troisièmement, un examen prospectif de la manière dont les changements technologiques peuvent remodeler la compétitivité industrielle à long terme ; et quatrièmement, une nouvelle méthode mise à disposition publique pour fusionner des bases de données micro-économiques n'ayant pas d'identifiant commun.

Résumé de thèse long

R.1 Introduction

R.1.1 Une brève introduction au Dr Compétitivité et à M. Climat

L'ouvrage de Robert Louis Stevenson, *L'Etrange Cas du Dr Jekyll et de M. Hyde*, dépeint le contraste saisissant entre l'aimable et respecté Dr Jekyll et son alter ego maléfique M. Hyde. Tout comme Stevenson questionne comment des traits si opposés peuvent coexister au sein d'un même individu, cette thèse étudie la relation entre compétitivité et décarbonation au sein de l'industrie lourde de l'Union Européenne (UE). Ces deux forces peuvent-elles être complémentaires ? Ou bien faut-il les considérer comme des priorités intrinsèquement contradictoires ? Loin d'être des considérations abstraites, ces questions sont au cœur des débats politiques actuels.

M. Climat. Au cours des trente dernières années, les décideurs politiques de l'UE n'ont cessé de « poursuivre la cible mouvante de politiques climatiques suffisamment ambitieuses » (Dupont et al., 2024) en étendant les politiques climatiques de l'Union à un nombre croissant de secteurs et en les rendant progressivement plus strictes. Malgré cette évolution encourageante, les politiques climatiques de l'UE ne sont toujours pas à la hauteur de ses ambitions (EEA, 2024a, 2024b).

Le secteur industriel représente un défi particulier: il contribue à la hauteur de 20% aux émissions de gaz à effets de serre (GES) totales de l'UE mais est considéré comme « difficile à décarboner » (EEA, 2024a, 2024b; Kumar et al., 2024). Ce secteur a été intégré aux politiques climatiques de l'UE en 2005 avec l'introduction du système européen d'échange de quotas d'émission (EU ETS pour l'anglais *EU Emissions Trading Scheme*; European Parliament and Council, 2003). Depuis, l'EU ETS a été amendé à plusieurs reprises pour devenir de plus en plus contraignant. Vingt ans plus tard, ce marché du carbone reste l'un des piliers principaux de la politique climatique européenne.

Dr Compétitivité. Compte tenu de la volonté de l'UE d'être un leader mondial en matière d'action climatique, pourquoi un décalage important entre ses politiques et ses objectifs climatiques persiste-t-il ? L'une des principales raisons pour cela réside dans la fragmentation des politiques climatiques mondiales (Clausing & Wolfram, 2023; Weber et al., 2025), qui suscite des craintes de fuites de carbone et de pertes de compétitivité chezs les responsables politiques européens (Markusen, 1975; Markusen et al., 1993).

Récemment, l'ambition de maintien de compétitivité économique et industrielle a pris une place plus centrale dans les politiques de l'UE (Weber et al., 2025).[1] Cette ambition a été alimentée par les vulnérabilités révélées lors de la crise du COVID-19 (Gelles et al., 2025), les dépendances matérielles vis-à-vis de la Chine (Gielen, 2021), et le revirement des États-Unis en matière de politiques climatiques depuis l'investiture du président Trump en 2025.[2] Pour répondre à cet objectif de compétitivité, l'UE a dévoilé son « Compas de la Compétitivité » en janvier 2025, une nouvelle feuille de route politique visant à « préserver l'avenir de l'UE en tant que puissance économique » tout en maintenant son ambition climatique (Draghi, 2024; European Commission, 2019, 2021b; Grubb et al., 2022).[3]

Cette thèse. Cette thèse s'inscrit dans le contexte mouvant des préoccupations européennes liées à la compétitivité et la décarbonation industrielles. Les quatre chapitres qui la constituent étudient chacun une dimension spécifique de la question suivante : **la décarbonation et la compétitivité peuvent-elles aller de pair au sein de l'industrie lourde de l'UE ?**

R.1.2 Intérêt de la recherche

Quels sont les enjeux de la question de recherche ?

Le changement climatique est une menace existentielle pour l'humanité. A ce jour, les émissions de GES humaines ont provoqué une hausse de 1,1°C des températures moyennes mondiales par rapport à la période 1850-1900, ce qui entraîne une augmentation d'événements météorologiques extrêmes dans la plupart des régions du monde et des

[1] Voir l'article d'E3G, qui analyse comment l'UE fait désormais de la compétitivité une priorité politique absolue : https://www.e3g.org/publications/europe-s-competitiveness-push-and-what-it-means-for-climate-action/

[2] Voir l'article du New York Times détaillant les mesures prises par le président Trump pour supprimer les politiques climatiques et environnementales aux États-Unis : https://www.nytimes.com/2025/03/02/climate/trump-us-climate-policy-changes.html (Gelles et al., 2025).

[3] Voir l'article « *Carbon leakage concerns dominate EU ETS debate* » publié par ENDS Europe, un média spécialisé sur les questions environnementales européennes : https://www.endseurope.com/article/1640202/carbon-leakage-concerns-dominate-eu-ets-debate?utm_source=website&utm_medium=social

dommages irréversibles à presque tous types d'écosystèmes (IPCC, 2023). Si les défis posés par le changement climatique sont considérables, l'humanité dispose pourtant de tous les outils nécessaires pour y faire face - les politiques publiques représentant une option particulièrement efficace (Stern, 2008). Cela étant, les mesures actuelles restent insuffisantes dans toutes les régions du monde, y compris au sein de l'UE.

Qu'est-ce qui empêche donc les décideurs européens d'agir plus fermement ? La réponse est bien sûr complexe et multidimensionnelle. Cette thèse se concentre sur un obstacle majeur : la crainte de pertes de compétitivité et de fuites de carbone, qui freine l'adoption de politiques climatiques plus ambitieuses.

Pourquoi s'intéresser à l'industrie lourde ?

Les matériaux industriels façonnent notre monde - du béton qui compose nos bâtiments et nos routes aux produits chimiques utilisés dans les pesticides pour notre agriculture, en passant par l'acier présent dans nos voitures, trains et avions. De plus, l'industrie lourde est indissociable de l'identité économique et culturelle de l'UE. En effet, l'UE est née d'une vision d'intégration fondée sur la coopération industrielle, notamment à travers « la mise en commun des productions de charbon et d'acier [qui a assuré] l'établissement [de] la première étape de la Fédération européenne [...] » (Schuman, 1950). Au fil des années, la politique industrielle européenne a évolué, mais n'a cessé de renforcer le rôle moteur de l'industrie lourde dans la croissance économique et l'identité régionale de l'UE (Kirk et al., 2012; Tagliapietra & Veugelers, 2023).

Ce legs industriel comporte toutefois des coûts environnementaux et humains importants: au-delà de la part importante d'émissions de GES provenant de l'industrie (EEA, 2024a), ce secteur est responsable de la diffusion massive de microplastiques toxiques dans l'air, l'eau et les écosystèmes (Eberhard et al., 2024; Li et al., 2023), ainsi que des résidus de pesticides qui imprègnent notre atmosphère et notre chaîne alimentaire (Ahmad et al., 2024).

Cette dualité crée un paradoxe : l'industrie lourde reste ancrée dans le tissu économique et culturel européen, mais sa forme actuelle est incompatible avec les objectifs climatiques de l'UE. Atteindre ces objectifs nécessite des transformations profondes et systémiques de la structure industrielle européenne (IPCC, 2023). Ces mutations ne peuvent s'improviser - elles exigent une analyse rigoureuse pour en atténuer les retombées économiques et sociales indésirables, notamment en termes de justice sociale et de pertes économiques.

Pourquoi prendre l'UE comme cas d'étude ?

L'UE s'est fixé pour objectif d'être un modèle mondial dans la lutte contre le changement climatique et poursuit cette ambition à travers des initiatives comme le Pacte vert pour l'Europe - projet phare d'Ursula von der Leyen lors de son premier mandat à la présidence de la Commission Européenne. Cette position de l'UE en fait un cas d'étude particulièrement intéressant pour analyser l'équilibre de politiques publiques ciblant action climatique et compétitivité économique.

Communiqué de presse d'Ursula von der Leyen accompagnant le Pacte verte pour l'Europe
(von der Leyen, 2019)

> « *Nous voulons être le leader en industrie verte, en technologies propres et en finance verte.* »

Le rôle moteur de l'UE se justifie également par sa responsabilité historique et géopolitique. Bien que ne représentant que 5% de la population mondiale, l'UE est à l'origine de 15 à 25% des émissions historiques de GES (Friman & Strandberg, 2014), ce qui lui confère une responsabilité disproportionnée dans le changement climatique. En plus de ceci, le principe de « responsabilités communes mais différenciées » de la Convention-cadre des Nations-Unies sur les changements climatiques (CCNUCC) souligne que les économies développées comme l'UE ont une capacité importante - et donc une obligation particulière - à mener les efforts de décarbonation.[4]

D'un point de vue académique, l'UE constitue également un cas d'étude particulièrement pertinent grâce à ses vingt ans d'expérience dans la mise en œuvre de politiques climatiques industrielles. Ce recul historique fournit des données empiriques riches et une littérature académique bien établie, qui ont toutes deux servi de fondement à cette thèse.

R.1.3 Trame de la thèse

La thèse commence par un chapitre qui fait une revue systématique de la littérature sur les fuites de carbone et les ajustements carbone aux frontières. Ce chapitre fait état des connaissances sur ces sujets et met en exergue les points importants n'ayant pas encore été étudiés par la littérature économique. Cette analyse met en évidences trois questions primordiales n'ayant pas encore de réponse:

[4]Voir l'explication de la CCNUCC sur ce sujet : https://unfccc.int/news/the-explainer-the-paris-agreement.

1. Comment expliquer les divergences entres les estimations *ex ante* et *ex post* des risques de fuites de carbone ?

2. Quels sont les impacts de la troisième phase (2013-2020) plus contraignante de l'EU ETS sur les firmes industrielles qui y sont soumises ?

3. Quel est le rôle de l'innovation verte dans les dynamiques de production et d'émission de ces firmes ?

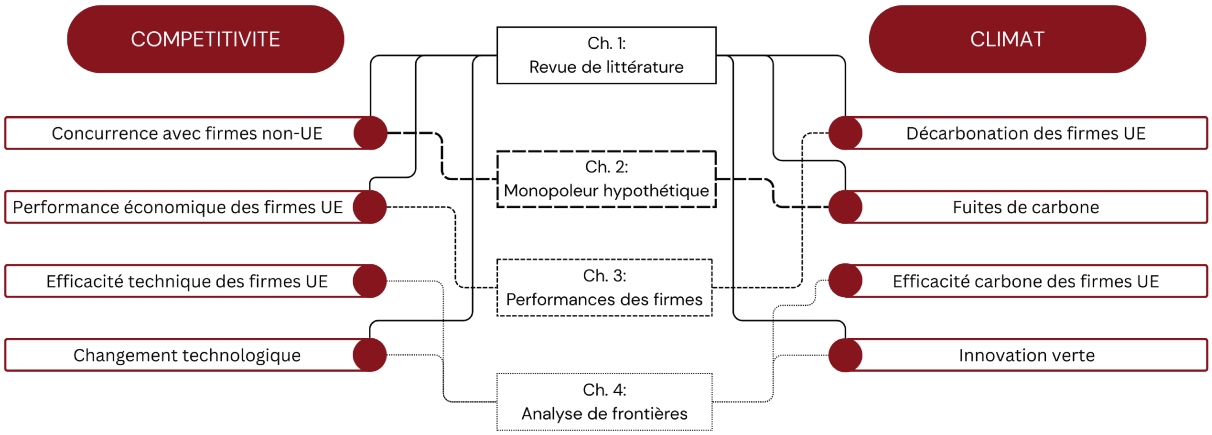
Le chapitre 2 aborde la question (1) en proposant une mesure *ex ante* des risques de fuites de carbone qui prend en compte la structure de marché des producteurs industriels. Ce facteur est souvent négligé dans les études *ex ante*, ce qui entraîne une surestimation des risques de fuites de carbone. La nouvelle mesure proposée dans ce chapitre se base sur le test du monopoleur hypothétique et est appliquée à quatre produits provenant des secteurs du ciment et de l'acier: le clinker, le ciment hydraulique, les produits d'acier plat et les produits d'acier long.

Pour répondre à la question (2), le chapitre 3 étudie l'impact de la décarbonation sur les résultats économiques et financiers de firmes industrielles soumises à l'EU ETS pendant sa troisième phase. Sur la base d'une analyse économétrique de panel au niveau microéconomique, ce chapitre constate que même au cours de cette phase, pendant laquelle les prix des quotas ont largement augmenté, la décarbonation n'a pas eu d'effet négatif sur les résultats des firmes étudiées.

Enfin, le chapitre 4 adopte une perspective dynamique en analysant la frontière technologique des firmes industrielles de l'EU ETS. L'analyse met en évidence que les brevets verts et les améliorations en termes d'efficacité technique ne sont pas suffisants pour que l'industrie lourde européenne atteigne ses objectifs climatiques. Des changements structurels et technologiques plus profonds sont nécessaires pour cela.

Dans l'ensemble, cette thèse fournit quatre contributions principales à la littérature sur le lien entre la politique climatique de l'UE et la compétitivité industrielle : premièrement, une revue systématique de la littérature existante ; deuxièmement, des analyses empiriques statiques portant sur les mécanismes sous-jacents aux fuites de carbone au cours de la troisième phase de l'EU ETS ; troisièmement, une étude des changements technologiques des firmes industrielles affectant leur compétitivité de long terme ; et quatrièmement, une nouvelle méthode mise à disposition publique pour fusionner des bases de données micro-économiques n'ayant pas d'identifiant commun. Le graphique R.1 offre une vue d'ensemble des principaux concepts étudiés et des chapitres où ils sont respectivement abordés.

Figure R.1: Résumé graphique de la thèse



Source: Auteure.

R.2 Chapitre 1 - Le cas des fuites de carbone et des ajustements carbone aux frontières : Où en est la science économique ?

R.2.1 Introduction

Lors de la mise en œuvre de l'EU ETS et de ses amendements successifs, les responsables politiques européens ont dû se questionner sur les effets qu'aurait ce marché sur les relations économiques de l'UE avec des pays extra-européens. En effet, si le surcoût de l'EU ETS s'avérait suffisamment important pour désavantager les producteurs européens par rapport à leurs concurrents hors-UE, ces premiers pourraient perdre des parts de marché ou décider de délocaliser leurs activités en dehors de l'UE. Ce problème est connu sous le nom de fuites de carbone (Naegele & Zaklan, 2019).

Le concept de fuites de carbone est le plus souvent compris comme un mécanisme par lequel les entreprises nationales réglementées perdent leur avantage concurrentiel au profit des entreprises en dehors de la zone réglementée. Cependant, ce mécanisme ne constitue que l'un des trois canaux par lesquels les fuites de carbone peuvent se produire, connu sous le nom de canal de la concurrence. Le deuxième canal est le canal de l'énergie et le troisième est le canal de l'innovation.

Ce chapitre a trois objectifs principaux. Premièrement, il présente le contexte et les débats politiques autour des fuites de carbone et des ajustements carbone aux frontières (ACF) au sein de l'UE. Deuxièmement, il présente l'état de la littérature économique sur les fuites de carbone par les trois canaux nommés ci-dessus et sur les ACF. Enfin,

il présente les limites principales de cette littérature et propose des pistes de recherche pour repousser ces limites.

R.2.2 Contexte politique et institutionnel

Le sujet des fuites de carbone est discuté dans la sphère politique européenne depuis la création de l'EU ETS. Cependant, ce n'est qu'à partir de la troisième phase du marché (2013-2020) que le sujet a réellement commencé à prendre de l'ampleur. En effet, pendant les deux premières phases du marché (2005-2012) les quotas carbones étaient distribués aux firmes gratuitement et le prix du carbone est resté bas, en-deçà de 30€ par tonne de carbone, ce qui a par conséquent largement réduit la contrainte imposée et les risques de fuites de carbone (Joltreau & Sommerfeld, 2019).

Néanmoins, l'allocation gratuite des quotas d'émission a créé des distorsions et des inefficacités sur le marché (Hepburn et al., 2006), ce qui a entraîné une révision de cette politique pendant la préparation de la troisième phase du marché. Pendant cette troisième phase, l'allocation gratuite des quotas carbones a été réduite progressivement à la faveur d'une mise aux enchères de ces quotas. Ce changement qui imposait un coût plus important sur les firmes de l'EU ETS et a relancé les débats autour des risques de fuites de carbone et de l'urgence d'adopter des mesures compensatoires.

C'est à cette époque que l'idée d'un ACF a commencé à gagner du terrain pour la première fois - bien qu'il n'ait pas été mis en œuvre à ce stade. La proposition était de mettre en place un ACF qui remplacerait les allocations gratuites de quotas, tout en protégeant les firmes européennes de concurrents non soumis à l'EU ETS en leur imposant un prix du carbone équivalent à la frontière. Le débat sur le remplacement des allocations gratuites par un ACF a été relancé avant le lancement de la quatrième phase de l'EU ETS (2021-2030). Rompant avec sa ligne politique précédente, la Commission Européenne a annoncé dans son Pacte vert de 2020 qu'elle présenterait une proposition d'ACF pour remplacer progressivement les allocations gratuites dans la quatrième phase de l'EU ETS (European Commission, 2021a).

Ce chapitre propose une revue systématique de la littérature économique sur les risques de fuites de carbone par trois différents canaux et sur les ACF. Ceci permet de mettre en perspective le contexte politique et institutionnel présenté ci-dessus en mettant en lumière les divergences entre compréhension politique et académique.

R.2.3 Le canal de la concurrence

Comment fonctionne le canal de la concurrence ?

Les fuites de carbone par le canal de la concurrence se produisent lorsqu'un pays ou une région met en œuvre une politique environnementale plus contraignante que celle d'autres pays ou régions. Les producteurs réglementés par cette politique subissent des coûts supplémentaires pour se conformer à la réglementation, ce qui les désavantage par rapport aux producteurs établis hors de la zone de réglementation. Cette perte d'avantage concurrentiel peut avoir deux conséquences : les producteurs réglementés peuvent perdre des parts de marché au profit de concurrents non réglementés ou choisir de délocaliser leurs activités vers des pays ou régions aux politiques environnementales moins strictes. Le canal de la concurrence a été initialement formalisé à l'aide de la théorie des jeux, qui modélise les échanges internationaux comme un jeu stratégique entre partenaires commerciaux (Hoel, 1991; Markusen et al., 1993).

L'EU ETS a-t-il engendré des fuites de carbone par le canal de la concurrence ?

Différentes approches méthodologiques ont été employées pour tester empiriquement la présence de fuites de carbone attribuables à l'EU ETS. Verde (2020) recense quatre principales méthodes : (1) des études microéconomiques évaluant l'impact de l'EU ETS sur des indicateurs de compétitivité (valeur ajoutée, emploi, productivité totale des facteurs) au niveau des entreprises ou des secteurs ; (2) des évaluations cherchant à identifier des délocalisations d'entreprises ; (3) des recherches sur les transferts d'émissions carbone entre régions ; (4) des études sur l'impact des prix des quotas de l'EU ETS sur les cours boursiers des entreprises réglementées.

La conclusion générale de ces quatre courants de recherche est que les fuites de carbone ne semblent pas s'être matérialisées sous l'effet de l'EU ETS. Ces études présentent néanmoins une limite importante : la plupart d'entre elles ne couvrent que les deux premières phases de l'EU ETS - et parfois le début de la troisième phase. Durant cette période caractérisée par une allocation gratuite majoritaire et des prix du carbone faibles, les conditions étaient sensiblement différentes de la situation actuelle où les prix ont triplé et où la mise aux enchères des quotas carbone a progressivement remplacé les allocations gratuites.

Quels facteurs influencent les fuites de carbone selon les modèles d'équilibre général *ex ante* ?

Les modèles d'équilibre général calculable (MEGC) constituent l'outil privilégié pour évaluer quantitativement les risques de fuites de carbone dans divers scénarios politiques et économiques de long terme. Ces modèles permettent d'identifier les conditions favorisant d'importantes fuites de carbone, les mesures politiques susceptibles d'atténuer ces risques, ainsi que les paramètres comportementaux et contextuels aggravants ou atténuants.

La littérature des MEGC montre qu'en dépit d'une incertitude quant à l'ampleur exacte des fuites induites par un prix du carbone, un consensus émerge sur deux points : (1) plus la tarification du carbone est contraignante, plus les risques de fuites de carbone augmentent, et (2) plus il y a de pays qui tarifient le carbone, plus ces risques diminuent. Parmi les facteurs influençant significativement les valeurs estimées de fuites de carbone figurent notamment les élasticités-prix croisées internationales et les hypothèses relatives à la structure des marchés.

R.2.4 Le canal de l'énergie

Comment fonctionne le canal de l'énergie ?

Les fuites de carbone par le canal de l'énergie sont un phénomène macroéconomique qui résulte d'une variation importante des prix sur les marchés internationaux de l'énergie. Lorsqu'une région renforce ses politiques climatiques et entame une transition de son système énergétique vers l'abandon des combustibles fossiles, sa demande intérieure en énergies fossiles diminue progressivement pour tendre vers zéro à long terme. Cette diminution de la demande exerce une pression à la baisse sur les prix mondiaux de ces produits. En conséquence, les producteurs des régions non réglementées sont incités à augmenter leur consommation d'énergies fossiles (Arroyo-Currás et al., 2015).

Quelle est l'ampleur des fuites via le canal de l'énergie ?

Le canal de l'énergie a été majoritairement étudié à travers des MEGC. Les méthodes empiriques n'ont pas pu être employées en raison de l'absence de chocs de demande sur les marchés internationaux de l'énergie résultant de politiques environnementales strictes. Les MEGC tendent à montrer que le canal de l'énergie a le potentiel de générer plus de fuites de carbone que le canal de la concurrence sur le long terme.

R.2.5 Le canal de l'innovation

Comment fonctionne le canal de l'innovation ?

Le canal de l'innovation fonctionne à l'inverse des deux autres canaux : il permet de réduire les émissions de GES à la fois dans la région qui impose une politique climatique contraignante et dans la région qui n'en impose pas. Ce processus peut être divisé en trois étapes. Dans la *première étape*, les politiques climatiques incitent les entreprises réglementées à investir dans la recherche et l'innovation bas-carbone, ce qui réduit leurs émissions sur le long terme. Ce mécanisme correspond à la forme faible de l'hypothèse de Porter (Porter, 1991; Porter & van der Linde, 1995). Dans la *deuxième étape*, ces innovations bas-carbone se diffusent vers les pays avec des politiques climatiques inexistantes ou non contraignantes. Enfin, la *troisième étape* intervient lorsque ces innovations sont adoptées par les entreprises des régions non réglementées, réduisant ainsi l'intensité carbone de leur production et abaissant leurs émissions.

Comment le canal de l'innovation est-il modélisé dans les modèles d'équilibre général ?

La plupart des MEGC intègrent le progrès technique comme un paramètre exogène fixe, ne tenant ainsi pas compte du canal de l'innovation. Certaines études estiment cependant que cette omission peut conduire à une surestimation significative du taux de fuites de carbone. Di Maria and Van Der Werf (2008) développent un cadre théorique qui étudie cet argument en endogénéisant le changement technologique. Gerlagh and Kuik (2014) testent ce cadre théorique dans un MEGC qui incorpore un progrès technologique endogène et orienté vers les technologies vertes. Leurs résultats montrent que le taux de fuites peut devenir négatif avec des niveaux modérés de diffusion technologique entre régions.

Quelles sont les preuves empiriques de l'existence du canal de l'innovation ?

Un consensus se dégage dans la littérature concernant la *première étape* du canal de l'innovation. Une majorité d'études trouve une relation positive et statistiquement significative entre les politiques climatiques et l'innovation verte. Certaines de ces études montrent spécifiquement que l'EU ETS a stimulé l'innovation bas-carbone (Teixidó et al., 2019). En revanche, peu d'études ont examiné l'impact de cette activité innovante sur la performance environnementale des entreprises, mesurée à la fois en termes d'intensité carbone et d'émissions totales.

Les études empiriques de la *deuxième étape* du canal de l'innovation analysent la diffusion des technologies vertes depuis des pays réglementés vers des pays non réglementés. Ces études révèlent une concentration des innovations vertes brevetées dans un nombre restreint de pays - principalement les États-Unis, le Japon, l'Allemagne et, plus récemment mais dans une moindre mesure, la Chine. Les transferts technologiques depuis les pays à haut revenu bénéficient principalement à d'autres pays à haut revenu, impliquant une faible diffusion hors zones réglementées.

Enfin, les preuves empiriques concernant la *troisième étape* du canal de l'innovation demeurent très limitées. Aucune étude ne s'est spécifiquement penchée sur la manière dont les transferts de technologies bas-carbone améliorent la performance environnementale et/ou la productivité de firmes dans des pays non réglementés.

R.2.6 Comment concevoir un ajustement carbone aux frontières ?

Les modèles MEGC s'accordent sur le fait qu'un ACF réduirait les fuites de carbone par le canal de la concurrence. Toutefois, l'ampleur de cette réduction ne parait pas très importante. Certains éléments peuvent néanmoins accroître l'efficacité d'un ACF : par exemple en couvrant le plus de secteurs économiques possibles et en utilisant un niveau de référence du contenu carbone de produits importés qui est mesuré de manière très désagrégée et spécifique au pays exportateur.

Les MEGC concluent généralement que si un ACF peut agir sur le canal de la concurrence, il reste inefficace contre le canal de l'énergie (Kuik & Hofkes, 2010). Cependant, un ACF peut servir d'outil stratégique pour inciter les pays non réglementés à adopter leurs propres régulations climatiques (Böhringer et al., 2016), atténuant ainsi les fuites par le canal de l'énergie. Le processus de mise en œuvre de l'ACF est également important : une approche collaborative permettrait à l'UE de mieux tenir compte des législations hors-UE dans l'ACF, encourageant les partenaires commerciaux de l'UE à instaurer leur propre tarification carbone.

Enfin, les décideurs politiques pourraient augmenter l'incitation à générer et diffuser des innovations vertes en réinvestissant les recettes de l'ACF dans un fonds international pour l'innovation verte.

R.2.7 Conclusion

Cette revue de la littérature met en lumière un décalage entre la littérature économique et les débats politiques concernant les fuites de carbone et les ACF. Les politiques

publiques actuelles négligent l'impact potentiel des canaux de l'énergie et de l'innovation. Pourtant, ces deux canaux pourraient fortement influencer les taux de fuites globaux, et peuvent être façonnés par la conception de politiques climatiques et de l'ACF européen. Les décideurs politiques européens devraient donc :

- Minimiser l'impact du canal de l'énergie en établissant une stratégie de coopération renforcée avec les pays non réglementés et en prenant en compte leurs initiatives de tarification carbone;
- Maximiser l'effet du canal de l'innovation en favorisant le développement et le transfert de technologies vertes et en créant un fonds technologique international financé par les recettes de l'ACF.

Cette analyse met aussi en évidence trois questions de recherche primordiales n'ayant pas encore de réponse dans la littérature académique. (1) Comment expliquer les divergences entres les estimations *ex ante* et *ex post* des risques de fuites de carbone ? (2) Quels sont les impacts de la troisième phase (2013-2020) plus contraignante du marché du carbone européen sur les firmes industrielles régulées ? (3) Quel est le rôle de l'innovation verte dans les dynamiques de production et d'émission de ces firmes ?

R.3 Chapitre 2 - Attention au marché: Une nouvelle mesure des risques de fuites de carbone

R.3.1 Introduction

Afin de respecter son objectif de neutralité carbone d'ici à 2050, l'UE doit rapidement réduire ses émissions industrielles. Bien que des politiques climatiques ambitieuses soient nécessaires pour inciter les entreprises à se décarboner, les craintes de fuites de carbone ont freiné leur mise en œuvre. Les associations industrielles invoquent l'argument des fuites de carbone pour faire pression sur les politiques (Fagan-Watson et al., 2015),[5] et les décideurs politiques considèrent ces fuites comme un risque majeur pour l'efficacité des politiques climatiques et la compétitivité de l'UE (Draghi, 2024; European Commission, 2019, 2021b). En revanche, les groupes environnementaux rejettent cet argument comme

[5]Voir également l'article intitulé "*Carbon leakage concerns dominate EU ETS debate*" publié par ENDS Europe, un média spécialisé dans l'actualité environnementale européenne, disponible à l'adresse https://www.endseurope.com/article/1640202/carbon-leakage-concerns-dominate-eu-ets-debate?utm_source=website&utm_medium=social.

étant un simple prétexte visant à bloquer des politiques climatiques plus strictes (Carbon Market Watch, 2015). Un véritable consensus sur l'ampleur des risques de fuites de carbone reste difficile à trouver dans les sphères de politique publique.

L'une des questions clés pour arriver à un consensus est de savoir comment définir une mesure équitable et transparente des risques de fuites de carbone. Définir une telle mesure est essentiel pour concevoir des politiques qui empêchent les fuites de carbone sans compromettre l'efficacité des politiques climatiques (Cosbey et al., 2019). Ce chapitre contribue à la littérature en proposant une nouvelle approche de l'évaluation des risques de fuites de carbone : l'application du test du monopoleur hypothétique - également connu sous le nom de test SSNIP[6] (Werden, 2003) - au niveau pays-produit.

R.3.2 Revue des mesures de fuites de carbone existantes

Définir une mesure des risques de fuites de carbone est un exercice complexe pour deux raisons principales. Premièrement, il n'y a pas d'observations empiriques de fuites de carbone car les politiques climatiques sont restées peu contraignantes pendant la majeure partie de la période étudiée dans la littérature (Cameron & Baudry, 2023; Verde, 2020). Deuxièmement, la conception de politiques publiques pour réduire les fuites fait débat, puisque les modalités de leur mise en œuvre influent considérablement sur les entreprises qui y sont soumises.

Les modèles *ex ante* prédisent des taux de fuite variables, mais généralement modérés.[7] À l'inverse, les études empiriques *ex post* ne détectent quasiment aucun effet - vraisemblablement parce que les politiques climatiques mises en œuvre n'ont pas été suffisamment strictes pour générer de tels effets.[8]

Sur le plan politique, l'UE évalue les risques de fuites de carbone sur la base de l'intensité de consommation énergétique des secteurs et de l'intensité de leur exposition au commerce international (intensité commerciale par la suite). L'intensité commerciale sert de proxy pour l'exposition des secteurs à la concurrence internationale, censée refléter la capacité des entreprises à répercuter leurs coûts sur l'aval de la chaîne de valeur. Ce critère d'intensité commerciale reste sommaire et ne s'appuie sur aucune justification économique solide. Plusieurs études ont évalué la méthodologie européenne et tendent à montrer qu'elle surestime les risques de fuites (Fischer & Fox, 2018; Fowlie & Reguant, 2018; Hourcade et al., 2007; Martin et al., 2014; Sato et al., 2015).

[6] *Small but Significant Non-Transitory Increase in Price* en anglais.

[7] Voir les revues de littérature de Branger and Quirion (2014) et Carbone and Rivers (2017) à ce sujet, ainsi que le Chapitre 1 de cette thèse.

[8] Se référer aux synthèses de Verde (2020), Joltreau and Sommerfeld (2019) et Dechezleprêtre et al. (2019), ainsi qu'au Chapitre 1 de cette thèse.

R.3.3 Contexte industriel du ciment et de l'acier

Le modèle proposé dans ce chapitre est appliqué à deux secteurs de l'industrie lourde: l'acier et le ciment. Ce choix s'explique par l'importance de ces secteurs pour la décarbonation de l'UE: ils ont une forte intensité carbone et sont responsables d'une part importante des émissions de GES au niveau européen, la production de ciment et d'acier représentant respectivement 4% et 5% des émissions totales de l'UE (Marmier, 2023; Somers, 2022). De plus, ces deux secteurs figurent sur la liste des industries à haut risque de fuites de carbone depuis la création de l'EU ETS.

L'étude comparative de ces secteurs présente aussi un intérêt particulier en raison de leurs caractéristiques distinctes. La production de ciment est beaucoup plus intensive en carbone que la sidérurgie, tandis que les producteurs d'acier ont une intensité commerciale plus élevée que ceux de ciment. Le ciment fait en effet l'objet d'échanges limités sur de longues distances en raison de son poids élevé et des coûts de transport importants qui en découlent.

R.3.4 Modèle économique

Le modèle économique de ce chapitre est composé de deux parties, toutes deux ancrées dans un cadre théorique de concurrence monopolistique. Le modèle comprend un producteur amont et un producteur aval dans chaque pays. Les producteurs amont ont comme intrants le travail et les matières premières (comme le calcaire ou le minerai de fer) et comme extrants des produits industriels (tel que du ciment ou de l'acier). Ces biens industriels deviennent à leur tour les intrants des producteurs aval, qui, les combinant au travail, produisent des biens finaux (comme des matériaux de construction ou des automobiles). Ceux-ci sont achetés par des consommateurs finaux.

Plusieurs variétés des biens industriels sont définies selon la structure de commerce international d'Armington (1969). Cela signifie que chaque variété est définie par le pays d'origine du bien et que chaque pays ne produit qu'une seule variété du bien industriel.

La première partie du modèle consiste en l'application du test de monopoleur hypothétique (Werden, 2003) au niveau pays-produit. Ce test délimite le marché pertinent d'un producteur amont en se basant sur ses taux de marge et profits et les élasticités-prix propres et croisées du producteur aval. Plus le marché pertinent est large, plus les producteurs aval ont accès à des variétés du même produit qu'ils considèrent comme étant équivalentes. Si des politiques climatiques strictes augmentent le prix des biens dans un pays, les producteurs aval pourront donc facilement se tourner vers des variétés provenant d'autres pays, induisant des fuites de carbone. Un marché pertinent plus large est donc

associé à un risque accru de fuites de carbone. Ce test est appliqué pour différents niveaux d'augmentation des prix du bien industriel dans un pays: 5%, 10%, 20% et 50%.

Certains paramètres utilisés dans le test proviennent de l'estimation d'un modèle de gravité, la seconde partie du modèle économique. Ce modèle tiré de la littérature économique du commerce international est lié théoriquement et empiriquement au test de monopoleur hypothétique dans ce chapitre.

R.3.5 Données

La principale source de données utilisée pour le modèle de gravité est la base BACI du CEPII (Gaulier & Zignago, 2010). Les données de production d'acier proviennent des Annuaires Statistiques de WorldSteel (WorldSteel, 2023). Celles du ciment hydraulique sont issues des statistiques du *United States Geological Survey* (United States Geological Survey, 2011, 2016, 2021).

Les données relatives à l'indicateur de distance géographique proviennent de la base Gravity du CEPII (Conte et al., 2022). Le paramètre α de la fonction Cobb-Douglas est dérivé de la base de données intrants-extrants WIOD de l'Université de Groeningen. Enfin, les données sur le chiffre d'affaires et les taux de marge sont extraites des Statistiques structurelles d'entreprises d'Eurostat.

R.3.6 Résultats

Les résultats du test de monopoleur hypothétique avec une augmentation de prix de 5% montrent que parmi les 4 produits industriels étudiés, seul le clinker semble faire face à une concurrence de pays hors UE. Lorsque l'augmentation de prix passe à 10%, certains pays commencent à apparaître dans le marché pertinent simulé du ciment hydraulique. Pour une hausse de prix de 20%, on observe un changement significatif concernant les produits d'acier long. Les résultats suggèrent l'existence d'un point de bascule entre 10% et 20% qui conduit à un élargissement important du marché pertinent de l'acier. Ces résultats mettent en évidence des seuils critiques différenciés selon les produits, avec des implications importantes pour l'évaluation des risques de fuite de carbone.

R.3.7 Discussion

Le clinker apparaît comme le produit le plus homogène parmi les quatre étudiés dans ce chapitre. Depuis les années 2000, sa composition chimique est standardisée, le rendant très uniforme à travers le monde (Herfort et al., 2010). Cette homogénéité du

clinker limite les possibilités de spécialisation des producteurs qui tenteraient de cibler des marchés spécifiques. La possibilité de spécialisation est légèrement plus importante dans le ciment hydraulique, et l'est encore plus dans la production d'acier, où différents pays et régions du monde se sont spécialisés dans la production de types et grades d'acier distincts (Carvalho & Sekiguchi, 2015; Steel Plate & Sections, 2024).

Le degré d'homogénéité et de spécialisation d'un produit influence considérablement son risque de fuites de carbone. Les consommateurs européens sont plus susceptibles de trouver des alternatives acceptables hors UE pour un produit homogène comme le clinker que pour des produits fortement différenciables et spécialisés comme l'acier. Pourtant, la mesure de risques de fuites de carbone de l'UE ne prend pas en compte ces facteurs.

R.3.8 Conclusion

Les régulateurs européens s'appuient sur un indicateur d'intensité commerciale pour mesurer les risques de fuites de carbone. Cependant, cet indicateur ne prend pas en compte la concurrence *potentielle* qui pourrait émerger suite à des modifications de prix d'un bien ou d'autres circonstances. La méthodologie du monopoleur hypothétique proposée dans ce chapitre complète la mesure européenne en évaluant le *potentiel* commercial et concurrentiel. Elle met en avant des caractéristiques telles que l'homogénéité des produits et la spécialisation des producteurs qui ont une influence importante sur les structures de marché et donc les risques de fuites de carbone.

Les résultats révèlent des différences significatives dans la définition des marchés pour chaque produit étudié, soulignant qu'une agrégation excessive des produits ou secteurs pourrait biaiser l'évaluation des risques de fuites de carbone (Fischer & Fox, 2018). Cette hétérogénéité des dynamiques sectorielles plaide pour une approche plus granulaire dans l'élaboration des politiques climatiques de l'UE.

R.4 Chapitre 3 - Intensité carbone et performance des entreprises : Une étude micro-économique des firmes industrielles soumises au marché du carbone européen

R.4.1 Introduction

L'argumentaire lié aux fuites de carbone et aux pertes de compétitivité repose sur l'idée que la réglementation climatique impose des coûts aux entreprises qui y sont soumises. Cependant, cette affirmation selon laquelle la décarbonation serait nécessairement préjudiciable aux entreprises fait débat depuis des décennies dans la littérature économique.[9]

D'un côté, la décarbonation peut effectivement augmenter les coûts de production des entreprises en raison des investissements nécessaires pour qu'elles réduisent leurs émissions de GES. D'un autre côté, les entreprises peuvent se décarboner en optimisant leur utilisation de matières premières et d'énergie, ou en investissant dans des innovations qui améliorent simultanément leur performance environnementale et leur productivité globale. Ces deux effets pourraient au contraire renforcer leur compétitivité tout en réduisant leurs émissions.

Ce chapitre étudie si la décarbonation des entreprises industrielles soumises à l'EU ETS a modifié leurs résultats économiques et financiers pendant la troisième phase du marché du carbone. Cette question revêt une importance particulière étant donné que l'UE est en train d'augmenter progressivement l'ambition de ses politiques climatiques pour atteindre la neutralité carbone.[10]

R.4.2 Littérature connexe

La littérature connexe au sujet de ce chapitre propose deux hypothèses pour expliquer la relation entre décarbonation et performance économique et financière des entreprises. La première est que la décarbonation engendre des coûts pour les entreprises, les obligeant à utiliser des ressources qui seraient autrement utilisées de manière plus productive (Jaffe et al., 1995; Schmalensee, 1993; Walley & Whitehead, 1994). Ces coûts peuvent également

[9] Voir Jaffe et al. (1995) pour une des premières revues de la littérature sur ce sujet et Dechezleprêtre and Kruse (2018) pour une revue récente.

[10] Voir la page de la Commission Européenne sur les fuites de carbone : https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en#carbon-leakage-list.

être indirects, résultant des relations inter-sectorielles et amont-aval, comme lorsque les secteurs industriels ont des coûts énergétiques plus élevés dûs au report en aval des coûts de l'EU ETS par le secteur électrique (Dagoumas & Polemis, 2020; Sijm et al., 2006).[11]

À l'inverse, une deuxième hypothèse existant dans la littérature soutient que performance environnementale et performance économique vont de pair, puisque les décisions de décarbonation peuvent améliorer la compétitivité globale des entreprises via la réduction des coûts des intrants matériels et énergétiques (Busch & Lewandowski, 2018), ainsi que par l'innovation (Porter, 1991; Porter & van der Linde, 1995). Cet argument est étroitement lié à la version forte de l'hypothèse de Porter, selon laquelle les politiques environnementales poussent les entreprises à réduire leurs émissions tout en résolvant leurs inefficacités techniques, augmentant ainsi leur productivité globale. Conformément à cette vision, l'un des objectifs de l'EU ETS est de fournir des incitations économiques pour que les entreprises innovent et adoptent des « technologies plus efficaces énergétiquement » (European Parliament and Council, 2003).

R.4.3 Données

Sources de données

Deux bases de données principales ont été fusionnées pour fournir des données sur les émissions et les résultats économiques et financiers des firmes industrielles soumises à l'EU ETS : la base de données ORBIS de Bureau van Dijk[12] et le registre européen des transactions de l'EU ETS (EUTL pour l'anglais *EU Transaction Log.*).[13]

Le couplage de ces deux bases de données a été réalisé selon une procédure qui utilise des techniques de traitement automatique du langage naturel (*Natural Language Processing* en anglais), décrite en détail dans les annexes de ce chapitre. Cette méthodologie permet d'assurer une correspondance précise entre les entités des différentes sources de données, malgré le fait qu'il n'y ait pas d'identifiant commun aux deux bases. Elle a été publiée par la Commission Européenne et le code sous-jacent ainsi que le résultat de la fusion d'ORBIS et de l'EUTL ont été mis à disposition publique (Cameron & Ho, 2024).

[11] L'ampleur de ce report sur les consommateurs dépend de plusieurs facteurs tels que l'élasticité-prix de la demande, les dynamiques concurrentielles - ou leur absence - et la géographie des marchés (Clò, 2010; De Bruyn et al., 2010; Fabra & Reguant, 2014; Veith et al., 2009).

[12] https://www.bvdinfo.com/en-gb/our-products/data/international/orbis

[13] https://union-registry-data.ec.europa.eu/report/welcome

Mesure de l'intensité carbone des entreprises

Jusqu'à présent, la plupart des études existantes ont considéré que l'intensité carbone des entreprises était le ratio entre les émissions totales de celles-ci et leur chiffre d'affaires (Dechezleprêtre et al., 2023). Cette approche est effectivement la plus simple à calculer avec les données disponibles aux chercheurs. Cependant, le chiffre d'affaires peut provenir d'activités autres que la production industrielle, comme le marketing ou la prestation de services, ce qui peut biaiser les résultats en fournissant une mesure inexacte de l'intensité carbone de la production industrielle.

Ce chapitre propose une mesure alternative de l'intensité carbone des entreprises, calculée comme étant le ratio entre les émissions et les volumes de production des entreprises. Ceci permet de mieux cibler l'intensité carbone de la production industrielle. Étant donné la rareté des données sur les volumes de production des entreprises, particulièrement lorsque le domaine d'étude s'établit au travers de différents pays et secteurs, ce chapitre propose un calcul des volumes de production qui se base sur le volume de quotas gratuits alloués aux installations dans le cadre de l'EU ETS :

$$V_{inst,t-1} = \frac{QG_{inst,t}}{B_{act} \times FCI_t \times FCT_{sec,t}} \tag{1}$$

où :

- $V_{inst,t-1}$ est le volume de production d'une installation en l'année $t-1$
- $QG_{inst,t}$ représente le nombre de Quotas Gratuits reçus par une installation en l'année t;
- B_{act} est le Benchmark d'intensité carbone de l'activité de l'installation;
- FCI_t est le Facteur de Correction Intersectoriel;
- $FCT_{sec,t}$ est le Facteur de Correction Transitionnel.

Pour atténuer les incertitudes liées à l'application du benchmark d'activité, une simulation Monte Carlo est utilisée pour estimer les volumes de production. Cette approche probabiliste permet de tenir compte de la variabilité potentielle dans les paramètres de calcul.

R.4.4 Méthodologie

Spécification empirique

Pour évaluer l'impact à court terme de l'intensité carbone des entreprises industrielles sur leurs performances économiques et financières, une stratégie d'identification intra-entreprise est adoptée. En s'inspirant partiellement de l'approche de Trinks et al. (2020), la spécification empirique suivante est utilisée comme modèle de base :

$$\log \text{PerfEntrep}_{f,t} = \beta_0 + \beta_1 \log \text{IntensCarb}_{f,t-1} + \boldsymbol{z\mu_f} + \Lambda + \varepsilon_{f,t} \tag{2}$$

où :

- La variable dépendante, $\text{PerfEntrep}_{f,t}$, représente la performance économique ou financière d'une entreprise f au cours de l'année t. Plusieurs indicateurs sont utilisés tour à tour pour mesurer différents aspects de la profitabilité et de la viabilité des entreprises :
  - Indicateurs financiers : retour sur actifs, marges de profits et marges EBITDA.
  - Indicateurs économiques : productivité du travail et ratio chiffre d'affaires/coûts
- La variable indépendante d'intérêt, $\text{IntensCarb}_{f,t-1}$, mesure la performance environnementale de l'entreprise via son intensité carbone, exprimée soit en valeur soit en volumes
- $\boldsymbol{z\mu_f}$ représente les effets fixes entreprise
- Λ désigne les effets fixes temporels
- $\varepsilon_{f,t}$ est le terme d'erreur

Traitement de l'endogénéité

Lors de l'évaluation de l'impact de la performance environnementale des entreprises sur leur performance économique, des problèmes de causalité inverse et de biais de simultanéité peuvent se poser. La littérature récente sur la tarification de l'énergie met de plus en plus l'accent sur l'utilisation d'instruments de type Bartik (*shift-share*) pour traiter ces sources d'endogénéité. Le même instrument Bartik que celui décrit dans Fontagné et al. (2023) est appliqué à la variable d'intensité carbone. Cet instrument est construit comme suit :

$$\text{IntensCarb}^{IV}_{f,s,t} = \left[\frac{\text{IntensCarb}_{f,s,t_0}}{\overline{\text{IntensCarb}}_{s,t_0}}\right] \times \overline{\text{IntensCarb}}_{s,t} \tag{3}$$

où :

- t_0 représente la première année où une entreprise est observée dans l'échantillon
- $\overline{\text{IntensCarb}}_{s,t}$ est l'intensité carbone moyenne au niveau sectoriel à la période t, calculée en excluant l'entreprise f afin de réduire l'endogénéité via une approche '*leave-one-out*' :

$$\overline{\text{IntensCarb}}_{s,t} = \frac{1}{N-1}\sum_{i \neq f}^{N} \overline{\text{IntensCarb}}_{i,s,t} \tag{4}$$

Cette méthode instrumentale permet de capturer les variations exogènes de l'intensité carbone, d'isoler l'effet causal de la performance environnementale et de réduire les biais liés aux facteurs non observés.

R.4.5 Résultats

L'analyse de ce chapitre révèle un effet modeste mais statistiquement significatif des variations d'intensité carbone des entreprises sur leur rentabilité, mesurée par leurs retours sur actifs. L'ampleur de cet effet s'accroît lorsqu'on tient compte de l'environnement concurrentiel spécifique à chaque entreprise, et apparaît plus marquée pour la période 2018-2019, caractérisée par un renforcement du cadre réglementaire de l'EU ETS. Concernant les autres indicateurs de performance économique et financière retenus dans cette étude, l'impact de la décarbonation ne se révèle pas significatif.

R.4.6 Conclusion

D'un point de vue politique, ces résultats suggèrent plusieurs enseignements importants. Durant la troisième phase de l'EU ETS, pourtant la plus contraignante, les entreprises industrielles ayant réduit leur intensité carbone n'ont pas subi de détérioration de leur performance économique. Bien au contraire, leur situation financière s'est même améliorée sur certains aspects, particulièrement en fin de période. Ces observations offrent une perspective encourageante : l'adoption de méthodes de production moins carbonées peut constituer un levier de résilience économique pour les entreprises industrielles. Il apparaît donc souhaitable que les firmes exploitent plus systématiquement ces synergies entre performance économique et réduction des émissions, afin d'accélérer leur transition

bas-carbone tout en consolidant leur compétitivité. Ces conclusions ouvrent des pistes pertinentes pour le raffinement des politiques climatiques européennes et l'élaboration des stratégies industrielles de décarbonation.

R.5 Chapitre 4 - Vert sur le papier ? L'effet des brevets verts sur les entreprises soumises à l'EU ETS

R.5.1 Introduction

Ce chapitre analyse l'intersection entre innovation bas-carbone et efficacité technique et climatique des entreprises industrielles soumises à l'EU ETS. Trois questions de recherche sont abordées. Premièrement, quelles caractéristiques distinguent les entreprises qui allient efficacité technique et climatique ? Deuxièmement, quelles firmes sont à l'origine des innovations technologiques qui repoussent la frontière technologique sectorielle ? Troisièmement, quels types de brevets s'avèrent les plus efficaces pour faire progresser cette frontière ?

Cette analyse présente une pertinence politique majeure à plusieurs égards. En identifiant les caractéristiques des entreprises performantes sur les deux dimensions technicité et climat, elle peut éclairer la conception de futures politiques climatiques européennes, ainsi que l'accompagnement des transitions industrielles au niveau sectoriel et les mécanismes d'incitation à l'innovation verte (Dakpo et al., 2016). Comme le soulignent Morfeldt and Silveira (2014), une évaluation rigoureuse des initiatives existantes s'impose pour guider les prochaines étapes de la transition bas-carbone. Cette étude contribue à ce besoin en fournissant des éléments empiriques sur les dynamiques d'innovation et d'adoption technologique pendant la troisième phase de l'EU ETS (2013-2020).

R.5.2 Littérature connexe

L'un des objectifs stipulés dans la directive fondatrice de l'EU ETS est de « favoriser le recours à des technologies plus efficaces sur le plan énergétique » (European Parliament and Council, 2003). Cet objectif a été évalué au travers de deux approches principales dans la littérature. La première étudie l'impact de l'EU ETS sur le progrès technologique des entreprises, mesuré par des indicateurs d'efficacité et de productivité. Ces travaux révèlent que l'EU ETS a effectivement entraîné des réductions d'émissions grâce à des gains d'efficacité, particulièrement dans l'industrie papetière (Löschel et al.,

2019). Néanmoins, cet effet reste modeste comparé à l'influence des prix des combustibles fossiles (Lundgren et al., 2015).

La seconde approche exploite les critères d'inclusion de l'EU ETS pour mesurer l'impact causal du marché du carbone sur les brevets ou les investissements en R&D, utilisés comme proxies du changement technologique. Ces études concluent à une augmentation significative des brevets verts parmi les entreprises régulées (Calel, 2020; Calel & Dechezleprêtre, 2014).

R.5.3 Cadre théorique

Ce chapitre s'appuie sur le cadre théorique des frontières technologiques, initialement formalisé par Shephard (1970) puis généralisé par Chambers et al. (1998). Une frontière technologique représente la production maximale qu'une entreprise peut atteindre avec un niveau donné d'intrants si elle est complètement efficace. Suivant Färe et al. (2005), dans ce chapitre, le cadre théorique des frontières technologiques est appliqué à un cas où les firmes génèrent simultanément une production désirable et des externalités négatives.

Conceptuellement, l'efficacité se définit comme la capacité d'une entreprise à minimiser ses intrants tout en maximisant sa production. En pratique, deux mesures complémentaires se distinguent : l'efficacité orientée intrants (réduction des intrants à extrants constants) et l'efficacité orientée extrants (augmentation des extrants à intrants constants). Les deux approches produisent des mesures de l'efficacité qui sont relatives au sein d'un secteur (Bogetoft & Otto, 2011).

Ce chapitre intègre à la fois une production désirable (production de biens industriels) et des externalités négatives (émissions de GES). Une mesure d'efficacité orientée extrants est adoptée. Celle-ci évalue la capacité d'une firme à maximiser sa production de la production désirable tout en minimisant ses émissions, pour un niveau donné d'intrants. Cette approche s'appuie sur la distance de Shephard (Shephard, 1970), qui quantifie l'écart entre la production de chaque entreprise et la frontière technologique de son secteur. Plus cet écart est important, plus l'inefficacité est marquée.

Dans ce cadre, le progrès technologique correspond à un déplacement vers le haut de la frontière de production entre deux périodes. L'objectif de ce chapitre est d'identifier les entreprises responsables de ce déplacement. Pour ce faire, une évaluation est faite de la position relative de chaque firme par rapport à la frontière de l'année précédente en confrontant ses intrants et sa production aux coefficients de la frontière de l'année antérieure. Cette méthode permet de calculer la distance d'une entreprise par rapport à la frontière de l'année antérieure.

R.5.4 Données

Sources de données

Trois bases de données principales ont été fusionnées dans ce chapitre : la base ORBIS de Bureau van Dijk,[14] le registre européen des transactions (EUTL),[15] et la base PATSTAT de l'Office européen des brevets.[16]

Classification sectorielle

L'analyse des frontières technologiques repose sur l'hypothèse fondamentale que les entreprises d'un même secteur partagent une technologie de production commune. Cette homogénéité technologique est cruciale car l'efficacité des firmes s'évalue par une mesure relative au sein d'un secteur. Des différences marquées dans les technologies, intrants ou dans la production des entreprises d'un secteur fausseraient les mesures d'efficacité (Walheer, 2024).

Dans ce chapitre, une évaluation des différentes nomenclatures disponibles a été menée par le biais d'une Analyse de Variance Multiple. Ceci a permis de déterminer la nomenclature sectorielle optimale garantissant une homogénéité intra-sectorielle maximale tout en évitant une fragmentation excessive des secteurs. Le jeu de données final couvre 17 secteurs de l'industrie lourde.

R.5.5 Approche empirique

Ce chapitre applique un programme linéaire déterministe pour effectuer une analyse des frontières technologiques. Cette approche offre une grande flexibilité en ne supposant qu'une forme fonctionnelle pour la fonction de distance directionnelle. Elle convient particulièrement à l'échantillon de taille limitée de cette étude.

Suivant Färe et al. (2005) et Baudry and Faure (à paraître), le programme quadratique-linéaire suivant est appliqué pour calibrer des frontières technologiques spécifiques à chaque secteur et année :

[14]ORBIS | Compare Private Company Data | Moody's (moodys.com)
[15]EU Emissions Trading System (ETS) data viewer — European Environment Agency (europa.eu)
[16]EPO PATSTAT (epo.org)

$$\min \left[\sum_{i=1}^{N} \overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; g) \right] \text{ tel que:}$$

(a) $\overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; g) \geq 0 \, \forall \, i$

(b) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial Y_{itg}} \leq 0 \, \forall \, i$

(c) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial Y_{itb}} \geq 0 \, \forall \, i$

(d) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial X_{itq}} \geq 0 \, \forall \, q \text{ et } \forall \, i$

(e) $\overrightarrow{D_{it}}(X_{it}, 0, 0; g) < 0 \, \forall \, i$

où $\overrightarrow{D_{it}}(X_{it}, Y_{itg} Y_{itb}; g)$ est définie comme une fonction quadratique de distance directionnelle :

$$\begin{aligned} \overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; g_y, -g_b) = & \beta_{0t} + \sum_{q=1}^{3} \beta_{tq} X_{itq} + \sum_{p=1}^{2} \beta_{tp} Y_{itp} + \sum_{q=1}^{3} \sum_{q'=1}^{3} \beta_{tqq'} X_{itq} X_{itq'} \\ & + \sum_{p=1}^{2} \sum_{p'=1}^{2} \beta_{tpp'} Y_{itp} Y_{itp'} + \sum_{q=1}^{3} \sum_{p=1}^{2} \beta_{tqp} X_{itq} Y_{itp} \end{aligned} \tag{5}$$

L'objectif de notre analyse empirique est d'étudier l'effet de déposer un brevet bas carbone - mesuré ici comme étant des brevets avec une classe technique catégorisée par l'Office européen des brevets comme "Y02" - sur le progrès technologique d'une entreprise - défini grâce à notre approche par les frontières. Nouw estimons donc l'équation suivante :

$$\begin{aligned} \text{ProgTech}_{i,t} = & \gamma_1 \log \text{InnovVerte}_{i,t-1} + \gamma_2 \log \text{Innov}_{i,t-1} \\ & + \sum_k \delta_k x_{i,t}^k + \mu_i + \mu_{ct} + \epsilon \end{aligned} \tag{6}$$

où:

- $\text{ProgTech}_{i,t}$ est la variable dépendante qui représente le progrès technique. Elle correspond soit à une variable continue mesurant la distance d'une entreprise à la frontière technologique de l'année précédente, soit à une variable binaire indiquant si l'entreprise a déplacé ou non cette frontière technologique ;

- InnovVerte$i, t-1$ et Innov$i, t-1$ désignent respectivement le nombre de familles de brevets bas carbone (mesuré en flux ou en stock) et le nombre de familles de

brevets non bas carbone (également mesuré en flux ou en stock) de l'entreprise i à la date $t-1$;

- x_{it}^{k} représente l'ensemble des variables de contrôle au niveau de l'entreprise ;
- μ_i sont les effets fixes propres à chaque entreprise ;
- μ_{ct} sont les effets fixes pays-année ;
- ϵ est le terme d'erreur.

R.5.6 Résultats

Cette étude révèle d'importantes variations dans l'efficacité des entreprises au sein des secteurs de l'EU ETS. Certains secteurs, comme le papier et la chimie, présentent une grande hétérogénéité, tandis que d'autres, comme le ciment et la sidérurgie à four électrique, sont plus homogènes. Le progrès technologique est généralement concentré dans un nombre restreint d'entreprises, souvent les mêmes d'une année sur l'autre. Les entreprises déposant des brevets verts semblent devenir moins efficaces par rapport à leurs concurrents, probablement en raison de la maturité et de la dépendance des technologies « brunes », par rapport à l'innovation verte encore en développement. Ces tendances suggèrent la nécessité de politiques ciblées pour soutenir les entreprises les moins performantes et encourager une transition verte réussie.

R.5.7 Conclusion

Cette étude analyse les liens entre l'efficacité des entreprises, les brevets verts, le progrès technologique et la réduction des émissions dans les secteurs industriels régulés par l'EU ETS. Les résultats révèlent une forte hétérogénéité des niveaux d'efficacité entre entreprises d'un même secteur, entraînant un potentiel de réductions d'émissions variable. Toutefois, même les secteurs avec le plus fort potentiel parmi notre échantillon ne peuvent atteindre des niveaux suffisants aux objectifs climatiques de l'UE. La plupart des secteurs devront opérer des transformations technologiques et structurelles plus profondes pour parvenir à une décarbonation significative. Par ailleurs, l'innovation technologique est principalement portée par quelques entreprises pionnières, créant une dynamique marquée entre leaders et suiveurs. Enfin, les brevets verts ne garantissent pas systématiquement d'améliorations d'efficacité ni le déploiement effectif de technologies bas-carbone. Ces conclusions soulignent la nécessité de politiques plus ciblées, privilégiant des indicateurs directs de progrès technologique et de baisse effective des émissions.

R.6 Conclusion

R.6.1 Retour au Dr Compétitivité et à M. Climat

Cette thèse a commencé par interroger une tension centrale dans la politique climatique de l'UE : la décarbonation industrielle et la compétitivité peuvent-elles être des forces complémentaires, ou alors faut-il sacrifier un objectif pour atteindre l'autre ? Formulée à travers un prisme de « Dr Compétitivité » et « M. Climat », la question est de savoir si l'UE peut harmoniser ces deux objectifs en une stratégie cohérente — et si oui, comment ? — ou si le bloc restera piégé dans une lutte à la Jekyll-et-Hyde qui se terminera comme le roman de Robert Louis Stevenson, par la mort du personnage principal.

Pour éviter ce funeste destin, l'UE a fixé pour objectif d'être un précurseur dans la lutte contre le changement climatique. Les décideurs politiques ont admis les opportunités offertes par la transition verte pour renforcer la résilience économique de l'UE et devenir un leader dans la nouvelle économie verte (Draghi, 2024; European Commission, 2019; Tagliapietra et al., 2019). Bien que ces aspirations soient louables, les niveaux d'ambition des politiques climatiques sont actuellement loin d'être suffisants pour réduire suffisamment les émissions de l'UE et atteindre la neutralité carbone d'ici à 2050 (EEA, 2024a, 2024b; IPCC, 2023).

Une raison majeure de cet écart entre les objectifs climatiques et les politiques mises en œuvre est la menace des fuites de carbone. Les décideurs politiques hésitent à imposer des politiques climatiques trop rigoureuses qui feraient perdre des parts de marché à leurs industries au profit de concurrents moins régulés et inciteraient leurs industries à délocaliser leur production hors de la région réglementée (Markusen, 1975; Markusen et al., 1993).

Les récents bouleversements géopolitiques — notamment la résurgence du protectionnisme, la domination chinoise dans les technologies propres et le revirement de la politique climatique américaine — ont intensifié cette tension, refaçonnant la décarbonation à la fois comme un impératif écologique et un enjeu géopolitique. La réponse de l'UE, incarnée par des initiatives comme la Boussole pour la Compétitivité, reflète un équilibre précaire : comment poursuivre l'action climatique tout en maintenant une forte compétitivité industrielle ?

R.6.2 Contributions de la thèse

Cette thèse dépasse les débats politiques en testant empiriquement le lien entre compétitivité et climat dans les industries lourdes de l'UE. À travers des analyses sectorielles et au niveau des entreprises des risques de fuites de carbone, de la performance économique des entreprises et des frontières technologiques, elle apporte un éclairage nouveau à cette problématique. La relation entre décarbonation et compétitivité n'est pas une loi universelle mais est contingente à la structure des marchés, aux trajectoires d'innovation et à la conception des politiques climatiques. Alors que certains secteurs démontrent une compatibilité entre décarbonation et compétitivité, d'autres font face à des arbitrages plus aigus, remettant en question l'idée d'une stratégie industrielle unique.

Dans son ensemble, cette thèse contribue à une meilleure compréhension des liens entre la politique climatique de l'UE et la compétitivité industrielle. Elle apporte quatre contributions clés : premièrement, une synthèse systématique de la littérature existante pour identifier ses lacunes et contradictions ; deuxièmement, une analyse statique des mécanismes de fuites de carbone dans la troisième phase de l'EU ETS ; troisièmement, un examen prospectif de la manière dont les changements technologiques peuvent remodeler la compétitivité industrielle à long terme ; et quatrièmement, une nouvelle méthode mise à disposition publique pour fusionner des bases de données micro-économiques n'ayant pas d'identifiant commun. À travers ces contributions, la thèse remet en question les hypothèses simplistes sur la relation entre décarbonation industrielle et compétitivité et fournit des recommandations politiques concrètes.

R.6.3 Limites et pistes de recherche

Comme toute recherche, cette thèse présente certaines limites intrinsèques qui ouvrent des pistes pour de futures recherches. Je soulignerai trois de ces limites et pistes dans cette section, en choisissant celles qui sont les plus pertinentes pour l'élaboration des politiques européennes et les plus étroitement liées au sujet de cette thèse, à savoir le nexus climat-compétitivité.

Données granulaires et actualisées. Une limite fondamentale de cette thèse réside dans les données utilisées. Malgré des efforts importants pour compiler des ensembles de données pertinents pour étudier les interactions entre politique climatique et compétitivité à un niveau détaillé, les travaux présentés ici n'analysent pas des échantillons pleinement représentatifs et les observations ne dépassent généralement pas 2020. Cela s'explique par

le fait que les bases de données existantes présentent souvent des données manquantes, sont fragmentées, insuffisamment structurées ou incomplètes dans leur couverture.

Bien que de nombreuses initiatives soient en cours dans ce domaine, il reste un long chemin à parcourir avant que des données granulaires et actualisées ne soient facilement disponibles et que ces différentes sources puissent être reliées au niveau des entreprises. Promouvoir la recherche en libre accès et les liens entre institutions et recherche peut aider à combler ces lacunes.

Période couverte par l'étude. Cette thèse examine principalement des développements jusqu'en 2020. Pourtant, la période post-2020 a introduit des changements profonds qui méritent des études plus poussées. Le paysage des industries lourdes de l'UE a été façonné par des chocs majeurs, notamment une forte hausse du prix des quotas sur l'EU ETS, la reprise économique post-COVID-19, la mise en œuvre du Mécanisme d'Ajustement Carbone aux Frontières, l'invasion russe de l'Ukraine et la crise énergétique qui en a résulté, ainsi que le retour au pouvoir du président Trump aux États-Unis. Ces développements créent un environnement politique et économique distinct que cette thèse ne prend pas entièrement en compte et qui devrait être exploré dans de futures recherches empiriques.

Changements majeurs pour une décarbonation profonde. Cette thèse n'aborde pas pleinement les changements structurels à long terme qui sont nécessaires à une décarbonation profonde de l'industrie lourde. Comme la plupart des travaux présentés ici sont empiriques et que ces changements structurels n'ont pas encore été mis en œuvre, leur impact sur la compétitivité n'a pas été évalué. Parmi ces changements figurent la sobriété, l'utilisation accrue de matériaux de construction alternatifs, le développement de la production basée sur l'hydrogène et la capture et l'utilisation ou le stockage du carbone. Ces changements vont bien au-delà d'améliorations marginales de l'efficacité matérielle ou énergétique des industries, et sont susceptibles de redéfinir la compétitivité industrielle d'une manière que les indicateurs économiques traditionnels ne peuvent pas prendre en compte.

Répondre à cette problématique nécessite une remise en question fondamentale des cadres analytiques actuels. Des indicateurs comme les profits, le chiffre d'affaires et la compétitivité-coût peuvent s'avérer inadaptés lorsque des industries entières subissent des transformations majeures — certaines se contractant ou disparaissant, tandis que d'autres émergent. Les recherches futures devraient explorer de nouveaux modèles conceptuels qui dépassent la simple préservation de la compétitivité dans les industries existantes pour se concentrer sur la compréhension de la manière dont les sociétés peuvent répondre à tous leurs besoins — y compris leurs besoins écologiques. Cela pourrait impliquer

de développer des indicateurs plus complets de la compétitivité industrielle, comme le propose le courant de recherche « Beyond GDP » dans le contexte des indicateurs de croissance (Bleys, 2012; Chancel et al., 2014). Développer des mesures de l'utilité d'un bien industriel, ou de son intensité carbone en termes d'unités fonctionnelles plutôt que de volume ou de valeur en sont des exemples. Plus le travail visant à s'éloigner des valeurs purement économiques de la compétitivité au profit de valeurs de bien-être social sera important, plus la transition sera aisée.

R.6.4 Remarques finales

Cette thèse a cherché à démontrer que lutter contre le changement climatique et maintenir la compétitivité des industries lourdes dans l'UE ne doivent pas nécessairement être des objectifs contradictoires. Des trajectoires spécifiques à chaque secteur peuvent être développées pour les harmoniser. Cependant, cela nécessitera des politiques publiques efficaces et équilibrées, fondées sur la science, une dose considérable de courage politique et de soutien public, ainsi qu'une flexibilité suffisante pour s'adapter à un paysage géopolitique en constante mutation.

Pour compliquer encore les choses, les questions posées dans cette thèse ne sont qu'une pièce d'un puzzle bien plus vaste. Les arbitrages entre action climatique et compétitivité font partie d'un ensemble plus large de tensions entre action climatique et justice sociale, démocratie, autonomie, sécurité, et équité mondiale, pour n'en citer que quelques-unes. Une transition véritablement durable nécessite une approche holistique, équilibrant la décarbonation avec tous les objectifs sociétaux auxquels aspirent les citoyens européens.

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[17] Même après nos moults échanges, je reste convaincue que les firmes ETS ne prennent pas en compte de la même manière les quotas gratuits et les quotas mis aux enchères... ;)

[18] Je profite de cette occasion pour rappeler à Sylvain qu'à ce jour, mon score au Kobo dépasse toujours le sien...

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[19]It feels like the stars aligned for us to defend just two days apart! I have no doubt that we will co-direct a research lab together at some point in our careers ;).

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Main Body of the Thesis

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Introduction

I.1 A brief introduction to Dr. Competitiveness and Mr. Climate

Robert Louis Stevenson's *Strange Case of Dr. Jekyll and Mr. Hyde* delves into the duality of human nature, portraying the stark contrast between the kind and respected Dr. Jekyll and his malevolent alter ego, Mr. Hyde. Just as Stevenson questions how such opposing traits can coexist within one person, this thesis examines the relationship between competitiveness and climate concerns within the European Union's (EU) heavy industry sector. Are these forces two sides of the same coin, inherently linked? Or must policymakers choose between them, treating them as conflicting priorities? Are there specific cases or sectors where they are in conflict and others where they are complements?

Far from being abstract considerations, these questions are prevalent in today's policy debates, in part due to the EU's longstanding pursuit of ambitious climate objectives and as a result of shifting geopolitical dynamics.

Mr. Climate. Over the last three decades, the EU's climate policies have become increasingly far-reaching and stringent as policymakers have "chas[ed] the moving goal of sufficiently ambitious climate policies" (Dupont et al., 2024). In 2019, the bloc explicitly placed climate ambition at the center of its new economic growth strategy, the European Green Deal (European Commission, 2019). Despite this encouraging dynamic, the EU's climate policies are still falling short of the bloc's ambitions. Given current and announced climate policies, the European Environmental Agency (EEA) has projected that the EU will be 0.3Gt of greenhouse gas (GHG) emissions above its 2030 objective, 1.3Gt above its 2040 recommended objective and 1.6Gt above carbon neutrality in 2050—equivalent to nearly half of the EU's current yearly total GHG emissions (EEA, 2024a, 2024b).

Industry is a particular sticking point; the sector makes up 20% of the EU's total GHG emissions and its emissions are particularly difficult to curb (EEA, 2024a, 2024b). The first reason these emissions are hard to abate is that heavy industry requires sub-

stantial and constant energy needs that cannot easily be electrified; the second reason is the lack of viable alternatives for technologies with high process emissions, like for the production of clinker or chemicals (EEA, 2024a, 2024b; Kumar et al., 2024). The industrial sector explicitly came under the scope of EU climate policies in 2005, when the EU Emissions Trading Scheme (ETS) was introduced (European Parliament and Council, 2003). Since then, the EU ETS has been revised several times to integrate lessons learned by policymakers and to reflect the EU's more ambitious climate objectives (Table I.1).[20] Twenty years later, it remains one of the pillars of EU climate policy.

Dr. Competitiveness. Given the EU's wish to be a global front-runner for climate action and the gap between current policies and stated objectives, why have policymakers not gone further? One major obstacle is the absence of binding global climate governance, which has led to a fragmentation of climate policies across the world, both in terms of stringency and policy mixes (Clausing & Wolfram, 2023; Weber et al., 2025). Policymakers worry that this fragmentation will lead to competitiveness impacts, resulting in two major losses: carbon leakage, which would undermine the core objective of climate policies, and the relocation of production to a less regulated or unregulated region, leading to the loss of the associated value added and employment (Markusen, 1975; Markusen et al., 1993).

Discussions about the competitive impacts of climate policies and potential protective measures to address these effects were once considered taboo during the era of trade liberalism (Bacchus, 2019), but this perspective is now shifting (Weber et al., 2025).[21] Competitiveness concerns are taking center stage amid concerns about supply chain vulnerabilities following the COVID-19 crisis (Gelles et al., 2025), dependencies on China for critical raw materials required for the energy transition (Gielen, 2021), and the US' U-turn on climate policies since the 2025 inauguration of President Trump.[22] As a response, the EU has announced its Competitiveness Compass, a new policy road map to "safeguard the EU's future as an economic powerhouse" and ensure that the EU is "the place where tomorrow's technologies, services, and clean products are invented, manufactured and marketed, as [it] stay[s] the course to climate neutrality" (European Commission, 2025b).

[20] Chapter 3 describes in more detail the EU ETS' implementation and characteristics phase-by-phase.

[21] See the following article by E3G, which discusses how the EU is now pushing competitiveness as a top policy priority: https://www.e3g.org/publications/europe-s-competitiveness-push-and-what-it-means-for-climate-action/

[22] See the following article by the New York Times, which discusses measures President Trump has taken to remove climate and environmental measures in the US: https://www.nytimes.com/2025/03/02/climate/trump-us-climate-policy-changes.html (Gelles et al., 2025).

Table I.1: Timeline of EU objectives and ETS phases

Year	GHG emission reduction target (base year 1990)	EU ETS phases & main characteristics
1990	Stabilization by 2000	-
1998	-8% by 2008–2012	-
2005	-	Phase I: pilot phase, 100% free allowances
2007	-20% by 2020	
2008	-	Phase II: cap reduction, 10% of allowances auctioned
2009	-80–95% by 2050	
2012	-	Phase III: EU-wide cap, more sectors included, faster annual reduction factor, auctioning of allowances as default, introduction of Market Stability Reserve, back-loading of emissions allowances
2014	-40% by 2030	
2019	Climate neutrality by 2050	
2020	-55% by 2030	Phase IV: faster annual reduction factor, phasing out of free allowances, Carbon Border Adjustment Mechanism, Market Stability Reserve strengthened, more sectors, EU ETS II proposed
2021	Climate neutrality by 2050 made legally binding (European Climate Law)	
2023	-90% by 2040 (recommendation by Commission)	

Sources: Cameron and Garrone (2024) and Oberthür and Dupont (2021). Updated by author.

This thesis. This thesis fits into the rapidly evolving context of EU competitiveness and climate policy concerns, as introduced above. The four research papers it comprises each aim to shed light on a specific aspect of the question "can EU industrial decarbonization and competitiveness go hand in hand?". To guide the reader in reading this manuscript, this introduction defines the key concepts of the thesis (Section I.2), motivates the research question that is explored (Section I.3), and provides a summary of the four chapters, along with the overarching narrative that structures the thesis (Section I.4).

I.2 Defining key concepts

Delving into the issues explored in this thesis hinges on having a clear understanding of its key concepts. Some of these concepts can be interpreted in multiple ways or are inherently ambiguous, so this section specifies the precise definitions used.

Carbon leakage. Following Naegele and Zaklan (2019), carbon leakage can be defined in the broadest of sense as the movement of carbon emissions between a region with stringent climate policies and a region with less stringent policies, as a result of these differences in policy stringency. This mechanism is most widely understood from a competitive perspective: firms in the more regulated region become less competitive than their foreign competitors as a result of higher costs of compliance and therefore lose market shares or relocate to less regulated regions. This has the effect of decreasing carbon emissions in the more regulated region and increasing them in the less regulated region (Markusen, 1975; Markusen et al., 1993).

However, this is not the only carbon leakage mechanism that exists. Others include the energy channel and the innovation channel. Both of these are discussed in detail in chapter 1. The rest of the thesis retains the more widely used definition of carbon leakage as a result of a competitive mechanism, unless explicitly specified otherwise.

Competitiveness. Competitiveness has both a macro and a micro definition. At the macro level, it refers to *national* competitiveness, the idea that nations compete on global markets in the same way that corporations do. In this sense, competitiveness measures a nation's ability to maintain its ascendant position relative to other nations.[23]

This thesis puts the macro definition of competitiveness aside and refers only to its micro/*firm-level* definition: "the capability of a firm to sustainably fulfill its double purpose i.e., meeting customer requirements at profit" (Chikán, 2008). Firms are competitive when they offer goods and services that customers value more than those offered by competitors—both national and international (Bhawsar & Chattopadhyay, 2015).

The micro and macro definitions of competitiveness are of course closely linked. Firms create value within a nation, which determines this nation's competitiveness, while nations provide the regulatory environment that firms operate in (Bhawsar & Chattopadhyay, 2015). When this thesis refers to the EU's (or another country or region's) competitiveness, this is in fact shorthand for the aggregated competitiveness of its firms. For instance, chapter 2 discusses country-level competition on product markets—this is a

[23] As discussed in Krugman (1994), this seemingly simple definition conceals the complexity of empirically defining and measuring national competitiveness.

simplified reference to the competitiveness of a specific industry within that country, i.e., of the firms within that sector and country.

Corporate performance. This refers to all the firm-level indicators that can be used to measure competitiveness. Past research has measured competitiveness through firm-level indicators such as cost, profitability, productivity or market shares (Bhawsar & Chattopadhyay, 2015). Chapter 3 follows this literature by studying firm-level economic and financial outcomes, namely through the indicators of profit margins, labor productivity, return on assets, and turnover over costs.

Decarbonization. The Intergovernmental Panel on Climate Change (IPCC)[24] defines decarbonization as the "process by which countries, individuals, or other entities aim to achieve zero fossil carbon existence" (IPCC, 2022). In heavy industry, decarbonization carries a precise, sector-specific definition. While current emission-reduction efforts have predominantly focused on incremental improvements—particularly energy efficiency gains—true decarbonization in heavy industry requires more transformative changes (Diesing et al., 2025). These include fundamental shifts in energy and material inputs and in production technologies, the development of alternative low-carbon construction materials, enhanced material efficiency, and the expansion of circular value chains (International Energy Agency, 2024; IPCC, 2023).

The IPCC's definition emphasizes the ultimate objective of decarbonization—i.e., eliminating fossil carbon entirely. For heavy industry, this would imply including both incremental and transformative changes. Since transformative changes are yet to occur and this thesis studies historical data, the definition of decarbonization in this thesis retains only the incremental changes in industrial emissions. As such, decarbonization refers to the process by which industrial firms have reduced their GHG emissions, both in absolute terms or through improved emission intensity.

Heavy industry. Heavy industry refers to a subset of secondary production characterized by high capital costs, high barriers to entry, and low transportability. Its output typically consists of large, heavy materials or bulk goods sold primarily to other producers rather than final consumers (Cambridge Dictionary, 2025; Monash University, 2025; Oxford Languages, 2025). In this thesis, the scope is narrowed to stationary installations covered by the EU ETS—excluding aviation and power generation—and encompasses the following sectors: metals, cement, pulp and paper, chemicals, ceramics and clay, glass, and lime and plaster.

[24]The IPCC is an intergovernmental body of the United Nations dedicated to the advancement of scientific knowledge about climate change caused by human activities.

Innovation. Innovation is fundamentally linked to the notion of novelty. It represents the introduction of new products or production processes into the market. It is important to distinguish between invention and innovation: while an invention refers to a new idea, scientific discovery, or technology that has not yet been applied, innovation involves the practical implementation of such advancements, such as launching a new product or effectively utilizing a novel production process (Brozen, 1951). In this thesis, the concept of innovation is closely associated with patenting. Patents often serve as a tangible measure of inventive activity (Verhoeven et al., 2016), which can turn into innovation if it is successfully implemented in production processes.

Market structure. Market structure is a key concept in industrial organization studies. It refers to the characteristics that determine the nature of competition firms face on the market. These characteristics include the distribution of market shares on a market, entry barriers, firm sizes and growth rates (Shepherd, 1972). This is closely related to the concept of competitiveness defined above, since the market structure affects the degree of profitability that firms can attain within a market.

Definition of key concepts, as used in this thesis

- **Carbon leakage**: A displacement of carbon emissions from a region with stringent climate policies towards a region with less stringent climate policies.
- **Competitiveness**: A firm's capacity to sustainably and profitably meet customer requirements.
- **Corporate performance**: Encompasses all indicators used to measure firm-level competitiveness.
- **Decarbonization**: The process by which firms reduce their greenhouse gas emissions.
- **Heavy industry**: Capital-intensive, stationary EU ETS-covered sectors—excluding power generation—producing bulk materials for industrial use (e.g., metals, cement).
- **Innovation**: New products or production processes that are introduced on the market.
- **Market structure**: Characteristics that determine the nature of competition firms face on the market.

I.3 Motivation

I.3.1 Why should we care about this research question?

Climate change is an existential threat to humanity. While this statement has been reiterated countless times, it bears repeating—especially as the consequences of rising global surface temperatures are starting to be felt around the globe.[25] So far human activity has caused a 1.1°C increase in global temperatures compared to the period 1850–1900, mostly through the emission of GHGs (IPCC, 2023). The impacts of this temperature rise are already evident and can be attributed with high confidence to human-driven GHG emissions. These consequences include a marked increase in extreme weather events—such as heatwaves, torrential rainfall, prolonged droughts, and intensifying tropical cyclones—across most global regions, alongside irreversible harm to virtually all ecosystem types (IPCC, 2023). These changes, however, represent only the initial phase of the profound transformations climate change will impose on Earth's systems. The gravity of these impacts cannot be overstated: as warming continues, cascading effects—from collapsing biodiversity to destabilized food and water security—will amplify risks to societies and natural environments alike.

While the challenges posed by climate change are significant, this is not a doom-filled diagnostic. Humanity has at its disposal all the tools needed to address climate change, with public policies representing a particularly effective option (Stern, 2008). Having said this, current policies are insufficient. Even if all countries achieve the climate goals they announced prior to COP26—which in itself is unlikely given the global reversal of climate ambition since then— global temperatures are still likely to surpass 1.5°C during the 21st century (IPCC, 2023).

The EU bears a particular responsibility in addressing climate change, both historically and geopolitically. According to the principle of "Common but Differentiated Responsibility" under the United Nations Framework Convention on Climate Change's (UNFCCC) principle[26], the EU carries a form of "climate debt" to the rest of the world. As the birthplace of the Industrial Revolution—widely seen as the starting point of large-scale anthropogenic GHG emissions—the EU played a foundational role in shaping the emissions trajectory of the modern role. Moreover, as a developed region, it holds a

[25]The phrase "Climate change is an existential threat to humanity" has for instance been used by Former President of the US Joe Biden, by the EU delegation to the COP29, by the OECD in research and policy papers, by the International Committee of the Red Cross and by many other political representatives, international and governmental organizations, as well as researchers.

[26]See the UNFCCC's Explainer on this topic: https://unfccc.int/news/the-explainer-the-paris-agreement.

greater capacity to act than many developing countries, reinforcing its responsibility to lead global climate action.

So, what prevents EU policymakers from taking stronger action? The answer is of course complex and multi-dimensional. In this thesis, I focus on one key barrier: the threat of competitiveness losses and carbon leakage, which serves as a significant obstacle to more ambitious climate policy (Draghi, 2024; European Commission, 2019, 2021b; Grubb et al., 2022).[27]

To avoid carbon leakage, EU policymakers have implemented carbon leakage mitigation measures together with climate measures (Sato et al., 2022). For most of the EU ETS' existence, these measures took the shape of the free allocation of allowances and the compensation of indirect cost increases in industry (European Commission, 2012; European Parliament and Council, 2013). Recently, a Carbon Border Adjustment Mechanism (CBAM) was introduced to gradually replace free allowances (European Parliament and Council, 2023).

While these policies were able to prevent carbon leakage from the EU ETS, they also reduced the incentives for firms to cut their emissions. As a result, no carbon leakage has been observed in the EU ETS to date (Grubb et al., 2022; Joltreau & Sommerfeld, 2019; Naegele & Zaklan, 2019; Verde et al., 2019). However, this should not be interpreted as carbon leakage being an idle threat. Forward-looking economic models warn of higher levels of leakage as climate policy become increasingly stringent (Branger & Quirion, 2014; Carbone & Rivers, 2017).

The central challenge for policymakers is to strike a delicate balance between implementing measures that prevent carbon leakage without watering down climate policies. Climate policies in the EU, as well as in other nations, are continually evolving. This makes it highly relevant to keep monitoring the interrelation between climate policies, decarbonization, competitiveness, and carbon leakage. A deeper understanding of these dynamics can guide policymakers toward designing balanced and effective policies that supports the broader goal of carbon neutrality.

I.3.2 What is interesting about heavy industry?

Industrial materials make up our world—from the concrete in buildings and roads to the chemicals used in pesticides and fertilizers to produce our food, and the steel in our

[27]See the article entitled "Carbon leakage concerns dominate EU ETS debate" by ENDS Europe, a media focused on European environmental news, available at https://www.endseurope.com/article/1640202/carbon-leakage-concerns-dominate-eu-ets-debate?utm_source=website&utm_medium=social.

cars, trains and planes. As an illustration, cement is the second most consumed material in the world, second only to water (Gagg, 2014).

Heavy industry is also closely linked to the EU's economic and cultural identity. The EU emerged from a vision of integration rooted in industrial collaboration, namely through the "pooling of coal and steel production [to set up] common foundations for economic development [...], and [to] change the destinies of those regions which have long been devoted to the manufacture of munitions of war" (Schuman, 1950). Over the decades, EU industrial policy has evolved—from state-led strategies in the mid-20th century to market-oriented reforms preceding the 2008 financial crisis—yet consistently reinforced heavy industry's role as a driver of economic growth and regional identity (Kirk et al., 2012; Tagliapietra & Veugelers, 2023). This policy framework was also designed to promote a level playing field across member states, reinforcing cohesion and economic convergence. However, this historically inward-looking approach to industrial policy stands in tension with the outward-facing nature of climate policy. Given the global character of greenhouse gas emissions, effective climate action requires international coordination—something traditional EU industrial policy has not been primarily designed to accommodate.

However, this industrial legacy carries environmental and human costs. Toxic microplastics now permeate air, water, and ecosystems (Eberhard et al., 2024; Li et al., 2023), while pesticide residues persist in the atmosphere and food chain (Ahmad et al., 2024). The industrial sector is also a significant contributor to global GHG emissions—making up 30% of global emissions (IPCC, 2023) and 20% of EU emissions (EEA, 2024a).

This duality presents a paradox: heavy industry remains intertwined with the EU's economic and cultural fabric, yet its current form is incompatible with climate goals. Achieving these goals requires profound and systemic changes to the way the EU's heavy industry is structured (IPCC, 2023). These changes cannot be pursued haphazardly but instead require rigorous analysis to mitigate adverse economic and social consequences.

I.3.3 Why take the EU as a case study?

The EU has set itself the goal of being a global model in addressing climate change and is pursuing this ambition through initiatives like the European Green Deal, Ursula von der Leyen's flagship initiative during her first term as Commission President. This ambition, however, is not driven solely by altruism. EU policymakers recognize strategic opportunities in the green transition, such as securing first-mover advantages in emerging markets (Karkatsoulis et al., 2016) and capitalizing on existing strengths in low-carbon technology industries (Tagliapietra et al., 2019). The EU's proactive stance provides a

particularly interesting test case for balancing climate action with economic competitiveness.

Ursula von der Leyen's press release accompanying the European Green Deal
(von der Leyen, 2019)

> "*We want to be the frontrunners in climate friendly industries, in clean technologies, in green financing.*"

The EU's leadership role is further justified by its historical and geopolitical responsibility. Accounting for 15–25% of historical global GHG emissions despite representing just 5% of the world's population (Friman & Strandberg, 2014), the bloc bears disproportionate responsibility for climate change. This compounds with the UNFCCC's principle of "Common but Differentiated Responsibility" mentioned above, which emphasizes that developed economies like the EU possess greater capacity—and thus obligation—to lead decarbonization efforts.

The EU also offers a compelling case study from an academic perspective due to its two-decade-long history of implementing industrial climate policies. This time span provides rich empirical data and a well-established academic literature, both of which have been used as building blocks for this thesis.

I.3.4 Recent policy developments related to this thesis

Recently, the cross-linkages between climate concerns and industrial competitiveness have resurfaced in the EU's public debate. Two high-level policy reports discussed this issue in 2024: Enrico Letta's *Much more than a market* report (Letta, 2024), which highlighted the opportunity presented by the green transition to reach for EU industrial leadership in new low-carbon markets; and Mario Draghi's report on *The future of European competitiveness* (Draghi, 2024), which argues that one of the EU's top three priorities to bolster its competitiveness should be to develop a joint plan for industrial decarbonization and competitiveness. Draghi's report also highlights the opportunity presented by decarbonization as a new source of growth. However, it also warns that without adequate policy coordination, decarbonization could come at the cost of competitiveness and growth. The report identifies three major obstacles to harnessing the opportunities of decarbonization: high EU energy costs, especially in comparison to the US and China; lost opportunities in clean technology sectors due to the weakness of the EU's innovation ecosystem; and asymmetrical decarbonization objectives between countries, which can lead to carbon leakage.

Mario Draghi's report on *The future of European competitiveness* (Draghi, 2024)

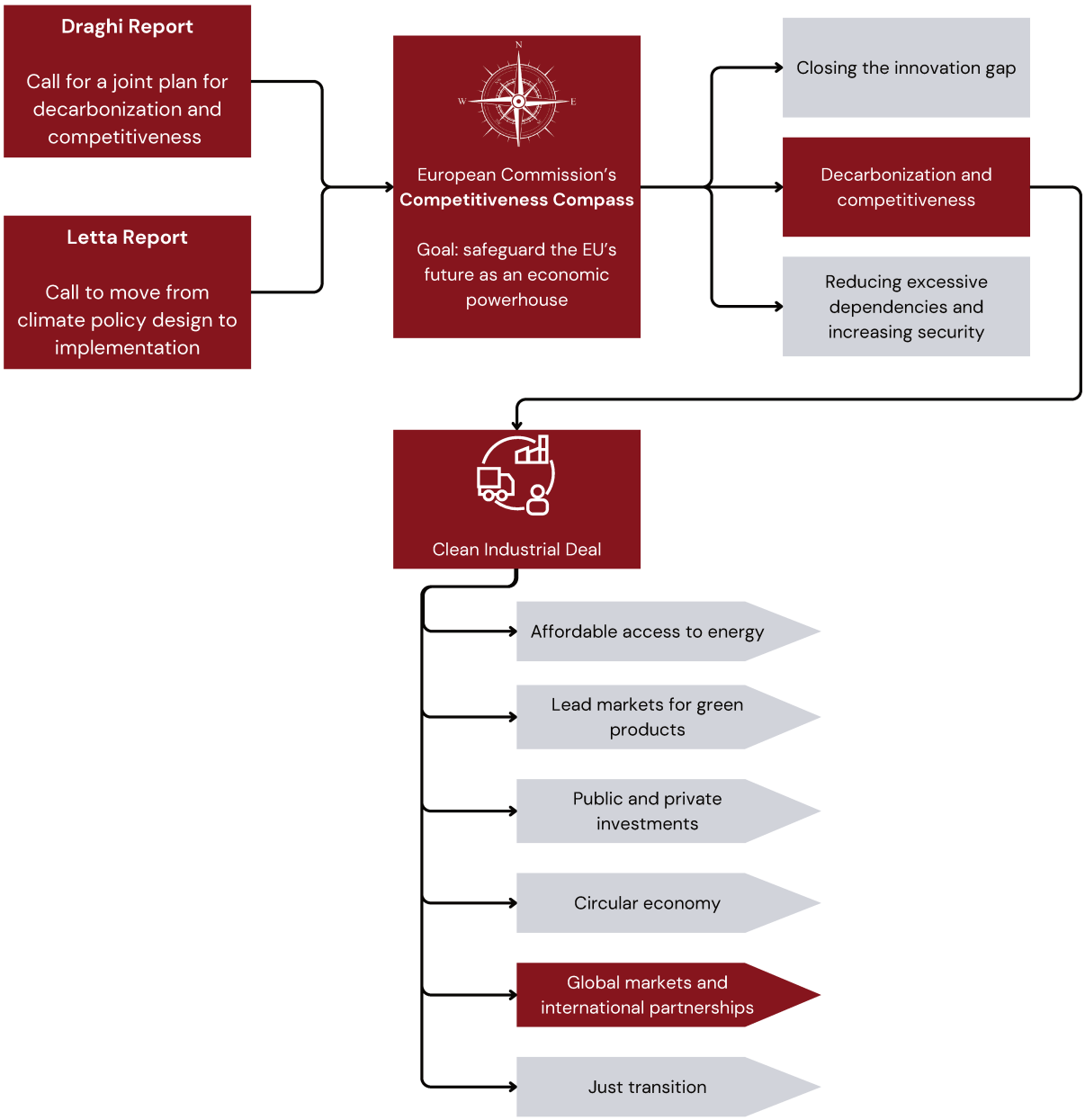
> "*Europe must confront some fundamental choices about how to pursue its decarbonization path while preserving the competitive position of its industry.*"

Based on the recommendations from this report, the European Commission (EC) announced a new policy road map in January 2025: the Competitiveness Compass (European Commission, 2025b). The announcement came the same week as Donald Trump returned to the Oval Office, an event that heralded a US departure from environmental objectives and an increase in global climate policy asymmetries. The Compass' overarching objective is to "safeguard the EU's future as an economic powerhouse" and ensure that the EU is "the place where tomorrow's technologies, services, and clean products are invented, manufactured and marketed, as [it] stay[s] the course to climate neutrality".

To reach this goal and address the Draghi report's call for a joint plan for decarbonization and competitiveness, the EC released its Clean Industrial Deal initiative on 26 February 2025 (European Commission, 2025a). The initiative details policy packages that will be deployed to address several different objectives, one of which is the articulation of EU climate policies within global markets and the development of international partnerships. This objective is closely tied to questions of how decarbonization can impact EU industry's relative standing in the face of international competition and fragmented climate policies (Figure I.1).

By examining the EU's evolving climate and industrial policies, this thesis contributes to both academic debates and real-world policymaking, offering insights into reconciling decarbonization with economic resilience in a complex, globally integrated region.

Figure I.1: Recent developments in EU climate policies and industrial competitiveness

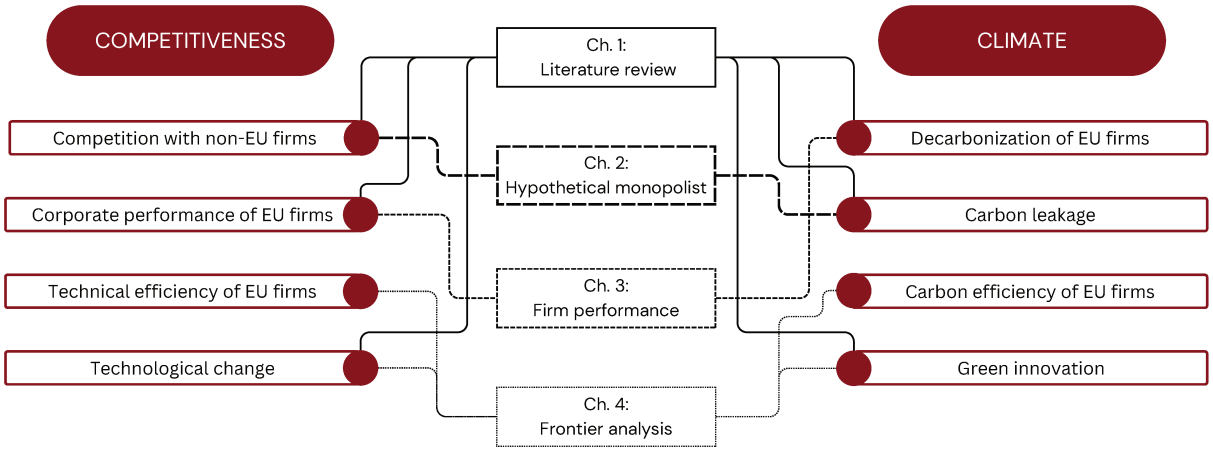


Note: The boxes highlighted in red are those most closely related to the topic of this thesis.
Source: Author

I.4 The strange case of this thesis

This section provides the overarching narrative that structures the four chapters of this thesis, then summarizes each of their contributions, methodology, results and limitations. Figure I.2 gives an overview of the main concepts that are studied and the chapters in which they are respectively covered.

Figure I.2: Thesis graphical abstract



Source: Author.

I.4.1 Thesis narrative

Chapter 1 begins by reviewing the literature on carbon leakage and border adjustments within the EU context, synthesizing its key findings while critically examining its limitations and contradictions. This aims to establish a foundation on the academic literature studying the relationship between competitiveness and climate policies.[28]

The chapter identifies gaps in the literature and proposes future research avenues informed both by academic and policy needs. These gaps have guided the construction of the subsequent chapters of this thesis, which address the following topics: (1) the divergence between *ex ante* and *ex post* carbon leakage estimates through the competitiveness channel; (2) the impacts of the EU ETS on heavy industry firms after Phase II; and (3) the role of policy-induced green innovation.

Chapter 2 tackles research gap (1) by developing an *ex ante* measure of carbon leakage risk that incorporates market structure—a factor that is often overlooked in *ex ante* studies. Most existing *ex ante* models assume perfect competition, even though it rarely

[28]This chapter appears as it was published in 2023 and therefore does not include literature from after this date. Chapter 1's appendix XX provides an update with more recent literature.

reflects the market structure in heavy industries. To address this, Chapter 2 introduces a novel measure of carbon leakage risk based on the hypothetical monopolist test—also known as the SSNIP test. This is a competition economics tool that empirically evaluates market structure for individual products without assuming competitive conditions. Unlike other *ex ante* models, this chapter finds relatively low risks of carbon leakage in the steel and cement sectors.

The discrepancy between *ex ante* and *ex post* leakage estimates may also stem from differences in policy stringency across studies. *Ex ante* analyses typically simulate policies aligned with long-term climate goals (e.g., EU climate neutrality by 2050), whereas *ex post* evaluations focus on historically implemented policies, many of which were not stringent enough to reach long-term climate goals. This temporal mismatch could explain why *ex ante* estimates tend to be larger than *ex post* estimates. This underscores the need to update *ex post* assessments with recent data reflecting stricter EU climate regulations (research gap (2)).

Chapter 3 addresses this gap by studying the impact of decarbonization on firm-level economic and financial outcomes during the EU ETS' third phase. Based on a micro-level panel econometric analysis, this chapter finds that even during this phase, when allowance prices started to significantly rise and the Market Stability Reserve was implemented, decarbonization did not negatively affect corporate outcomes in heavy industry sectors.

The methodologies in Chapters 2 and 3 are static and short-term by design, omitting the role of technological change in shaping long-term competitiveness (research gap (3)). Chapter 4 bridges this gap by analyzing the technological frontier of EU ETS-regulated heavy industries during Phase III. The analysis reveals large differences in how efficiently firms operate, even within the same industry. It also shows that if all firms improved to match the best performers, the overall emission cuts would still fall short of what is needed to achieve climate objectives—highlighting the importance of deeper structural changes in heavy industry. The chapter also finds that firms filing green patents do not become more efficient relative to others in terms of emissions and industrial production. This suggests that innovation on paper does not always lead to real-world impact, at least not in the short term.

Taken as a whole, this thesis advances the literature on EU climate policy and competitiveness through four contributions: first, a systematic review of existing research; second, static analyses of carbon leakage mechanisms in recent years; third, an exploration of dynamic technological changes affecting long-term competitiveness; and fourth, a new and open-source method to match micro-level databases that do not have a common identifier. The rest of this section provides more details on these contributions by summarizing each of the four chapters of this thesis.

The conclusion of this thesis synthesizes the four chapters' findings and highlights their policy implications. It also identifies remaining research gaps and proposes future research avenues to address them.

I.4.2 Summary of Chapter 1

The case for carbon leakage and border adjustments: Where do economists stand?

Summary. This chapter reviews the economic literature on carbon leakage and border carbon adjustments. It examines three key strands of research: (1) theoretical studies explaining the mechanisms behind carbon leakage, (2) *ex ante* modeling work identifying factors that influence leakage risks, and (3) *ex post* analyses measuring the actual effects of climate policy on leakage and related indicators. The discussion focuses on three leakage channels—competitiveness, energy markets, and innovation—before connecting these findings to the political economy of EU leakage mitigation measures, including the design of the CBAM. By synthesizing these insights, the chapter identifies research gaps with policy relevance.

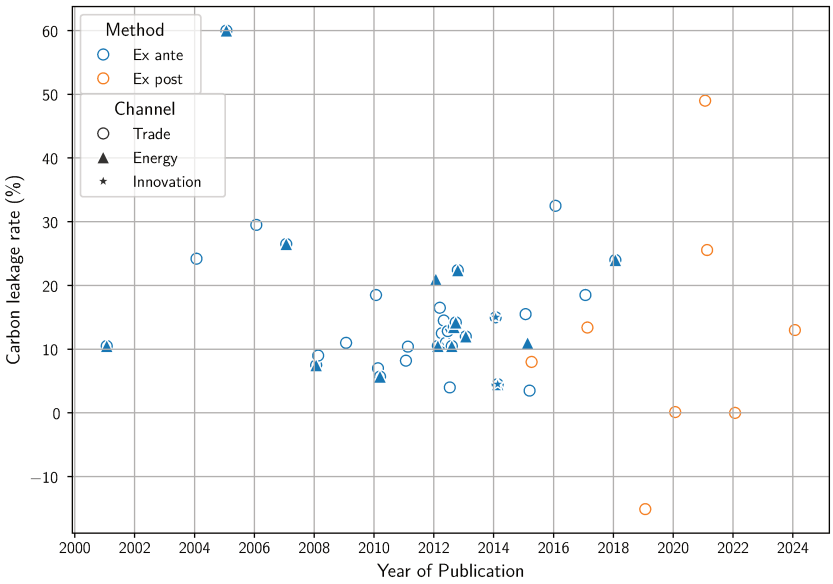
Contributions. This chapter provides the first systematic review synthesizing all types of economic literature on all three carbon leakage channels, offering a holistic framework to better understand carbon leakage. It highlights the underappreciated roles of the energy and innovation channels, challenges the EU's over-reliance on competition-centric policies like free allowances, and proposes actionable recommendations—such as international technology funds and a cooperative CBAM design—to address leakage across all channels.

Methodology. A structured literature review methodology is employed.

Main results. The analysis reveals that (1) leakage via the competition channel has been minimal in early ETS phases due to low carbon prices and free allocations but may rise as policy stringency increases; (2) the energy channel could drive significant long-term leakage (up to 60–70% in some models) but remains unaddressed by current policies; and (3) the innovation channel, though under-exploited, holds potential for negative leakage via green technology spillovers, contingent on international diffusion efforts. Overall, there is not a strong consensus on the true level of carbon leakage risk across the literature; there is a notable gap between *ex post* empirical estimates of carbon

leakage that tend to be low, and estimates from *ex ante* models that tend to be higher, as highlighted in Figure I.3.

Figure I.3: Estimates of carbon leakage in the literature



Note: All values of estimates can be found in Appendix I.A.
Source: Author.

Limitations. A central limitation of this chapter is its reliance on *ex post* literature that mostly focuses on the EU ETS' first two phases (2005–2012), which operated under low carbon prices (5–30€/tCO_2). This limits insights into firm behavior during Phases III (2013–2020) and IV (2021–present), where prices surged to 60–100€/tCO_2—a critical gap given that the EU ETS' stringency is set to keep increasing. Chapters 3 and 4 address this limitation by explicitly studying Phase III of the EU ETS. While Chapter 1 highlights differences between *ex ante* model projections and *ex post* empirical findings, it does not resolve these discrepancies or propose frameworks to align theoretical and empirical approaches. Chapter 2 looks into this issue.

I.4.3 Summary of Chapter 2

Mind the market: A novel measure of carbon leakage risk

Summary. This chapter addresses the challenge of defining a fair and transparent measure of carbon leakage risk in the EU. This is critical for policymakers to balance climate policy effectiveness with industrial competitiveness. To assess market structure at the country-product level, the chapter introduces a novel application of a methodology that

combines the hypothetical monopolist test and a gravity model. The findings advocate for policymakers to adopt product-specific leakage risk assessments that account for market structure to avoid overestimating risks.

Contributions. *Ex ante* approaches to carbon leakage risk measurement typically assume perfect competition, whereas *ex post* analyses incorporate the imperfect competition observed in real markets. The difference in results from these two strands of research highlights the importance of this parameter to measure leakage risk. Despite this, current *ex ante* EU leakage risk metrics fail to account for market structure. This chapter proposes a theoretically-grounded alternative measure of *ex ante* carbon leakage risk that integrates market structure by applying a tool from industrial organization: the hypothetical monopolist test.

Methodology. This chapter applies the hypothetical monopolist test at the product level. This method defines relevant markets by measuring substitution patterns in response to price changes. The parameters required for the test are derived from a gravity model, estimated using product-level trade data. This approach links estimated trade elasticities to market structure, enabling a granular risk assessment for four industrial products: clinker, hydraulic cement, flat steel products, and long steel products.

Main results. Key findings include: (1) clinker exhibits highest leakage risk due to comparatively lower product differentiation and trade costs; (2) hydraulic cement faces moderate leakage risk due to higher trade costs but low specialization; (3) flat steel shows the smallest leaking risk, reflecting a very limited relevant market due to regional specialization; (4) EU producers' already limited presence on foreign countries' relevant markets suggests carbon pricing impacts on industrial exporters may be overstated. These results underscore the necessity of risk assessments that account for product-level discrepancies and market structure to tailor anti-leakage policies effectively.

Limitations. The analysis is restricted to four products, limiting the ability to generalize results across all industrial sectors. The reliance on trade data may overlook non-price competition factors (e.g., quality, branding). While the methodology addresses aggregation biases found in computable general equilibrium models, it does not directly reconcile discrepancies between *ex ante* and *ex post* leakage estimates, which may be caused by multiple factors. Finally, this methodology is static and does not include any aspects on technological change, which may influence long-term competitiveness and carbon leakage risks.

I.4.4 Summary of Chapter 3

Carbon intensity and corporate performance: A micro-level study of EU ETS industrial firms

Summary. This chapter investigates the relationship between decarbonization efforts and corporate performance in EU industrial firms regulated under the EU ETS' third phase (2012–2020). Analyzing 1,200 firms, it introduces a novel indicator of volume-based emission intensity and employs an instrumental variable approach to address endogeneity. Results reveal an inverse relationship: firms reducing emission intensity do not harm—and may even improve—their economic and financial outcomes. These findings suggest decarbonization can align with competitiveness under robust climate policies like the EU ETS.

Contributions. This study is the first to assess the carbon intensity-corporate performance link within the context of the EU ETS' third phase. It makes three key contributions: (1) developing a volume-based emission intensity metric using EU ETS free allowance data, addressing a known limitation in the literature where carbon intensity is typically measured with value-based denominators (e.g., value added); (2) creating a novel firm-level dataset by matching EU ETS and financial records (EUTL-ORBIS) through a Natural Language Processing approach; and (3) analyzing climate-performance linkages at the firm level specifically for Phase III. The instrumental variable strategy using a Bartik instrument strengthens causal inference.

Methodology. A fixed-effects panel model with a within-firm estimator is applied to isolate the effect of emission intensity changes on a range of corporate performance metrics (return on assets, profit margins, labor productivity, turnover over costs). Endogeneity is addressed via a Bartik shift-share instrumental variable. Emission intensity is calculated as emissions per estimated production volume. Controls for trade exposure (import competition, intra-branch trade) are included to contextualize competitiveness.

Main results. Key findings include: (1) reducing emission intensity correlates with stable or improved financial performance; (2) this effect is stronger when accounting for international competition; (3) no evidence of short-term competitiveness losses from decarbonization, even in trade-exposed sectors.

Limitations. This analysis focuses on short-term effects and does not account for the long-term impacts of deep decarbonization, which would require transformative capital investments. Although Monte Carlo simulations help mitigate measurement uncertainty, data constraints—such as sub-installation production volumes—remain a limitation. Additionally, the study does not incorporate recent policy developments, including Phase IV of the EU ETS and the introduction of the CBAM. Finally, the analysis does not examine dynamic mechanisms, such as innovation, that may shape the long-term relationship between climate performance and corporate outcomes.

I.4.5 Summary of Chapter 4

Green on paper? The effect of green patents on EU ETS firms

Summary. This chapter addresses some of the limitations highlighted in the previous chapters by examining the relationship between innovation, technical efficiency, and emission reductions for firms regulated under the EU ETS' third phase (2013 to 2020). Using a two-stage approach, the chapter first estimates sector-specific production frontiers to measure individual firms' technical and climate inefficiencies. It then investigates how patenting activity and firm characteristics influence firms' ability to displace these frontiers. The analysis aims to identify pathways for reducing inefficiencies and inform policies that work to align decarbonization with industrial competitiveness.

Contributions. This study has three key contributions: (1) it introduces parametric linear programming with directional distance functions to estimate firm-level inefficiencies, addressing methodological critiques of other parametric frontier estimation approaches—namely the inconsistent handling of bad outputs like emissions in econometric models; (2) it links patent data (PATSTAT) with EU ETS firm-level data (EUTL-ORBIS), enabling a granular analysis of how innovation drives frontier shifts; and (3) it focuses on the entirety of the EU ETS' third phase, providing a comprehensive evaluation of climate policy impacts during a period of increasing regulatory stringency.

Methodology. The two-step methodological framework involves:

1. A technological frontier analysis: a linear-quadratic minimization program is applied to a multi-input, multi-output production system (using ORBIS operational and financial data and EUTL emissions data) to construct yearly, sector-specific frontiers. A directional distance function quantifies firm-level inefficiency, accounting for both climate and technical inefficiency.

2. An analysis of the determinants of efficiency: a regression analysis explores how patent metrics (e.g., green patents, total numbers of patents) and firm characteristics (e.g., size) correlate with firms' ability to displace the technological frontier from one year to the next.

Main results. This paper finds evidence of wide variations in the distribution of firm-level efficiency across EU ETS sectors, with some (like Paper and Chemicals) showing high heterogeneity while others (like Cement and EAF Iron and steel) being more uniform. Technological progress is generally concentrated in a few firms, often the same over time, and differs in magnitude by sector. Firms that file green patents tend to become less efficient relative to other firms in their sector of activity, likely due to the maturity and path dependency of brown technologies compared to the still-developing state of green innovation. These patterns suggest the need for targeted policies to support lagging firms and encourage effective green transitions.

Limitations. The study is limited by its reliance on current firm-level efficiency metrics and a short-term analysis window, which may not fully capture the long-term impact of green innovation. Furthermore, the role of innovation in upstream and downstream sectors was not explored, which may be critical in understanding the true impact of green patents on emissions reductions.

Appendix

I.A Carbon leakage estimates found in the literature

Paper	Year of Publication	Method	Carbon leakage rate	Trade channe
Paroussos et al. (2015)	2015	CGE (ex ante)	15.50	Yes
Antimiani et al. (2013)	2013	CGE (ex ante)	12.00	Yes
Kuik and Hofkes (2010)	2010	CGE (ex ante)	18.50	Yes
Arroyo-Currás et al. (2015)	2015	Hybrid (ex ante)	11.00	No
Böhringer et al. (2017)	2017	CGE (ex ante)	18.50	Yes
Parrado and De Cian (2014)	2014	CGE (ex ante)	15.00	Yes
Boeters and Bollen (2012)	2012	CGE (ex ante)	21.00	No
Caron (2012)	2012	CGE (ex ante)	10.50	Yes
Weitzel et al. (2012)	2012	CGE (ex ante)	16.50	Yes
Antimiani et al. (2016)	2016	CGE (ex ante)	32.50	Yes

Note: CGE stands for Computable General Equilibrium. PE stands for Partial Equilibrium.
Source: Author.

Paper	Year of Publication	Method	Carbon leakage rate	Trade channe
Mattoo et al. (2009)	2009	CGE (ex ante)	11.00	Yes
Winchester et al. (2011)	2010	CGE (ex ante)	7.00	Yes
Tan et al. (2018)	2018	CGE (ex ante)	24.00	Yes
Burniaux and Oliveira Martins (2012)	2010	CGE (ex ante)	5.70	Yes
Alexeeva-Talebi et al. (2012)	2012	CGE (ex ante)	12.50	Yes
Balistreri and Rutherford (2012)	2012	CGE (ex ante)	14.50	Yes
Gerlagh and Kuik (2014)	2014	CGE (ex ante)	4.50	Yes
Böhringer, Carbone, and Rutherford (2012)	2012	CGE (ex ante)	11.00	Yes
Dong et al. (2015)	2015	CGE (ex ante)	3.50	Yes
Ghosh et al. (2012)	2012	CGE (ex ante)	12.84	Yes
Aichele and Felbermayr (2015)	2015	Ex post	8.00	Yes
Fowlie and Reguant (2022)	2021	Ex post	49.00	Yes
Larch and Wanner (2017)	2017	Ex post	13.40	Yes

Note: CGE stands for Computable General Equilibrium. PE stands for Partial Equilibrium.
Source: Author.

Paper	Year of Publication	Method	Carbon leakage rate	Trade channe
Naegele and Zaklan (2019)	2019	Ex post	-15.10	Yes
Lanzi et al. (2012)	2012	CGE (ex ante)	4.00	Yes
Böhringer et al. (2017)	2012	CGE (ex ante)	10.50	Yes
Fischer and Fox (2012)	2012	CGE (ex ante)	13.50	Yes
Springmann (2012)	2012	CGE (ex ante)	14.20	Yes
Bednar-Friedl et al. (2012)	2012	CGE (ex ante)	22.40	Yes
Mckibbin et al. (2008)	2008	CGE (ex ante)	7.50	Yes
Peterson and Schleich (2007)	2007	CGE (ex ante)	26.50	Yes
Babiker (2005)	2005	CGE (ex ante)	60.00	Yes
Mathiesen and Maestad (2004)	2004	PE (ex ante)	24.20	Yes
Monjon and Quirion (2011a)	2011	PE (ex ante)	8.20	Yes
Demailly and Quirion (2008)	2008	PE (ex ante)	9.00	Yes
Demailly and Quirion (2006)	2006	PE (ex ante)	29.50	Yes

Note: CGE stands for Computable General Equilibrium. PE stands for Partial Equilibrium.
Source: Author.

Paper	Year of Publication	Method	Carbon leakage rate	Trade channe
Monjon and Quirion (2011b)	2011	PE (ex ante)	10.40	Yes
Misch and Wingender (2021)	2021	Ex post	25.56	Yes
Kruse et al. (2024)	2024	Ex post	13.00	Yes
Paltsev (2001)	2001	CGE (ex ante)	10.50	Yes
Dechezleprêtre et al. (2022)	2022	Ex post	0.00	Yes
Dechezleprêtre et al. (2020)	2020	Ex post	0.13	Yes

Note: CGE stands for Computable General Equilibrium. PE stands for Partial Equilibrium.
Source: Author.

Chapter 1

The case for carbon leakage and border adjustments: Where do economists stand?

***

Abstract

While the EU is working towards the implementation of the world's first Carbon Border Adjustment (CBA) Mechanism, a gap remains between the ways in which carbon leakage and CBAs are discussed in policy spheres and economic evidence on these topics. The aim of this paper is to bridge this gap by presenting the EU's policy context, systematically reviewing the economic literature on carbon leakage and CBAs, and discussing potential research avenues that should be explored in the future. Three channels of leakage are identified in our literature review: the competition, energy and innovation channels. The main finding of this paper is that while the competition channel is taken into account in policy decisions, the energy and innovation channels are generally under-evaluated. Policy recommendations are provided to better account for these two channels.

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Chapter dissemination

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It was further updated in a forthcoming OECD report that cannot be shared before its publication.

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- 2021 Annual Conference of the Climate Economics Chair
- 2021 Climate Economics Chair Doctoral Seminar

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1.1 Introduction

As the EU has progressively established its Emissions Trading System (ETS), it has had to grapple with the ways in which this system impacts its economic ties with non-EU countries. Under the EU ETS, producers must buy or be allocated emissions allowances, which they can then trade with other participants. At the end of each year, they must turn in enough allowances to cover the greenhouse gas (GHG) emissions from their annual production. This system acts as a price on carbon, which increases participants' production costs.

If the additional cost is high enough to put them at a competitive disadvantage compared to foreign producers, EU producers could lose parts of their market shares. They might also choose to relocate their activity outside the EU to avoid paying this additional cost. Both of these effects would decrease production within the EU, and increase production outside the EU. Not only would this undermine the EU's emission reduction efforts – since any internal reduction in emissions would be compensated by an external increase in emissions – it would also harm its economy and labor market.

This problem is known as carbon leakage, defined in the economic literature as a displacement of carbon emissions from a region with stringent climate policies towards a region with less stringent climate policies (Naegele & Zaklan, 2019). Carbon leakage is most commonly understood as we have described it above – a mechanism through which regulated domestic firms lose their competitive edge to unregulated foreign firms. However, this is only one of three channels through which carbon leakage can occur, known as the competition channel.

The second channel is the energy channel. It is an indirect leakage channel working through global energy markets. As a regulated region reduces its demand for fossil fuels, the price of these goods will drop on international markets. This price drop can create an incentive for firms in the unregulated region to increase their fossil fuel consumption, consequently also increasing their GHG emissions.

Finally, the third channel is the innovation channel, which has an opposite effect to the other two channels. More stringent environmental regulation encourages firms in the regulated region to invest in R&D, innovate, and adopt carbon-abating technologies and processes. Innovations resulting from this may then be diffused to other regions, including those without any environmental regulation. This channel is not discussed much in policy circles, despite its potential for generating negative carbon leakage, i.e., to reduce carbon emissions both in the regulated and the unregulated region.

A fourth channel known as the income channel is sometimes mentioned in the literature. This channel could work through a change in the terms-of-trade between countries

as a result of carbon pricing, which could indirectly modify global consumption patterns. However, this channel is very uncertain and likely only has a negligible impact compared to the other channels if it does exist (Cosbey et al., 2019).

Up until now, the EU has dealt with the threat of leakage by lowering the stringency of its ETS. This was accomplished by freely allocating emissions allowances to firms covered by the ETS and by allowing the use of international carbon offsets to comply with regulation requirements. However, a new policy option is now being considered to replace free allocations: on 14 July 2021, the European Commission (EC) formally adopted a proposal for a Carbon Border Adjustment Mechanism (CBAM), as part of its Fit for 55 program (European Commission, 2021a). The CBAM imposes a carbon price on foreign goods imported to the EU which should level the playing field between foreign and domestic producers and reduce the risk of leakage. The current proposal foresees a gradual implementation of the CBAM starting in 2023.

The aim of this paper is threefold. First, we present the context and policy debate surrounding carbon leakage and Carbon Border Adjustments (CBAs) in the EU. Second, we discuss the state of the economic literature on carbon leakage and CBAs. Finally, we include discussions on further research that is necessary in this field to answer policy concerns and unresolved research questions.

Several other literature reviews on carbon leakage and/or border adjustments exist, focusing on specific aspects or methods in the literature. Cosbey et al. (2019) briefly review the economic and legal literature on these topics, before giving an in-depth discussion on policy recommendations for a CBA - although these are not EU-specific. Dechezleprêtre and Sato (2017) review the empirical evidence on the effects of asymmetrical environmental regulation on key aspects of firms' competitiveness, but do not directly discuss leakage effects, while Verde (2020) reviews the same effects but only in the context of the EU ETS. For reviews of the literature using computable general equilibrium (CGE) models, Carbone and Rivers (2017) and Branger and Quirion (2014) are key references. Finally, Popp (2019) looks at recent empirical research delving into the link between environmental policies and green innovation.

The aim of the present literature review is to be broader than the ones cited above, and to provide readers with a global understanding of issues related to the different channels of carbon leakage and to carbon border adjustments. To achieve this, we describe the mechanisms underpinning each of the three channels of carbon leakage, and give a full review of existing evidence from empirical, theoretical, and structural strands of the literature. This allows for a better understanding of this literature, and gives some context to the discussions and literature on CBAs which are also presented. Additionally, our description of the EU's policy context and history dealing with carbon leakage

is an addition to existing literature and puts the findings from economic research into perspective.

In this paper, we highlight the discrepancy between the economic literature and policy debates about CBAs. Policymakers tend to focus on the competition channel when designing leakage-prevention measures, without taking into account the potential impacts of the energy and innovation channels. To address this discrepancy, we recommend that policymakers also aim to minimize the impact of the energy channel by developing cooperation with unregulated countries and taking foreign carbon pricing and regulation initiatives into account in the CBA. Additionally, they should work to maximize the impact of the innovation channel by promoting green technology diffusion to unregulated countries and reinvesting CBA funds into an international technology fund.

The paper is structured as follows. Section 1.2 anchors the problem of carbon leakage in the EU's political and institutional context, discussing the bloc's history of carbon leakage mitigation measures, as well as the debate surrounding the proposal for a CBA. Sections 1.3, 1.4 and 1.5 review the literature on the competition, energy, and innovation channels of carbon leakage, respectively. This review includes discussions on further research that may be needed for each channel. Finally, section 1.6 presents existing literature on CBAs, and looks at the impact of such a policy on each of the three leakage channels. Section 1.7 concludes.

1.2 Political and institutional contexts

This section discusses the political and institutional contexts in which carbon leakage has been apprehended in the EU throughout the different phases of the EU ETS. We present the policy choices that have been considered over the years and give some insight into why free allocations and international offsets were preferred to CBAs until now. Our aim is to give a solid understanding of the political considerations linked to leakage mitigation policies so they can be put into perspective with the economic literature presented in sections 1.3, 1.4, and 1.5.

1.2.1 A brief history of leakage mitigation in the EU

Carbon leakage has been discussed in the EU policy sphere since the ETS' inception. However, it was not a central issue during the first two phases of the EU ETS (2005-2012). This is mostly due to three factors: first, most emissions allowances were freely given out to firms; second, firms were allowed to use international carbon credit offsets to comply with their obligations; and third, carbon prices remained low. As a result,

complying with the EU ETS during its first two phases did not represent a large financial constraint, which nullified the risk of leakage (Joltreau & Sommerfeld, 2019).

The EU ETS' first phase (2005 to 2007) was designed as a pilot phase, so producers could adapt to the new regulation and give feedback on its implementation. 95% of allowances were given out freely, based on a grandfathering approach[1]. To determine the total number of allowances needed on the market, countries were asked to develop National Allocation Plans, in which they estimated how many allowances their firms would need based on historical emission data. The goal was to develop an equitable, bottom-up approach to allowance distribution. In practice however, most countries overestimated their producers' needs to protect their national interests. This created an oversupply of allowances throughout the entire trading phase[2]. As soon as the oversupply was revealed, allowance prices dropped. They remained low and volatile until the end of the first trading period (Le Cacheux & Laurent, 2009).

In the second phase (2008 to 2012), a larger proportion of allowances was auctioned off to producers, but the majority (90%) remained freely allocated using the same grandfathering approach as in the first phase. Allowance oversupply was avoided in this phase through a stricter oversight of National Allocation Plans by the EC (Kossoy & Ambrosi, 2010).

Despite this, allowance prices remained low during this phase for two main reasons. The first was a policy choice. The EU ETS was designed with a link to the United Nations Framework Convention on Climate Change's Clean Development Mechanism. This link allowed EU firms to cover their carbon emissions not only by turning in ETS-issued allowances, but also by turning in international credits from the Clean Development Mechanism[3]. The possibility of complying with EU ETS obligations in this alternative manner, which could be cheaper than buying allowances, reduced demand for EU ETS allowances[4], thus lowering prices on the EU carbon market (Trotignon, 2011). There

[1]The grandfathering approach allocates emissions allowances proportionally to each installation's historical emissions. This means that installations with historically higher levels of carbon emissions are given more emissions allowances than installations with historically lower levels of carbon emissions (European Commission, 2015).

[2]At the end of the first trading period, it was estimated that verified GHG emissions in 2005 totaled 2 billion tons, while the annual total allocation was far higher, totaling 2.2 billion tons (European Commission, 2006). However, Ellerman and Buchner (2008) argue that in 2005-2006, there was no significant over-allocation. In their opinion, the difference between total emissions allowances and total observed emissions is not substantial, and could be the result of lower production levels and abatement strategies.

[3]These credits represent the amount of carbon removed from the atmosphere or reduced compared to a business-as-usual scenario as a result of a firm's project in a developing country. EU ETS participants have been allowed to use Certified Emission Reduction (CER) credits from Clean Development Mechanism projects since the first phase of the EU ETS. However, the two systems were only directly linked for accounting purposes in 2008, and the economic incentive to use this link was stronger in the second phase of the EU ETS. This meant that CER credits were only used for compliance with EU ETS obligations starting in the second phase (Ellerman et al., 2010).

is also evidence that CDM credits were granted quite liberally, and that many projects that were awarded these credits would have been built without them (Calel et al., 2021). This implies there was a strong incentive for firms to invest in CDM projects - that were lucrative anyways - rather than invest in the decarbonization of their domestic production.

The second reason why prices remained low was circumstantial: the 2008-2009 financial crisis led to a collapse in production which cut down demand for allowances, mechanically driving carbon prices down as well (de Perthuis & Trotignon, 2014).

While leakage itself was not an issue during this second phase of the EU ETS, the subject began taking up more space in policy debates as planning for the EU ETS' more ambitious third phase started. In 2008/2009, during the review period before the launch of the EU ETS' third phase (2013 to 2020), carbon leakage was more explicitly discussed, mostly in terms of the threat it posed to the competitiveness of EU industry. In this third phase, free allocations were to be gradually replaced by an auctioning mechanism, potentially increasing EU firms' compliance costs and making them more vulnerable to competition from unregulated foreign firms. This shift was motivated by the fact that auctioning reduces distortions caused by free allocation, increases market efficiency, and addresses distributional impacts of the EU ETS. Additionally, it is more compatible with EU State aid legislation and can more easily be combined with a price cushioning mechanism or a CBA (Hepburn et al., 2006).

This review period before the EU ETS' third phase is when the idea of a CBA gained some traction for the first time – though it was not implemented at this stage. By imposing a carbon price on imports, equal to the EU's internal carbon price, a CBA was seen as an option to mitigate the risk of carbon leakage and of loss of competitiveness.

A first proposal for a CBA on imports and exports of goods "subject to significant risk of carbon leakage or to international competition" was included in a draft proposal amending the EU ETS[5]. Additionally, the French government published a white paper promoting a "Carbon Inclusion Mechanism" in 2009 and pushed for this policy in Brussels (Simon, 2010). However, the idea was not taken up and the final amendment proposal did not include any mention of a CBA. Instead, it included the use of targeted free allocations for sectors at risk of carbon leakage. A list of these sectors was drawn up in 2010 and amended in 2014 on the basis of their carbon intensity and exposure to international trade. They received a higher share of free allocations than other sectors. On top of this, international carbon offsets remained available to firms who wished to use them for compliance.

[4]Participants used international credits to comply with obligations for 1.058 billion tons of emissions in the EU ETS' second phase (Commission, 2016).

[5]Draft Proposal 2007/XXXX (COD) for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the EU greenhouse gas emission allowance trading system.

The debate over a CBA replacing free allocations was taken up again during the review period for the EU ETS' fourth phase (2021 to 2030). In 2016, a second French government white paper proposed a CBAM that would only be applied to the cement sector as a test. However, this was rejected in the European Parliament in favor of keeping targeted free allocations.

Breaking with its previous policy line, the EC announced in its 2020 Green Deal that it would be putting forward a proposal for a CBA to gradually replace free allocations in the fourth phase of the EU ETS. Published on 14 July 2021, this proposal provides for a CBAM that would cover imports from 5 sectors: cement, electricity, fertilizers, iron and steel, and aluminium. Importers would have to buy CBAM allowances from a pool of emissions allowances that mirrors but is separate from the EU ETS. They would then have to surrender enough of these allowances to cover the total embedded emissions of their yearly imports. These allowances would be priced at the level of the weekly average of EU ETS certificate closing prices. The regulation is expected to enter into force in 2023, with a transition period running until 2026 (European Commission, 2021a).

The idea of introducing a CBA instead of free allocations is not new, but until now, it had not been taken up by policymakers for implementation. Why did the EU not take up this option before? And why might a CBA now be considered to be viable? The following subsection aims to answer these questions.

1.2.2 Has a CBA become a viable policy option?

Up until now, the EU had rejected the idea of a CBA, in part because of the complexity of its implementation. It is unclear whether a CBA could be designed to comply with WTO law as well as with the UNFCCC's principle of Common but Differentiated Responsibilities. Additionally, such a policy could expose the EU to retaliations from trade partners who view it as a protectionist measure. We discuss each of these issues here.

Compliance with WTO law is uncertain for several main reasons. The first is that certain principles of WTO rules might not be compatible with a CBA, depending on how it is designed. The principles of Most Favored Nation[6] and of National Treatment[7] could be challenging in this regard. The second reason is that certain technical aspects of WTO rules might not allow for a CBA to be implemented at all – namely the fact that a CBA would tax CO2, an intangible and not easily measurable output in the production

[6]In WTO law, the Most-Favored-Nation clause forbids countries from implementing trade policies that discriminate between different WTO member nations.

[7]In WTO law, the National-Treatment clause forbids countries from implementing trade policies that favor their domestic producers over foreign producers.

of a good. Both of these issues could be overcome if the EU can successfully argue the necessity and proportionality of a CBA for the protection of the environment. However, this is also a challenge given that preliminary studies on CBAs do not clearly indicate that the policy would have strong environmental benefits (see section 1.3). For a full discussion on WTO-compliance issues, see Mehling et al. (2019). The main takeaway from the legal debate on CBAs is that the design of the policy should focus on ensuring environmental benefits can be obtained from it. This would make it more likely to be WTO-compliant.

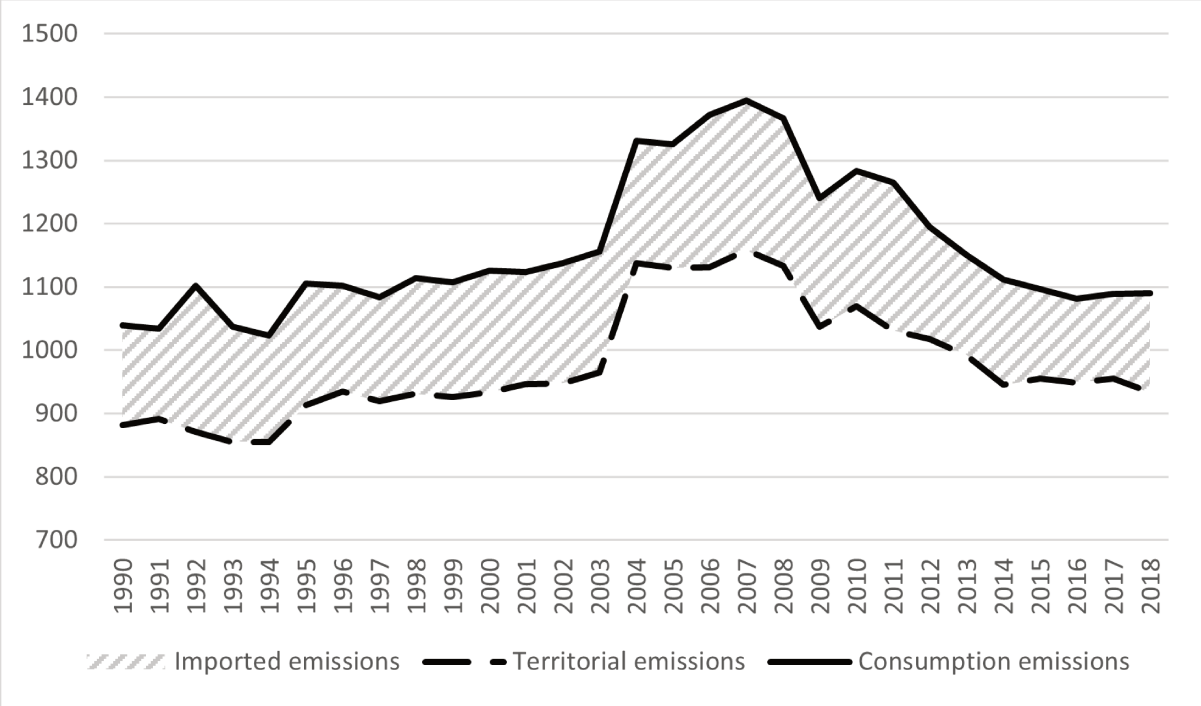
Another issue which makes designing a CBA so complex is the necessity of complying with the UNFCCC's principle of Common but Differentiated Responsibility. The principle states that while all countries are commonly responsible for addressing climate change and environmental destruction, each country's contribution to this cause should be proportional to its capacity to act and to its share of responsibility in historical global emissions. This means that developed countries are expected to contribute more than developing countries, the latter being responsible for a small share of historical global emissions and having more limited means of action. Böhringer et al. (2018) show that a CBA in OECD countries shifts the burden of decarbonization from developed countries onto developing countries, due to an adverse terms-of-trade effect caused by higher export prices. Additionally, Magacho et al. (2024) highlight that some developing countries are particularly exposed to the costs of an EU CBAM given their heavy reliance on exports of products that will be covered by the regulation. This is especially salient when looking at the weight of these exports in some countries' total exports and GDP. As such, this policy could unduly shift burden onto developing countries, making it non-compliant with the UNFCCC's principle of Common but Differentiated Responsibility.

Given that the EU is a net carbon importer (see figure 1.1), a CBA would also create adverse terms of trade for its main trading partners. To avoid shifting this burden onto developing countries, they could be excluded from the CBA's scope, or compensated with the revenue from the CBA. However, this would create more complications for WTO compliance.

Finally, the last major argument used against implementing a CBA is the fear of retaliation from trade partners. The EU's carbon imports mostly come from China, the US, India, and Russia (Peters et al., 2011). These would be the countries most capable and inclined to retaliate with their own trade measures. This risk is especially present given the frayed state of the current international trade environment, and the fact that a CBA's environmental benefits are not yet certain.

[8]For territorial emissions: Friedlingstein et al. (2020) For consumption emissions: updated from Peters et al. (2011), 2011. Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences 108, 8903-8908. http://www.pnas.org/content/108/21/8903.abstract

Figure 1.1: The EU's carbon loophole (million tonnes of CO2 emissions per year)



Note: EU changing composition
Source: Authors' visualization based on The Global Carbon Project[8]

Each of the three points presented above have stopped the EU from implementing a CBA until now. The bloc's recent shift in policy preference could be explained by several factors. One of them is that the current global geopolitical environment is very different from what it was when a CBA was first proposed. Some of the world's largest international players – the US first and foremost – have turned to more protectionist and unilateral trade policies. In such an environment, if the EU were to impose its own unilateral trade policy, not only would the opportunity cost be lower, but there would also be less risk of a coordinated retaliation from its trade partners. Another factor which might sway the EU towards a CBA is the internal pressure EU countries are facing from their population as the bloc's environmental ambition increases. In order to be socially acceptable, the EU cannot let its producers bear the full brunt of compliance with environmental regulation while competing with unregulated foreign producers, nor can it let its consumers pay for fully passed-through compliance costs.

Beyond these geopolitical considerations, a CBA may now be the preferred leakage mitigation measure because free allocations have proven to have significant flaws. Indeed, with some time having passed since the EU ETS' inception, researchers have been able to assess the effectiveness of free allocations, focusing on two main questions. First, have they effectively protected EU firms from unregulated foreign competitors? Second,

have they also inadvertently muted the ETS' price signal and reduced its environmental effectiveness?

To answer the first of these two questions, evidence seems to indicate that EU firms did not suffer any competitiveness losses as a result of participating in the EU ETS (Joltreau & Sommerfeld, 2019). Due to data availability, most studies with this result only look at the first, second and beginning of the third phase of the EU ETS, when free allocations were the general rule. Thus it seems that during these initial phases, free allocations were effective at protecting EU firms from competition with unregulated foreign firms. However, as discussed above, the absence of competitiveness losses could also be the joint consequence of low carbon prices in this period, and of the possibility of using international carbon offsets.

To answer the second question and understand the impact of free allocations on environmental outcomes, researchers have studied how this mode of allocation impacts firms' incentives to abate their emissions (see Verde et al. (2019) for a full review on this topic). In theory, there should be no difference in firms' abatement decisions whether allowances are freely allocated or auctioned, because the opportunity cost of an allowance is the same in both cases. If allowances are freely allocated, a firm deciding not to abate its emissions will lose out on potential income it could have received from selling its allowance. This lost income is the same amount as what it has to pay to buy an allowance if they are auctioned.

In practice however, the hypothesis of neutrality of the mode of allocation does not seem to hold. Evidence from De Vivo and Marin (2018) points to a difference in behavior between firms freely receiving allocations and those subject to auctioning. There could be two main reasons for this. The first is that firms may not be making fully rational decisions; they may choose to change their abatement decisions based on a false sense that auctioning is more burdensome than free allocations. The second is that while the method of allocation may be neutral on a firm's opportunity cost, auctioning has an impact on its total compliance burden, while free allocations do not. The opportunity cost determines a firm's abatement decisions (i.e., whether or not to reduce its production to meet emission goals) while the total compliance burden determines its investment strategy (i.e., long-term investments to improve the efficiency of production). As a result, switching to auctioning could have an effect on firms' investment decisions. This possibility would have to be confirmed with further empirical research as the data currently available does not allow a validation of either of these hypotheses.

This is a particularly important research question, since the EU's carbon price is set to gradually increase in the coming years, and with it, the long-term incentive for firms to invest in decarbonizing processes. If free allocations mute this incentive, then

the environmental efficacy of the EU ETS is at risk. It is crucial to ensure that firms receive strong and long-term price signals so they can make investment decisions that take environmental factors into account. Firms will only invest in long-term technology and process transformations to decarbonize their production if they feel that the alternative – buying enough allowances to cover their emissions – is more expensive. As such, free allocations risk causing a high-carbon technology lock-in.

This section has described the most prominent concerns related to carbon pricing and leakage in the EU, from legal and policy perspectives. The crux of the problem is that unevenly ambitious global environmental regulations may cause carbon leakage - a risk which policymakers readily associate with the EU ETS. It is therefore crucial to understand exactly what degree of carbon leakage risk the EU ETS actually generates.

To answer this question, we turn to the evidence of carbon leakage in the academic literature, through each of the three channels we have presented in section 1.1. Our aim is to bridge the gap between the policy debates we have just described, and the risks and opportunities identified in the academic literature.

1.3 The competition channel

As stated in section 1.1, most EU policy debates surrounding carbon leakage center on the competition channel[9]. This section aims to give an in-depth understanding of the workings of this channel, highlighting major findings from different strands of the academic literature. We first present the basic functioning of the competition channel through its roots in game theory, before turning to empirical evidence from the ex-post literature and finishing with partial and general equilibrium models. The choice of organizing this literature by methodology is driven by the fact that both quantitative and qualitative results greatly depend on the methodology used in each study.

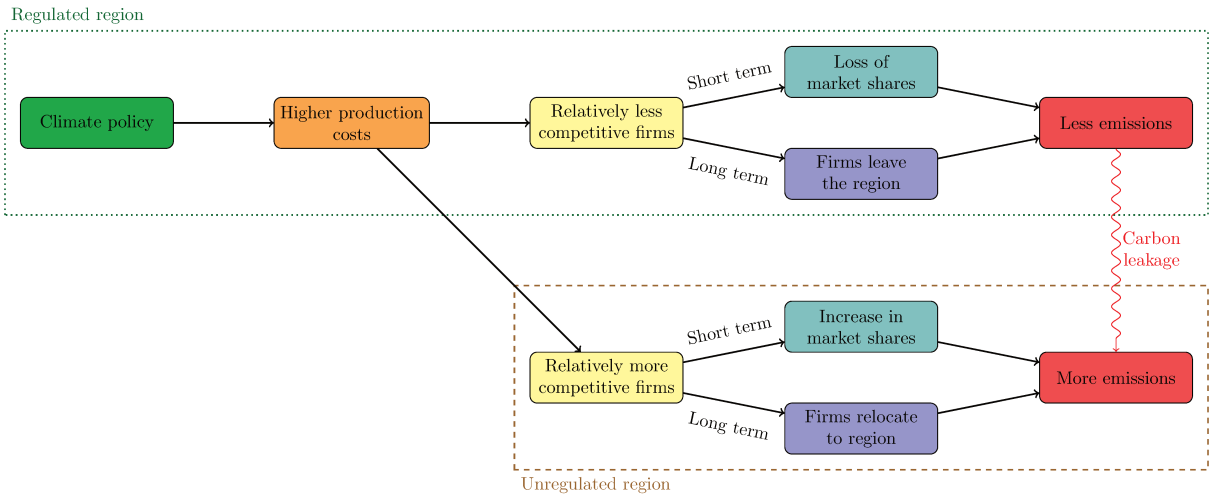
1.3.1 How does the competition channel work?

Carbon leakage through the competition channel occurs when a region implements environmental policies on its territory that are more constraining than in other regions. Its domestic producers face additional costs to comply with the regulation, which puts

[9]An illustration of this can be found in the EU's Impact Assessment Report of a CBAM (European Commission, 2021a). In this document, carbon leakage is defined as "increasing emissions outside the Union through relocation of production or increased imports of less carbon-intensive products", implying the official stance is to consider leakage only through the competition channel. It is also the only channel which is discussed by third parties in the consultations led by the EC. On the other hand, the energy channel is briefly mentioned just twice in the whole document, in the technical section describing the CGE model they use to estimate the impact of a CBAM.

them at a competitive disadvantage compared to foreign producers who supply the same markets but are not subject to the additional compliance costs (see figure 1.2).

Figure 1.2: The competition channel



Source: Authors

In a perfect competition setting, there are two possible consequences to this loss of a competitive edge. First, in the short run, domestic producers may lose market shares to unregulated foreign competitors. Second, in the long run, domestic producers may choose to relocate part or all of their activity to countries with less stringent climate policies. This second consequence is also sometimes called investment leakage.

While classical economic theory and most CGE models use a perfect competition setting, carbon leakage has also been modeled in the context of more realistic settings with strategic interactions and imperfect competition. The competition channel was in fact first formalized using game theory, which models international trade as a game between trade partners that may exhibit strategically motivated behaviors. Within game theory, two foundational strands exist: one at the country level and one at the firm level.

Hoel's (1991) seminal paper is at the core of the first, country-level strand. He sets up a two-country model, in which each country aims to maximize its benefit function and can decide on the quantity of emissions it abates domestically as well as its level of production. Its cost function increases with the amount of emissions it decides to abate domestically, while its benefit function increases with the sum of emissions both countries decide to abate. In this setup, and in the absence of an international agreement on emissions reductions, both countries will always choose not to abate their emissions. If one country were to abate its emissions unilaterally, the other country would mechanically increase its emissions to reduce its cost function, without any loss to its benefit function. This is an expression of carbon leakage at the country level as an uncooperative and

non-Pareto efficient Nash equilibrium. Emissions are simply shifted from one country to the other, without any global reductions.

The second, firm-level strand of game theory literature on carbon leakage was developed by Markusen et al. (1993). In their model, if one region decides to implement constraining environmental regulation, firms in this region decide to relocate their activity to an unregulated region and export part of their production back into the regulated region. Many firms may relocate at once if the constraint from the new environmental policy exceeds the fixed cost of relocating production. As such, there is also only a redistribution of emissions between countries, rather than a global decrease in emissions.

The analytical conclusions derived from these early works are the foundation for empirical tests and structural models that have been developed since then to evaluate the risk of carbon leakage. In the case of the EU ETS, the question is therefore to understand whether the financial constraint of compliance has been large enough to induce a leakage effect. According to theoretical models, this should be the case. The following subsection discusses empirical testing of this hypothesis.

1.3.2 Has the EU ETS caused carbon leakage through the competition channel?

Different strategies have been adopted to empirically test for carbon leakage caused by the EU ETS. Most studies find no evidence of carbon leakage so far. Verde (2020) surveys the econometric literature on this topic and concludes that very little, if any, carbon leakage can be causally linked to the EU ETS. The author identifies four major strands of research.

The first comprises of microeconomic studies of firm-level or sector-level competitiveness indicators such as value added, employment or total factor productivity. The EU ETS' short-run impact on these indicators depends on the specific measure that is used. However, most of the effects are either null or weakly negative – and in some cases even positive, meaning the ETS has actually improved EU firms' competitiveness. This could be because some carbon cost passthrough may be occurring or because firms are investing in carbon-abating innovations which are also productivity-enhancing.

The second strand Verde identifies is composed of studies looking at long-term investment leakage. The EU ETS' long-run impacts have been studied less than its short-run impacts and results are consequently not as clear cut. Two studies looking at investment leakage find that the EU ETS may have increased multinational firms' FDI towards non-EU countries. However, they look only at Italian and German firms, respectively (Borghesi et al., 2020; Koch & Mama, 2019). These studies find a relatively small effect.

The third strand of this literature comprises very few studies, and tries to find direct evidence of carbon leakage. Rather than looking at indicators of competitiveness, studies from this third strand look into the displacement of carbon emissions between regions. Naegele and Zaklan (2019) study the carbon content of trade to and from the EU using a gravity model, while Dechezleprêtre et al. (2022) study carbon leakage within multinational firms. The latter study has been updated and extended in Dechezleprêtre et al. (2020), which covers the first two years of the EU ETS' third phase. Each of these studies finds no evidence of carbon leakage resulting from the EU ETS. A recent study by Eskander and Fankhauser (2021) looks more broadly into the impact of climate regulation on carbon imports and exports. Interestingly, they find that legislation from 3 years ago and older has in fact led to a small, but significant, negative leakage effect. However, this is not an ETS-specific result.

Finally, Verde discusses a last, more distinct, strand of the literature which studies the effect of EU ETS allowance prices on participating companies' stock returns. The papers in this strand aim to measure the impact of carbon pricing on investors' beliefs about a firm's future profitability, rather than its present profitability. Their results do not measure how much leakage has occurred, but rather how much investors believe ETS prices affect the firm's profitability, which may in turn lead to leakage – although this is not tested for. Two main results emerge from this literature. First, the relationship between carbon prices and stock prices is generally found to be positive in the EU ETS' first phase and negative in the second and third phases. This suggests the mode of allocation has an effect on investors' perception of firm profitability. Second, more carbon-intensive firms' stock prices tend to be negatively correlated with EU ETS prices, while less carbon-intensive firms' stock prices tend to be positively correlated with them.

The common conclusion from all four strands of this literature is that carbon leakage does not seem to have materialized as a result of the EU ETS. However, an important caveat should be highlighted: due to data availability, most of the surveyed literature looks only at the first two phases of the EU ETS – and the first years of the third phase for a few of them. During this period, free allocation was the general rule and carbon prices remained low. Researchers exploited breaks in this general rule to study leakage, but this may not accurately reflect the current situation in which prices have tripled, and free allocations have gradually been replaced by auctioning[10]. As a result, the ETS' financial impact on firms is likely greater than it was during the period that is studied in the literature, which could imply more carbon leakage is occurring than previously measured.

[10]As of 2013, 100% of allowances were auctioned in the power sector. In the manufacturing sector, 20% of allowances were auctioned in 2013. This was gradually increased to 70% in 2020, excluding sectors on the list of high leakage risk. In the aviation sector, 15% of allowances were auctioned in the third phase. Overall, 57% of allowances were auctioned in this phase.

Going back to the distinction between short- and long-run effects from the theoretical models of leakage through the competition channel, empirical studies have therefore only looked at the short run (2-7 years). Long-run effects will have to be studied separately as more time passes and further data is made available.

Additionally, there may be a stronger risk of within-firm leakage than of between-firm leakage inside the EU. Since the EU ETS regulates only installations whose emissions are above a certain level, certain firms with multiple installations may be switching some of their production from regulated installations to unregulated installations - thus artificially reducing emission levels in the regulated installations. While this phenomenon has not yet been studied in depth in the EU ETS' context, it has been observed in the context of environmental regulations in the US (Gibson, 2019; Soliman, 2020). The only study looking at this in the EU ETS context finds no evidence of within-firm leakage. However, this is once again using data which does not go further than the second phase (Wagner et al., 2014).

While observed leakage remains quite low for now, the EU is planning on tightening its ETS to become gradually more stringent. Free allocations will be fully phased out for sectors that do not have a high risk of leakage by 2030 and the ETS' cap will be tightened by reducing the overall number of allowances on the market by 2.2% each year from 2021 onwards, instead of 1.74% as is currently the case. This should increase the price of carbon over time as well as the financial constraint on participants that do not receive free allocations. This might in turn increase the risk of leakage.

The impacts of this policy tightening cannot yet be tested empirically. As such, *ex ante* models can provide valuable insights into the potential impacts of a more constraining ETS. We now turn to the description of these models and their main conclusions about carbon leakage through the competition channel.

1.3.3 What drives carbon leakage according to *ex ante* general equilibrium models?

CGE models have been the workhorse models used to quantitatively assess the risk of carbon leakage linked to different policy scenarios in the long run. These models identify the conditions under which significant carbon leakage can occur, the policy choices that can mitigate this risk, and the behavioral and contextual parameters which can exacerbate or reduce the problem. Most of them use data from the Global Trade Analysis Project (GTAP) to calibrate behavioral parameters and elasticities, which are then used in *ex ante* policy simulations, generally imposing a carbon price on a given region. To avoid

any distortionary effects, most of these studies include revenue recycling for this carbon price, in the form of a lump-sum transfer back to consumers (Carbone & Rivers, 2017).

Though these models provide quantitative results on the amount of carbon leakage which can be expected given certain assumptions – which we briefly discuss below –, these results are quite sensitive to the calibration choices made in each model. Additionally, CGE models are too broad in scope to model specific existing policies like the EU ETS. Instead, they generally model uniform price increases across an entire region. As such, the qualitative insights from this literature are more important to understand leakage. The exact time frame studied in these models is also not too significant but they are meant to capture long-run effects.

Branger and Quirion (2014) perform a meta-analysis of CGE studies on the topic of carbon leakage and find that estimates of the leakage ratio[11]range from 5 to 25%. This means that up to one quarter of the emission reductions a climate policy induces in the region where it is implemented are compensated by an increase of emissions in the unregulated region.

Carbone and Rivers (2017) review the CGE literature specifically studying the impact of environmental policies on competitiveness indicators. They find that the literature identifies an average 5% reduction in the output of energy-intensive and trade exposed (EITE) sectors resulting from a 20% unilateral emission abatement objective. This seems to indicate that in a scenario where carbon pricing becomes more stringent, there could be a higher risk of carbon leakage, especially for EITE sectors. However, the magnitude of this phenomenon is not clear and highly depends on the parametrization of each CGE model.

Some of the parameters that are used in CGE models have a particularly large influence on the size of the estimated carbon leakage ratio. The most determining parameters are the Armington elasticity[12], the size of the abating coalition, and market structure assumptions. This is somewhat problematic given that there is uncertainty surrounding the value of these parameters, as described below.

Estimates of the Armington elasticity, which measures the degree of substitutability between foreign and domestic products, can vary substantially; differences in estimates are largely driven by the level of data aggregation, as well as data size, frequency, and dimension (Bajzik et al., 2020). Despite the uncertainty surrounding the real value of

[11]The carbon leakage ratio is the measure most often used in CGE models to assess the amount of carbon leakage linked to a policy scenario. It is generally measured as the increase in emissions outside the regulated region divided by the decrease in emissions inside the regulated region.

[12]Armington structures of trade assume that identical products from different countries are imperfect substitutes. The extent to which products are differentiated by country of origin is measured by Armington elasticities, which are cross-elasticities between two identical products from different countries (Armington, 1969).

this elasticity, Branger and Quirion (2014) note in their meta-analysis that the choice of a high Armington elasticity has a positive and statistically significant impact on a model's estimate of the carbon leakage ratio. To get around this, some studies carry out sensitivity analyses using relatively higher and lower values of the Armington elasticity to produce a range of leakage estimates. However, this does not remove all of the uncertainty related to this parameter.

Finally, market structure assumptions can also influence the amount of leakage that models find. Most CGE models assume perfectly competitive Armington structures of international trade. However, Babiker (2005) and Balistreri and Rutherford (2012) show that departing from this structure can lead to much higher leakage estimates. Babiker adopts an oligopolistic structure and assumes energy-intensive goods are Heckscher-Ohlin in structure – meaning that goods produced in different countries are perfectly substitutable. In this scenario, the leakage ratio exceeds 100%. Babiker (2005) explains this surprising result by the fact that unexploited economies of scale in energy-intensive industries could be unlocked when production is relocated to developing countries. Balistreri and Rutherford (2012) apply Melitz's (2003) "New" New Trade theory, a monopolistic competition structure, to an otherwise standard CGE model. They find that adding firm heterogeneity to their model exacerbates the problem of carbon leakage through the competition channel because resources are reallocated to the most productive firms in the unregulated region, which do not have any incentive to reduce their emission intensity.

Mathiesen and Maestad (2004) make the argument that the broad scope of general equilibrium models does not allow for enough sectoral specificities when estimating the carbon leakage ratio. Their paper focuses on the steel sector. They use a partial equilibrium framework and show that adding substitution possibilities between different types of steel production and between inputs to steel production halves the leakage ratio compared to what general equilibrium models – which do not include these specificities – generally find. Another potential source of effect overestimation is that most CGE models apply an economy-wide carbon tax, without any sectoral exemptions. This does not reflect the EU ETS's functioning, as the regulation only applies to certain industries and thus has a more restricted perimeter which should create a smaller risk of leakage.

The main takeaway from the CGE literature is that while the magnitude of leakage caused by an ETS is uncertain, there is a general consensus around the fact that the more constraining carbon pricing is, and the smaller the abating coalition is, the more of a problem carbon leakage may become.

1.3.4 What are the remaining gaps in the literature for the competition channel?

As we have seen, the economic literature is inconclusive about how much of a problem leakage through the competition channel actually is. While the empirical literature shows that leakage has not been a problem in the first phases of the EU ETS, it does not yet give results about the more constraining recent phases of the system. On the other hand, *ex ante* literature points to a higher risk of leakage, the magnitude of which is uncertain.

This literature could therefore be completed with empirical assessments of more recent phases of the EU ETS, once data becomes available. Concerning *ex ante* modelling, more work could be done on the impact of the EU ETS on value-chains inside and outside the EU, and how network effects could exacerbate leakage.

Additionally, non-price competition is not taken into account in existing models, despite the fact that it may have a significant impact on international trade patterns (Bas et al., 2015). Vertical competition through quality or branding could significantly affect the leakage ratio if consumers have a strong preference for higher quality products. For example, if EU steel producers manage to successfully decarbonize their production, they will likely be able to pass on higher production costs to construction companies which face increasing pressure and mounting regulatory standards to include environmental criteria in their production decisions.

1.4 The energy channel

The energy channel is less discussed than the competition channel in policy circles, but it has been identified in the economic literature as a potentially significant, long-term threat to the effectiveness of a region's environmental strategy. In this section, we first discuss the mechanism underlying this channel, before reviewing the literature studying the magnitude of leakage that could occur through it. This is generally studied using CGE models. We also discuss the empirical evidence that can be linked to this channel, before highlighting research areas that should be explored in the future.

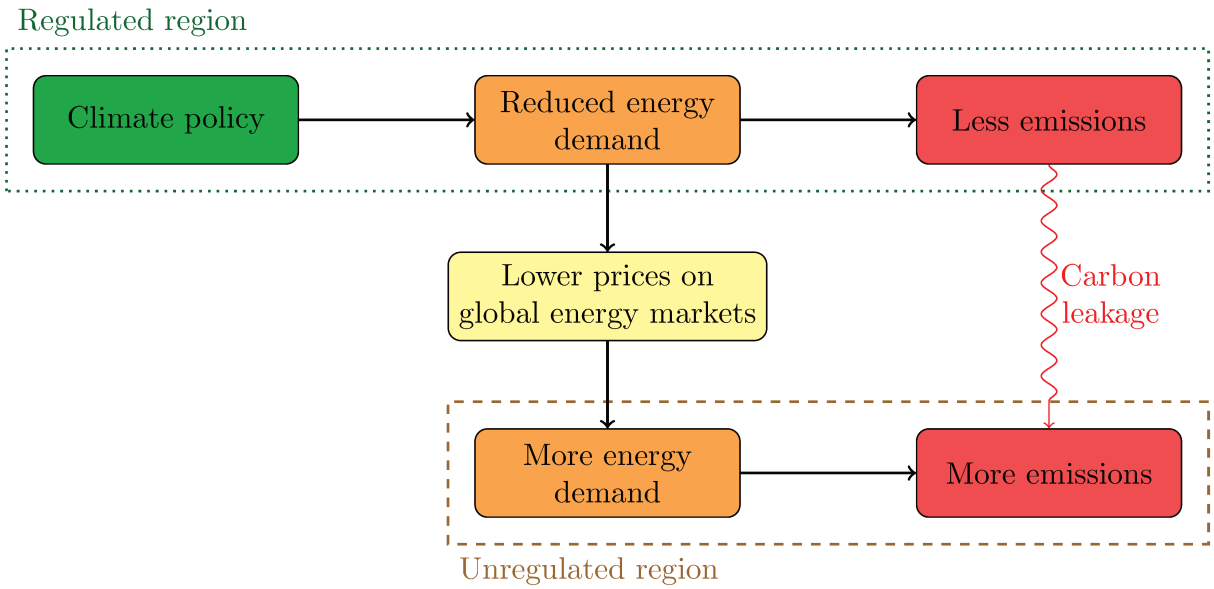
1.4.1 How does the energy channel work?

Carbon leakage through the energy channel is a macroeconomic phenomenon resulting from a price change on international energy markets (see figure 1.3). As a region increases the stringency of its environmental policies and transitions its energy system

away from fossil fuels, its domestic demand for fossil fuels should decrease and tend towards zero in the long run. The region's lower demand for fossil fuels puts a negative pressure on the price of these products on global markets. As a result, producers in unregulated regions have an incentive to increase their fossil fuel consumption as these fuels get cheaper. They do this either by substituting them into their production process, or by increasing their output. The regulated region's lower demand for fossil fuels, and consequent decrease in emissions, are therefore compensated by an increased demand in unregulated regions (Arroyo-Currás et al., 2015).

From a policy perspective, it is important to understand the relative weight of the energy channel compared to the competition channel. Policy instruments like free allocations and CBAs are only effective to tackle leakage through the competition channel but have no impact on energy markets and prices. As such, they are not adequate policies to tackle leakage through the energy channel. If the energy channel is larger in magnitude than the competition channel, other policy instruments should be developed to deal with this second leakage channel.

Figure 1.3: The energy channel



Source: Authors

1.4.2 What is the magnitude of leakage through the energy channel?

To get an initial idea of the potential risk the EU faces from leakage through the energy channel, we first need to understand how much sectors covered by the EU ETS

weigh in the bloc's overall final demand for fossil fuels. Using Eurostat's commodity balances[13], we estimate that in 2020, sectors covered by the EU ETS accounted for roughly 50% of the EU's demand for gas, 20% of its oil demand and 95% of its demand for solid fossil fuels. This estimate accounts for both energy and non-energy use. The actual impact of a significant and rapid reduction of this usage depends on how much the EU weighs in global energy demand. The studies that try to model this impact are described hereafter.

The energy channel has almost exclusively been studied through *ex ante* structural models. Empirical methods have not been used due to the absence of observable country-specific demand shocks on fossil fuel markets resulting from stringent environmental policies. The *ex ante* literature does not decisively converge on the relative importance of the energy channel compared to the competition channel, mostly because of the sensitivity of estimates to certain parameters. For instance, the EC's own estimates of carbon leakage under different policy scenarios includes effects from the energy channel, but their study does not discuss the decomposition between the energy and the competition channel - or of how the former channel affects leakage rates under a CBAM scenario (European Commission, 2021a).

By far the most determining parameter in energy channel leakage estimates is the elasticity of fossil fuel supply in the energy sector (Burniaux & Oliveira Martins, 2012). This channel hinges on the effect of a downward price pressure on global fossil fuel markets. If fossil fuel suppliers cannot adapt their production levels to a negative demand shock (low supply elasticity), lower prices should incentivize producers in unregulated regions to increase their consumption of fossil fuels. This will generate high levels of leakage. However, if suppliers can adapt their production levels when faced with a negative demand shock (high supply elasticity), they can drive prices back up by cutting supply, which would significantly limit leakage.

In their study, Burniaux and Oliveira Martins (2012) run sensitivity analyses on a simplified static CGE model to determine which parameters have a significant influence on the value of leakage estimates. Aside from highlighting the importance of the elasticity of fossil fuel supply, they also note that the Armington elasticity, which largely determines leakage through the competition channel but does not impact leakage through the energy channel (Balistreri et al., 2010), has a smaller influence on the overall leakage ratio. This could indicate that the energy channel makes up a larger share of the overall leakage ratio than the competition channel does.

Boeters and Bollen (2012) further explore the question of the relative importance of each channel of leakage. To disentangle leakage through the energy channel from leakage

[13]Eurostat's nrg_cb series for solid fossil fuels (nrg_cb_sff), gas (nrg_cb_gas) and oil (nrg_cb_oil) were used.

through the competition channel, the authors compare dynamic CGE models in which they fix the price of fossil fuels at their business-as-usual levels (thus removing leakage through the energy channel) with dynamic CGE models in which they do not. They fix fossil fuel prices by adding a compensatory output tax in the system of equations modeling supply and demand responses to a demand shock. The tax adjusts to stabilize the buyer's price and allows for the stock of natural resources to remain untouched in the case of a negative demand shock. The authors include two different model specifications for the redistribution of revenue from their tax: one in which the revenue is redistributed to exporters from the unregulated region, and one in which it is redistributed to importers from the regulated region. These alternative specifications do not impact the results related to leakage, but allow the authors to demonstrate that welfare in the regulated region is larger when revenue is redistributed to importers. Their results show that the energy channel causes a larger share of leakage than the competition channel does, especially if Europe unilaterally abates its emissions without partnering with other UNFCCC Annex I countries.

Huppmann and Egging (2014) find a similar result using a dynamic bottom-up energy system model rather than a top-down elasticity of substitution model, as is common in CGE models. They conclude that tightening the EU ETS could lead to a leakage ratio of 60 to 70% via the energy channel.

Contrary to these findings, Arroyo-Currás et al. (2015) argue that leakage through the energy channel might be more restricted than is commonly thought because demand for fossil fuels in unconstrained regions will eventually saturate. They argue that substitution possibilities between fossil fuels are also not infinite. Their dynamic model thus imposes an upper bound on the amount of leakage that is possible through global energy markets. It includes transport costs for international fossil fuel trade, as well as low carbon prices even in unconstrained regions, which further lowers their leakage estimates. The overall leakage ratio their model finds does not exceed 15%.

The CGE models discussed in this section mostly study the period between 2010 and 2050. They compare data from a baseline year (generally 2010) to projected values for a final year (generally 2050), thus measuring change over the course of a relatively long time frame. Much like for the competition channel, these studies can therefore be considered to measure the impact of climate policies over the long term. A notable exception is the paper by Boeters and Bollen (2012), which compares a baseline year in 2004 to projected values in 2020.

A separate but related strand of the literature focuses on inter-temporal carbon leakage, a mechanism which also operates through global energy market prices and is

founded on the Hotelling rule[14]. In this literature, stringent climate policies only change the temporal profile of the extraction and consumption of fossil fuels, but not the total, long-term amount that is ultimately extracted and consumed. When prices are low (high), producers extract and sell more (less). As a result, implementing gradually increasing carbon prices may actually incentivize forward-looking fossil fuel producers to increase their present extractions and sales in anticipation of lower future scarcity rents. This is a mechanism known as the green paradox, developed by Sinn (2012). For a full literature review on this topic, see Jensen et al. (2020).

As we have seen, CGE models tend to indicate that the energy channel causes more leakage than the competition channel, with some notable exceptions such as the study by Arroyo-Currás et al. (2015). However, there are some significant caveats attached to this conclusion due to the modelling characteristics we have discussed.

1.4.3 Can the energy channel be examined through empirical testing?

To our knowledge, no empirical studies exist testing for the presence of cross-country carbon leakage through the energy channel, whether caused by the EU ETS or any other environmental regulation. This is because there has not yet been a large unilateral shock to fossil fuel demand in any region as a result of environmental policy. However, there are a few empirical studies of inter-temporal leakage through this channel, related to Sinn's (2012) concept of the green paradox.

While most studies looking into the green paradox have been theoretical and analytical, some authors have been able to exploit data related to policy shocks in the US and China to provide empirical analyses of this phenomenon. Jensen et al. (2020) discuss some of this literature in the US context. Zhang et al. (2017) both review the empirical literature and contribute to this strand of research in the Chinese context. Overall, there is limited evidence of any effect in the US, and some evidence that there is a small green paradox effect in China. It should be noted that authors studying both cases highlight that their results are very context-dependent and cannot be generalized to other countries and/or policies.

One other study is of note in relation to the energy channel - more specifically in relation to cross-country rather than inter-temporal leakage through this channel.

[14]In its most basic form, the Hotelling rule implies that for an infinite time span there will always be an initial price and a price pathway which guarantees market equilibrium in each period and ensures that the stock of non-renewable natural resources is never exhausted. This rule assumes that this resource is essential on the demand side, that supply is perfectly elastic, and that producers are indifferent between selling in one period or another.

Though derived from a different context, the conclusions from Knittel et al. (2018) are relevant and potentially insightful. The authors study the impact of the Shale Revolution on international coal trade. The Shale Revolution came from the rapid improvement and expansion of hydraulic fracturing and horizontal drilling technologies, around 2006/2007 (Wang et al., 2014). These new technologies very rapidly made natural gas cheaper than coal in the US. This acted as a fairly sharp negative demand shock on the coal industry in this country, which the authors take as an object of study. They find that the total amount of coal traded on international markets before and after the Shale Revolution are more or less the same, but US coal producers displaced other suppliers. Indeed, they were able to fully replace the domestic demand that disappeared as a result of the Shale Revolution with foreign demand. This seems to indicate that there could be 100% leakage through the energy channel for coal.

1.4.4 What are the remaining gaps in the literature for the energy channel?

The largest gap in the literature is of course empirical validation of the energy channel. While this channel is difficult for policymakers to apprehend because it does not yet present a tangible risk, it could invalidate the policy choice of implementing a CBA. Empirical testing will only be possible if a large enough and fast enough country-specific demand shock occurs on fossil fuel markets. The EU's Green Deal will have to be closely monitored for this type of an effect.

The intertemporal aspect of this channel could also be further explored. Existing studies look at the effect of intertemporal leakage on overall leakage, but do not consider the impact the energy channel could have on intertemporal leakage.

1.5 The innovation channel

Finally, the last of the three channels through which carbon leakage can occur is the innovation channel. It works in an opposite manner compared to the first two we have discussed, in the sense that it generates negative carbon leakage. When a region imposes a stringent environmental regulation, emissions are reduced in the unregulated region as well. We first describe how this channel works, before turning to the way it is represented in CGE models. We then review the empirical evidence related to it and conclude by identifying remaining gaps in the literature focused on this channel.

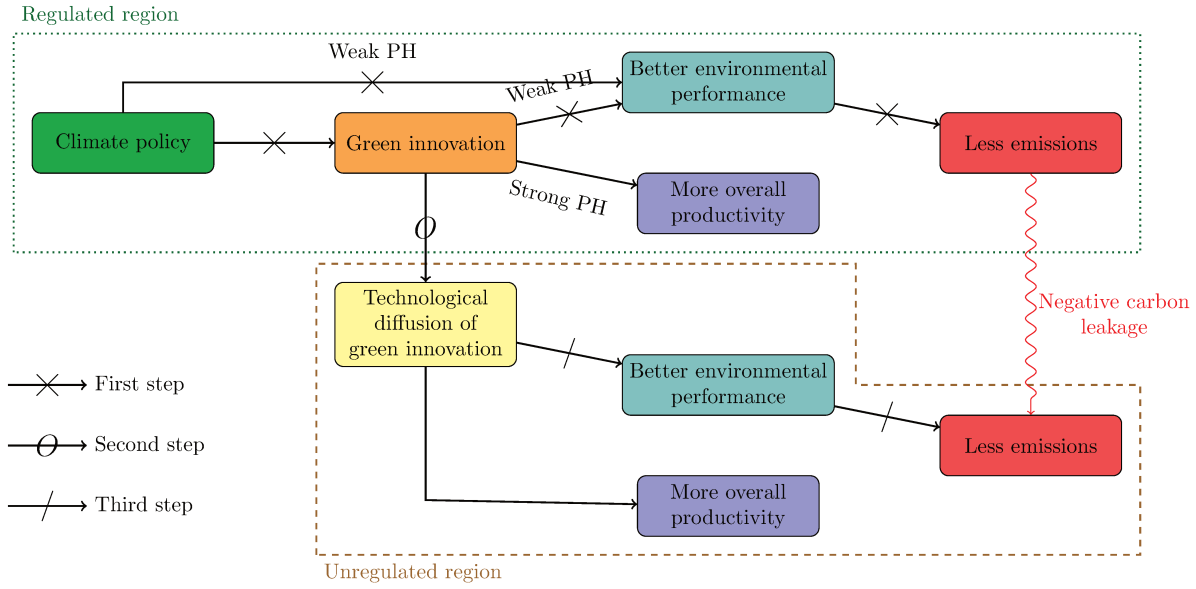
1.5.1 What is the innovation channel?

Carbon leakage through the innovation channel can be described as a three-step process (see figure 1.4). In the *first step*, climate policies make existing low-carbon processes and technologies more economically viable, which induces firms to start using them. Additionally, firms have more of an incentive to invest in low-carbon research and innovation, which also improves their environmental performance in the long run. As a result, emission levels in the regulated country are brought down. This first step is known as the weak form of the Porter hypothesis (Porter, 1991; Porter & van der Linde, 1995)[15].

In the *second step*, these low-carbon innovations are diffused to countries that do not have climate policies in place. In practice, this diffusion may be hindered by the lack of a market for low-carbon products in unregulated countries, as well as lax intellectual property laws and barriers to trade. On the other hand, this channel can be encouraged through international innovation funds and technology transfer initiatives.

Finally, the *third step* occurs when these innovations are used by firms in the unregulated region and successfully reduce the carbon intensity of their production, thus bringing down overall emission levels.

Figure 1.4: The innovation channel



Note: PH = Porter Hypothesis

Source: Authors

[15]Some argue that these green innovations also improve firm competitiveness, leading to higher productivity as well as environmental benefits. This is known as the strong form of the Porter hypothesis (Ambec et al., 2013) and is an argument used to improve the acceptability of climate regulation.

This is the only leakage channel that has a clearly negative leakage effect. Through this channel, stringent climate policies in one region can decrease emissions in other unregulated regions, instead of increasing them like the competition and energy channels. As such, policies that target the development of this channel could have significantly positive impacts on the global climate. The innovation channel increases the efficiency of unilateral climate policies. It is therefore important to understand the magnitude and drivers underlying this channel to design policies aimed at developing it.

1.5.2 How is the innovation channel modeled in general equilibrium models?

To better understand the functioning of the innovation channel, we first turn to CGE models, which can give some insight into the potential magnitude of the channel. Most of these models include technical change as a fixed exogenous parameter and consequently do not account for the innovation channel. However, some studies argue that this omission can lead to a significant overestimation of the overall leakage ratio.

Di Maria and Van Der Werf (2008) build a theoretical framework exploring this argument. They compare a baseline two-sector, two-country model in which technological change is endogenous and undirected with a model which has exactly the same characteristics except that technological change is directed in the sense given by Acemoglu et al. (2012). In the latter model, stringent climate policies direct technological innovation towards climate-friendly innovations in the regulated country. Allowing for directed technological change leads to a significant reduction in the overall leakage ratio. As a result, the authors argue that most CGE models may be overstating the risk of leakage because they fail to account for the green innovation that stringent climate policies should induce. It is worth noting that in this model, innovations are diffused from one country to another immediately and at no cost, which could lead to overstated numerical results compared to a more realistic diffusion scenario. Qualitatively however, the argument stands.

Gerlagh and Kuik (2014) test Di Maria and van der Werf's theoretical framework in a CGE model which includes endogenous and directed technological progress. In their setup, the elasticity of substitution between a carbon energy input and a non-carbon energy input is constituted of a technology parameter and a non-technology parameter. Both parameters sum to the total elasticity of substitution between the two inputs. A price increase for either of the inputs induces investments in input-saving technological innovation which modifies the technology parameter of the elasticity of substitution. If the carbon energy input becomes relatively more expensive than the non-carbon input for instance, technology will improve so that less of the carbon energy input is required for the

same level of output. Interestingly, the authors find that the leakage ratio can be negative, even at moderate levels of technological diffusion between countries. This is because the innovation channel has the potential to induce large amounts of negative leakage, which can trigger large emission reductions both in the regulated and the unregulated region. To verify the validity of the CGE results we have discussed, we now turn to existing empirical evidence studying the innovation channel.

1.5.3 Is there any empirical evidence pointing to the existence of the innovation channel?

As we have described in section 1.5.1, the innovation channel operates as a three-step mechanism: climate policies create incentives for firms in the regulated country to improve their environmental performance through process improvements and low-carbon innovation (step 1). The technology they develop is then diffused to unregulated countries (step 2), thereby reducing their overall carbon emissions as well (step 3). In this section, we sequentially review empirical evidence for each of these three steps.

There is a general consensus in the literature concerning the *first step* of the innovation channel, which is closely related to the weak form of the Porter hypothesis. Indeed, most studies find a positive and statistically significant relationship between environmental policies and green innovation[16].

There is also evidence that the EU ETS, specifically, has led to low-carbon innovative activity (Teixidó et al., 2019). Of particular note in this strand of literature is the paper by Calel and Dechezleprêtre (2014), due to the robustness of its methodology and findings. The authors use a matched difference-in-differences specification to compare the innovative behavior of firms regulated under the EU ETS with the innovative behavior of firms not regulated under the EU ETS. They find that regulated firms started patenting more low-carbon innovations than their unregulated counterparts in 2005, when the EU ETS was first implemented. In a more recent study, Calel (2020) found further evidence that the EU ETS has increased low-carbon patenting and R&D in regulated UK firms by 20-30% compared to unregulated UK firms. Though insightful, the approach developed by Calel and Dechezleprêtre is somewhat limited for three reasons. First, it only considers technological progress as innovative activity and not the adoption of new technologies, which can lead to an underestimation of the EU ETS' effect through the innovation channel. Second, if carbon-abating innovation is occurring in sectors that are not directly covered by the EU ETS, but instead in sectors upstream of covered sectors, there can also be an underestimation of the innovation channel's effect. Third, the more recent work

[16]See Ambec et al. (2013) for a complete literature review on this topic and Baudry (2022) for a recent update.

by Calel (2020) highlights that in spite of having a higher innovation rate as measured by patenting, the carbon intensity of firms covered by the EU ETS did not significantly fall, suggesting that patented inventions did not actually turn into technical change.

Borghesi et al. (2015) take a different approach to explore this question, exploiting data from the 2006-2008 Italian Community Innovation Survey to test whether manufacturing firms covered by the EU ETS adopt more environmental innovations than those not covered by the EU ETS. This avoids one of the problems mentioned above since the authors are not measuring innovative activity as a proxy for technological progress, but measure technological adoption instead. Their results show that participating in the EU ETS makes firms more likely to adopt environmental innovations. Given that their study uses data from the first and second phases of the EU ETS, when free allocations were the general rule and prices were low and volatile, this could mean that firms were anticipating higher future prices and acting accordingly. If this is true, firms' anticipation of future regulatory pathways could be as important in determining their innovative behavior as current regulation is.

Fewer studies look into the impact of this low-carbon innovative activity on firms' environmental performance, measured both as carbon intensity and overall carbon emissions. Baudry and Faure (2021) adopt a technological frontier framework which allows for a classification of firm-level technology based on its carbon intensity. They show that while the EU ETS has led to technological progress which reduces firms' carbon intensity, there has also been a rise in overall carbon emissions as a result of higher production levels. Their findings highlight the fact that even when firms covered by the EU ETS reduce the carbon intensity of their production, they can still have higher overall baseline (or Business As Usual) emissions.

Two further elements should be noted. First, there could be a time component affecting this channel. Most empirical studies do not discuss the expected time frame for the innovation channel to operate, but assume it implicitly through the choices made in data collection. Works adopting a difference-in-differences approach to assess the impact of the EU-ETS (Calel, 2020; Calel & Dechezleprêtre, 2014; Löfgren et al., 2014) consider a time window ranging from four to seven years after its implementation in 2005. It is worth noting that the response time for companies may have been longer since the ETS project was announced several years in advance by the European Commission. In their study using the Community Innovation Survey, Borghesi et al. (2015) assume a similar delay. However, these authors are careful to specify that "the time span between the introduction of the EU ETS and the observed innovation effects - though rather limited in the present context - allows to have a clear time lag between the 'policy dose' and the 'innovation response', and it is commonly used in the literature that evaluates firms' reaction to the implementation of policies". It should however be stressed that the aforementioned

works also meet a requirement to assess the impact of the EU ETS relatively early after its inception in order to fuel the debate on possible reforms, and therefore they could not *de facto* consider a more substantial time lag. Among the few papers that explicitly question the dynamics of innovation effects, we can mention the literature review by (Dechezleprêtre & Kruse, 2018), which highlights the fact that environmental regulation could initially have a negative effect on innovative activity, which turns positive in the long run. Another interesting paper with this respect is the one by Schmidt et al. (2012) which shows that it is mainly the perceived long-term emissions reduction targets of the EU ETS that affect low-carbon R&D.

The second element to be noted is that the type of green innovation that is developed could matter. For instance, innovations improving firms' resource efficiency seem to provide positive returns to profitability, while innovations improving other parts of the production process do not (Rexhäuser & Rammer, 2014; van Leeuwen & Mohnen, 2017). A related strand of literature looks at the strong version of the Porter hypothesis, which posits that environmental regulation improves firm productivity. Proving its validity can be an important factor to improve the social acceptability of environmental regulation. Cohen and Tubb (2018) conduct a broad meta-analysis of studies on this topic and find considerable heterogeneity in the sign and significance levels of results. They find that the most likely conclusion is that environmental regulation is neither significantly beneficial nor significantly detrimental to productivity.

Empirical studies of the innovation channel's *second step* study technological diffusion from regulated to unregulated countries. One strand of these studies provide descriptive analyses of the geography of green innovation activity. These works point to a concentration of patented green innovations in very few countries, namely the US, Japan, Germany, and, more recently but to a lesser extent, China. Innovations patented in high-income countries are mostly transferred[17]to other high-income countries. The small amount that is transferred to middle-income countries (roughly one third of total transfers) mostly goes to China (around 72% of transfers from high- to middle-income countries). Virtually no transfers are made to low-income countries (Dechezleprêtre et al., 2011; Probst et al., 2021). This is a first indication that there may not be perfect diffusion of technology between all countries as modeled by Di Maria and Van Der Werf (2008).

Another strand of this literature looks at the role of technology transfers in specific low-carbon sectors, such as wind and solar power generation. Many papers study the case of China, a country where expertise in both of these fields was developed in large part thanks to strong flows of foreign direct investments and technological transfers. In the

[17]In the paper by Dechezleprêtre et al. (2011), technology transfers are patents that were originally patented in another country then extended to the transfer country.

case of wind turbines for instance, large parts of Chinese demand were developed through the sale of Clean Development Mechanism credits on the ETS (Baudry and Dumont, mimeo). In the case of photovoltaic cells, technology transfers from Western countries, especially Germany, were key to develop China's manufacturing expertise (Huang et al., 2016). This underlines the potential strength of the innovation channel if diffusion is made more widespread.

Finally, empirical evidence concerning the *third step* of the innovation channel is quite sparse. To our knowledge, there are no studies looking specifically at the ways in which low-carbon technology transfers to unregulated countries improve these countries' environmental performance and/or productivity. The most closely related paper is a recent study by Eskander and Fankhauser (2021) which measures carbon leakage as the impact of climate policies on the import and export of carbon emissions. The authors take a macro perspective and find that climate legislation passed more than 3 years ago has generated small negative leakage rates. Without getting into any analysis on technology development and diffusion, they note that this result matches the hypothesis of the innovation channel. Some literature also looks at the impact of technology transfers on the receiving country's knowledge base, but results are mixed and do not allow for a general conclusion on the success or failure of technology transfers as a method of knowledge sharing (Kirchherr & Urban, 2018).

It is also worth highlighting evidence from two further papers, which are more indirectly related to this issue. First, Barrows and Ollivier (2021) look at the impact of foreign demand shocks on the carbon emissions of a third country - India. They find that while positive foreign demand shocks drive reductions in emission intensity, they also generate a strong, positive scale effect - meaning firms produce more - leading to overall greater carbon emissions in India. Jaraite et al. (2021) also note a similar effect when studying the impacts of the Clean Development Mechanism (CDM) on Indian manufacturing firms. This is an important result in our context, since it underlines the fact that even if environmental regulation does lead to more diffusion of carbon-abating technologies in third countries, it might not lead to overall emission reductions if there is also a scale effect.

To summarize, papers studying the innovation channel seem to indicate that it does not yet have a large magnitude but could in the future. Green innovation remains highly concentrated in a few, mainly OECD countries and diffusion is quite limited beyond OECD borders. While policy-induced innovations do seem to improve the environmental performance of firms in the regulated region, their impact on firms in unregulated countries has not yet been studied.

1.5.4 What are the remaining gaps in the literature?

This topic has garnered a lot of attention in the economic literature, in part due to its close relation to the Porter hypothesis. However, many questions remain unanswered. Further studies of the ETS' impact on innovative activity within the EU should be conducted, especially with a focus on the environmental impact of these innovations. Research on policies which could act to avoid a rebound effect should also be prioritized as the EU ETS becomes increasingly stringent.

Another area of interest could be to look at the EU ETS' impact on the innovative behavior of sectors that are not directly covered by it, but that are upstream or downstream of sectors that are. For instance, in the sector of wind power generation, most innovation occurs in sectors upstream of those covered by the EU ETS, so it would be interesting to study how the policy is affecting these sectors. This could complement works such as those by Calel (2020) which give insights into the innovative activity of firms directly covered by the EU ETS.

To better understand the innovation channel's third step, studies could also focus on the ways in which green innovation is absorbed by unregulated countries' production processes once it is transferred there. Testing whether innovations are well-absorbed and whether they effectively reduce emissions in unregulated countries would be particularly important to quantify the innovation channel's environmental impact.

1.6 Designing a Carbon Border Adjustment

Policies aiming to minimize overall carbon leakage can target any or all three of the channels we have described. They should try to minimize positive leakage (i.e., emissions increasing in the unregulated region) through the competition and energy channels, while maximizing negative leakage (i.e., emissions decreasing in the unregulated region) through the innovation channel. Our interest in this section is to explore whether a CBA can achieve these objectives. We present the economic literature on this topic and aim to answer the two following questions:

1. Is a CBA an appropriate instrument to minimize leakage?
2. How can it be designed to best reduce overall leakage?

Most of the literature on designing a CBA is focused on mitigating positive leakage through the competition channel. Our contribution is to add considerations about the other two channels based on our previous discussions on their functioning. Given that a

CBA has not been implemented on a large scale anywhere in the world, the evidence we present is mostly based on theoretical and CGE models.

1.6.1 How can a CBA reduce leakage through the competition channel?

The idea that a country with domestic carbon pricing could impose an import tariff to avoid carbon leakage was first put forward by Markusen (1975) in a two-good, two-country game-theory model. It was then generalized by Hoel (1996) in a game-theory model with N number of goods. The results from these seminal works indicate that the optimal tariff to avoid leakage is always non-zero and below the domestic (Pigouvian) carbon tax rate. The reason it is lower than the domestic rate is that a carbon tariff decreases the relative price of the polluting good in the unregulated region, mechanically increasing demand for it. This is sub-optimal both from an environmental and a competition perspective, implying the tariff should be lower than the domestic carbon price. One important element to note is that this holds only when the country or coalition of countries that imposes the carbon price is large enough to have some market power at the international level. If it does not, its tariff will have no effect on the foreign price of the polluting good or on production decisions in the unregulated region.

More recently, Balistreri et al. (2019) modified Markusen's framework to align it with the current WTO context. In Markusen's model, the optimal tariff rate is a function of the domestic carbon price, a strategic element, and an environmental element. Balistreri et al. (2019) neutralize the strategic element, in line with WTO law which states that countries cannot impose import tariffs for strategic reasons. Even in this setup, the optimal tariff is not zero, and remains below the Pigouvian tax. Testing their model in a numerical simulation, the authors find that if a coalition made up of UNFCCC Annex I countries were to implement a domestic carbon price, the optimal tariff for imports to this coalition would be roughly 40% of the domestic price. Theoretical works clearly indicate that a tariff could be an effective manner of reducing carbon leakage through the competition channel.

CGE models tend to confirm these theoretical results. Branger and Quirion (2014) provide a meta-analysis of 25 studies looking at CBAs, and find that all else being equal, CBAs reduce the leakage ratio by an average 6 percentage points. This is a 6 percentage-point reduction in already relatively small leakage rates (5-25% in most CGE models). While CBAs do seem to decrease leakage risk, the CGE-predicted magnitude of this reduction appears quite small compared to the burden of such a complex legislation.

Some studies point to possible differences in the effect of a CBA depending on the sector that it is applied to. For instance, Kuik and Hofkes (2010) find that CBAs can significantly reduce leakage in the iron and steel industries, while the effect is smaller in sectors such as mineral products, including cement. This difference can mostly be explained by the differences in carbon intensity between sectors. The most carbon intensive sectors, namely iron and steel, are more protected by a measure targeting carbon intensity in imported products.

It appears from these general analyses that a CBA may not be a highly effective policy for carbon leakage prevention. However, there are some design elements which could maximize a CBA's leakage reduction effect on the competition channel. Table 1.1 summarizes the different design choices available to policymakers when implementing a BCA.

Table 1.1: Design choices for a CBA

Category	Examples of policy options
Type of policy instrument	**Price-based** (tax or custom duty) or **quantity-based** instrument
Scope and coverage	**Coverage of trade flows** (imports and/or exports), **geographic scope** (all foreign countries or only some trade partners, developing countries excluded...), **sectoral scope** (only carbon intensive industries, electricity and energy sources, ETS sectors, ...), **emissions scope** (direct and/or indirect)
Determination of embedded carbon	**Based on domestic average**, **foreign average**, **regional/country-level average**, **sectoral or product-level** benchmark
Calculation of crediting for policies	Adjusting for **foreign carbon pricing or not**, choice of **including foreign emission standards**
Use of revenue	**General budget, earmarked for decarbonization projects, lump-sum transfers to affected developing trade partners, international clean technology fund**, ...

Source: Marcu et al. (2020)

These design choices need to be carefully weighed based on their capacity to mitigate leakage as well as their administrative costs and legal feasibility. Böhringer et al. (2022) provide a helpful summary of the issues related to this.

Böhringer, Bye, et al. (2012) compare the cost-effectiveness of CBA designs in a CGE setup. They test variations of a CBA's design along three dimensions: the emissions scope (direct, direct plus indirect emissions from electricity, and all embodied carbon), the sectoral coverage (only energy-intensive and trade-exposed sectors, versus all sectors), and the determination of embodied carbon in products (domestic emissions benchmark,

foreign emissions benchmark, and regional emissions benchmark). They find that the most effective design for a CBA, with regards to cost and environmental benefits, is one which targets all embodied emissions (direct and indirect), which uses a benchmark for carbon content based on foreign emissions, and which covers all sectors.

The literature review by Branger and Quirion (2014) confirms that most studies find that including all sectors rather than only carbon-intensive ones in the scope of the CBA greatly increases its effectiveness. A larger sectoral scope reduces the risk of reshuffling – a practice through which foreign exporters circumvent the regulation by exporting products not covered by the CBA, namely products that are more downstream in the value chain. For example, if a CBA is applied to steel, but not cars, exporters can choose to stop exporting steel to car manufacturers in the regulated region and instead produce cars outside the regulated region then export the cars into the region. This allows them to avoid paying the CBA tariff. However, the authors also find that the inclusion of indirect emission in the accounted emissions is not statistically significant in all studies, contradicting findings from Böhringer, Bye, et al. (2012).

Böhringer et al. (2017) add to this with their own CGE analysis, which highlights that a CBA targeting firm-level carbon intensity can limit leakage through the competition channel considerably more than a CBA targeting industry-level carbon intensity, while also mitigating adverse distributional effects of an industry-level CBA. The intuition behind this is that the more targeted a CBA is, the more it protects truly carbon-efficient firms. With industry-level benchmarks, dirty producers would pay exactly the same tariff as clean producers in the same industry, which reduces their incentive to invest in less carbon-intensive modes of production.

Finally, Fischer and Fox (2012) explore the environmental and cost efficiency of four types of policies: a border tariff on imports, border rebates on exports, a full border adjustment (including both a tariff and rebates), and domestic output-based rebating. Using a numerical simulation, they find that while none of these policies reduce global emissions, a full border adjustment is the most effective at reducing leakage rates.

To summarize the evidence found in the CGE literature, there is a consensus around the fact that a CBA would reduce carbon leakage through the competition channel. However, the magnitude of this reduction is not predicted to be very significant by CGE models. Some design elements can nonetheless increase a CBA's effectiveness at reducing leakage through the competition channel: covering all sectors in the economy, using a foreign benchmark for the carbon content of products, targeting carbon intensity at the firm or sub-industry level, and including export rebates as well as an import tariff.

1.6.2 Is a CBA ineffective at reducing leakage through the energy channel?

CGE models generally find that while a CBA can have an effect on the competition channel, it cannot impact the energy channel and is therefore not effective if most leakage is transmitted through this channel (Kuik & Hofkes, 2010).

However, a CBA can be used as a strategic tool to encourage unregulated countries to impose environmental regulations of their own. Böhringer et al. (2016) study this possibility in a numerical game theory set-up. They find that the threat of a carbon tariff can act as a strong incentive for unregulated countries to impose their own environmental regulation, especially if the coalition of regulated countries is large and has strong market power. This is important for the energy channel because cross-country leakage would be avoided if other countries also implement environmental policies that limit carbon emissions and the use of fossil fuels. The more countries have regulations which restrict demand for fossil fuels, the less leakage can occur through the energy channel.

If a CBA is implemented for strategic purposes as described above, two design elements can accentuate its power to incentivize other countries to impose their own domestic environmental policies. First, a CBA can take into account carbon pricing initiatives and climate policies in other jurisdictions. This could mean for instance that goods produced in Japan, covered by the country's domestic carbon tax, only pay a tariff at the rate of the difference between the EU's carbon price and Japan's carbon price. Countries exporting to the EU would be more strongly incentivized to have a domestic pricing system since their producers would not be doubly penalized, and they would receive the additional revenue instead of the EU. Further, if regulations other than carbon pricing, such as emission standards for instance, are also taken into account, there would be more flexibility for countries to regulate in ways that correspond to their particular context.

Second, the implementation process of the CBA is also important in itself. The more collaborative the process is, the more the EU will be able to take foreign legislation into account, potentially incentivizing trade partners to impose their own carbon pricing.

1.6.3 How can a CBA be designed to encourage spillovers through the innovation channel?

Finally, we look at the potential impact of a CBA on the innovation channel. To our knowledge, there is no literature looking into this question, so we put forward some preliminary considerations which should be further explored to maximize a CBA's positive impact on the innovation channel.

One interesting consideration is to ask whether the weak form of the Porter hypothesis could hold true in the context of a CBA. Since a CBA imposes a cost on carbon emissions for foreign producers exporting to the regulated region, it could create an incentive for these producers to invest in carbon-abating technological innovation and adoption. The emissions reductions induced by this could then be multiplied by a diffusion of these technologies to other producers within the unregulated region which are not exporting to the regulated region.

A more indirect channel through which a CBA could impact the innovation channel is through trade. There is evidence in the innovation literature that trade is a very strong channel for technology diffusion between countries (Xu & Wang, 2000). If it is imposed by a large enough trading bloc such as the EU, a CBA should restrict trade in carbon-intensive goods, while encouraging trade in low-carbon goods. As a result, it is possible that a CBA would increase technology diffusion through the trade channel. However, this would only be the case if the CBA is based on actual carbon content, or foreign content benchmarks rather than domestic content benchmarks. This hypothesis would have to be tested when a CBA is fully implemented. It would likely take some time for this type of technology diffusion to occur.

Additionally, policymakers could push for further green innovation and international technology diffusion by reinvesting the revenues from the CBA into an international green innovation fund. This fund could be focused on investing in projects transferring low-carbon technologies to producers in unregulated, and especially developing, countries. This would strengthen the innovation channel and mitigate the risk of burden shifting onto developing countries.

1.7 Conclusion

This paper has presented the state of the economic literature on the issue of carbon leakage and CBAs. We have first discussed the EU's political and institutional contexts to ground this literature in concrete policymaking problems. Second, we have given an in-depth review of the ways in which each of the three leakage channels – competition, energy, and innovation – function and where research should be focused in the future. Finally, we have linked this to a discussion on a CBA's role in minimizing carbon leakage by minimizing the effect of the competition and energy channels and maximizing the effect of the innovation channel.

To sum up, further empirical research should focus on assessing the impacts of more recent phases of the EU ETS on the competition channel, as well as the impacts of non-price competition and network effects. Research looking to empirically validate (or

invalidate) the energy channel would also be welcome, allowing for a better understanding of this channel. Finally, looking at the innovation channel, empirical analysis could focus more on the impacts of policy-induced green innovation, as well as the effects of this policy on unregulated upstream and downstream sectors. To better understand innovation diffusion effects and optimize international efforts for innovation sharing, research could also look into the need and absorption capacity of unregulated countries with regards to green innovations.

We have noted a discrepancy between the economic literature and policy debates concerning carbon leakage and CBAs. The latter do not consider how such a policy could impact leakage through the energy and innovation channels. However, both channels could have a strong impact on overall leakage rates in the future, depending on the ways in which a CBA is implemented. Policymakers should therefore aim to minimize the impact of the energy channel by developing cooperation with unregulated countries and taking foreign carbon pricing initiatives into account in the CBA. They should also work to maximize the impact of the innovation channel by promoting green technology diffusion to unregulated countries and reinvesting CBA funds into an international technology fund.

Chapter 2

Mind the Market: A Novel Measure of Carbon Leakage Risk

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Abstract

DEFINING a fair and transparent measure of carbon leakage risk is essential to ensure the effectiveness of the EU's climate policies. This paper proposes a novel methodology to assess this risk, which takes market structure into account – a key factor often overlooked in both academic research and policymaking. The methodology involves applying the micro-founded hypothetical monopolist test (or SSNIP test) at the country-product level. It allows for the definition of the relevant market for four products in the steel and cement industries. The inputs required for the hypothetical monopolist test are derived by estimating a product-level gravity equation. The findings from this study illustrate that market structure differs substantially at the product level, even within a single industry. Clinker appears as the product most at risk of carbon leakage. This suggests that carbon leakage risks should be computed by policymakers at a highly granular level and taking market structure into account.

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- 2022 SESTEF Conference (Paris)
- 2022 ETH Zürich Doctoral Winter School
- 2022 Florence School of Regulation (European University Institute) Summer School
- 2022 Climate Economics Chair Doctoral Seminar

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2.1 Introduction

The EU's industry makes up 22% of its total greenhouse gas (GHG) emissions (EEA, 2024a). To stay in line with its objective of carbon neutrality by 2050, the EU must rapidly and significantly cut down these industrial emissions. Although ambitious climate policies are necessary to incentivize firms to decarbonize, concerns around the risk of carbon leakage have slowed their development. Trade associations invoke this risk to warn of competitiveness losses (Fagan-Watson et al., 2015),[1] while policymakers raise it as a threat to the effectiveness of climate policies (Draghi, 2024; European Commission, 2019, 2021b). On the other hand, environmental groups dismiss it as a mere excuse used to block stringent climate policies (Carbon Market Watch, 2015). A true consensus on the magnitude of carbon leakage risk remains elusive in policy circles.

One of the key questions is how to provide a fair and transparent measure of carbon leakage risk. Defining such a measure is essential to design policies that effectively tackle carbon leakage *without* undercutting the impact of climate policies (Cosbey et al., 2019). Overestimating the risk of carbon leakage can hinder climate policies from having a real impact, while underestimating it can lead to heavy carbon leakage and losses both in terms of environmental and competitiveness outcomes. This paper contributes to the discussion by proposing a novel methodology to assess carbon leakage risk, one which accounts for market structure – a key factor often overlooked in both academic research and policymaking.

This paper takes the EU as a case study as it is a region with one of the world's oldest and most stringent carbon markets, the EU Emissions Trading Scheme or EU ETS (World Bank, 2023). The bloc has also implemented several "anti-leakage" measures hand-in-hand with its carbon market; these included the free allocation of allowances to sectors considered at risk of carbon leakage (European Parliament and Council, 2013), some compensation for indirect cost increases (European Commission, 2012), and more recently, a Carbon Border Adjustment Mechanism (CBAM; European Parliament and Council, 2023).[2] In each of these cases, the European Commission (EC) computed an indicator of carbon leakage risk to determine which sectors and products would be covered by anti-leakage policies.

[1] See also the article entitled "Carbon leakage concerns dominate EU ETS debate" by ENDS Europe, a media focused on European environmental news, available at https://www.endseurope.com/article/1640202/carbon-leakage-concerns-dominate-eu-ets-debate?utm_source=website&utm_medium=social.

[2] Industrial installations at risk of carbon leakage received 100% of their allowances for free during the third phase of the EU ETS (2012-2020) and will continue to receive more than half of their allowances for free until 2030. Free allowances will be fully phased out by 2034 and replaced by a Carbon Border Adjustment Mechanism (European Parliament and Council, 2023).

This paper belongs to a vast strand of economic literature focused on carbon leakage. It was initially studied through the prism of game theory in Markusen's foundational papers (Markusen, 1975; Markusen et al., 1993), which showcase high risks of carbon leakage when a country unilaterally imposes a stringent climate policy on its producers. Carbon leakage was then transposed to computable general equilibrium (CGE) models, which calibrate behavioral parameters and elasticities to assess the risk of carbon leakage in various policy and geopolitical world scenarios. They tend to assume perfect competition in all sectors as a simplifying assumption to be able to model the world economy as a whole (Cameron & Baudry, 2023). However, this may not be an accurate reflection of industrial sectors' market structure which tends to be oligopolistic (Cook, 2011; Sourisseau, 2018). Due to their global coverage, CGE models also represent sectors at a fairly aggregated level, which induces a bias in measures of carbon leakage (Fischer & Fox, 2018; Sato et al., 2015). Overall, CGE models have found moderate carbon leakage rates, around 10 - 30% (Böhringer, Balistreri, & Rutherford, 2012; Carbone & Rivers, 2017).

As climate policies have been increasingly implemented in different jurisdictions, empirical works have also emerged, evaluating whether these policies generated carbon leakage (Joltreau & Sommerfeld, 2019; Verde, 2020). They have generally uncovered low or null leakage rates (Cameron & Baudry, 2023; Caron, 2022). While these studies capture true market conditions given they study empirical data, they have mostly focused on time periods when climate policies have not been very stringent and industrial sectors were protected by anti-leakage policies. This could explain the low carbon leakage rates found. Since they are backwards-looking by nature, the results from empirical studies say nothing about *potential* leakage risk as climate policies become more stringent.

Today, the EU has over a decade of experience with anti-leakage policies and the measurement of carbon leakage risk. The EC measures carbon leakage risk based on two criteria: trade intensity and energy or carbon intensity. This measure has been criticized for overestimating the true risk of carbon leakage, leading to an overly generous allocation of free allowances and a muting of the EU ETS' price signal (De Vivo & Marin, 2018).

This paper aims to contribute to the literature evaluating carbon leakage risk by proposing a new approach: applying the hypothetical monopolist test – also known as the SSNIP[3] test (Werden, 2003) – on a country-product level. The hypothetical monopolist test provides a definition of a country-product's relevant market, i.e., the set of products and the geographic area in which a country's producers competes. This is defined by the extent to which consumers are willing to substitute between products in response to price changes. The larger the relevant market, the more adequate substitutes are available to consumers. If stringent climate policies increase the price of domestic goods, consumers

[3]Small but Significant Non-Transitory Increase in Price.

will easily be able to switch to alternatives from foreign producers, inducing carbon leakage. A wider relevant market is therefore associated with a higher risk of carbon leakage. Some of the parameters used in the test are estimates of a constant elasticity of substitution (CES) derived from a gravity model, which is linked both theoretically and empirically to the hypothetical monopolist test in this paper.

This approach has several advantages compared to other existing methods. First, it allows for a highly disaggregated sectoral analysis, even allowing for theoretically consistent product-level estimates, which avoids the aggregation bias found in this literature. Second, it simultaneously takes into account the impact of trade elasticities, like CGE models, and market structure – an element which has been omitted in most approaches so far but is found to be of importance in empirical evaluations of EU ETS sectors.

Results from this approach provide important insights into the EU's relevant market for four industrial goods: clinker, hydraulic cement, and flat and long steel products. Clinker stands out as the product most at risk of carbon leakage, consistently showing the largest relevant market across all simulations due to its high homogeneity and low trading costs. In contrast, hydraulic cement has a more restricted relevant market. Both steel products have smaller relevant markets than the cement products studied in this paper. Flat steel products have the most limited relevant market of all four products, indicating greater product-level differentiation and regional specialization. The analysis also shows that EU producers are currently not highly competitive on foreign markets, which might indicate that the competitive impacts of domestic carbon pricing may be overstated. All of these findings underscore the importance of granular product-level analyses to assess carbon leakage risks and call for measures that consider the specific market structure of each product.

This paper first reviews how carbon leakage risk has been measured in existing literature (Section 2.2). Section 2.3 then provides contextual information on the products this paper focuses on, namely on their characteristics related to trade and carbon intensity. Section 2.4 presents the theoretical model that links the hypothetical monopolist test and the gravity model, as well as the empirical strategy that is used for the estimation of the latter. Section 2.5 describes the data used in this paper. Finally, Section 2.6 presents and discusses the main results of this analysis. Section 2.7 concludes.

2.2 A review of carbon leakage measures

Defining a measure of carbon leakage risk is a difficult task for two main reasons. First, carbon leakage has never been empirically observed because climate policies have not been very stringent for most of the period that has been studied in the literature

(Cameron & Baudry, 2023; Verde, 2020). This makes it difficult to apprehend the impacts a particular policy or carbon price level can have on firms, especially since effects may not be linear. Second, the design of these policies is contentious, because the details of their implementation make a big difference for firms that are covered by climate policies. Firms that were freely allocated their allowances in the first phases of the EU ETS were able to generate large rents by passing onto consumers the opportunity cost of these allowances (Sato et al., 2015). As a result, competitiveness and carbon leakage concerns are often raised by industry trade associations to lobby the EU on its climate policies (Fagan-Watson et al., 2015).

Ex-ante approaches. A large strand of economic literature has attempted to measure the risk of carbon leakage in various policy contexts. Theoretical approaches using game theory were first developed in the 1990s (Hoel, 1991; Markusen et al., 1993) to explain the mechanisms underlying carbon leakage. These models were then applied to CGE models simulating the impact of stringent policies on a variety of outcome parameters. These models have found variable, but generally low, leakage rates.[4] While game theory models allow for firms to act strategically, their CGE counterparts generally make the simplifying assumption that global industrial markets are perfectly competitive. Two studies notably depart from this assumption: Babiker (2005) and Balistreri and Rutherford (2012). Both papers find higher leakage estimates than the rest of the literature.[5]

Ex-post approaches. Empirical papers have attempted to quantify carbon leakage induced by existing climate policies. Overall, they have found almost no effect of climate policies – likely because these policies have not been stringent enough to induce this kind of effect.[6] Generally, these empirical papers either study the economic outcomes of firms covered by climate policies or changes in trade flows caused by these policies. The most recent and robust study on this subject is the one by Dechezleprêtre et al. (2023), which finds that the EU ETS actually had a small but positive effect on firms' economic returns. Additionally, Branger et al. (2016) develop an analytical demand model for cement and steel specifically, and find no evidence of carbon leakage in the first two phases of the EU ETS. More macro studies have also looked into country-level changes in emission patterns caused by climate policies, but have also found low or no carbon leakage (Aichele & Felbermayr, 2015; Naegele & Zaklan, 2019).

[4]See Branger and Quirion (2014) and Carbone and Rivers (2017) for reviews of the literature on this topic.

[5]See Cameron and Baudry (2023) for a more detailed discussion on this topic.

[6]See Dechezleprêtre et al. (2019), Joltreau and Sommerfeld (2019), and Verde (2020) for reviews of the literature on this topic.

EU indicator. On the policy side, the EU measures the risk of carbon leakage based on sectors' trade and energy intensities. Trade intensity is used as a proxy of how much international competition a sector faces, which itself is used as an indication of its ability for cost pass-through.[7] Emission intensity is used as a proxy of the compliance costs imposed by the EU ETS.[8] This criteria is fairly rudimentary, and is not based on any strong economic justification. Some literature has assessed the EU's methodology and proposed alternative criteria to measure carbon leakage risk. Overall, this strand of research tends to show that the EU's measure of carbon leakage overstates risks because it aggregates sectors too much (Fischer & Fox, 2018), omits any country-level (Sato et al., 2015) or firm-level (Martin et al., 2014) differences in exposure, does not accurately measure pass-through capacities (Sato et al., 2015), or foreign output elasticities (Fowlie & Reguant, 2018) and does not account for non-price trade barriers such as integrated production processes, service specification, or the location of resources used as inputs (Hourcade et al., 2007). Additionally, the EU's measure does not consider whether there is any form of market power in the sectors that are considered, although evidence points to some existing (Cludius et al., 2020; Ganapati et al., 2020) and potentially being exacerbated by climate policies (Ryan, 2012).

2.3 Industrial context: cement and steel

The model proposed in this paper is applied to two heavy industry sectors: steel and cement. The choice of these sectors was driven by multiple factors. First, both sectors are central to the EU's decarbonization strategies. They are highly carbon intensive, and responsible for large amounts of emissions within the EU; cement and steel production are respectively responsible for 4% and 5% of the EU's total emissions (Marmier, 2023; Somers, 2022). Additionally, they have both been included in the list of sectors at risk of carbon leakage since the inception of the EU ETS. This is in part because of their high carbon intensity and the fact that they are considered "hard to abate" sectors, and in part due to their exposure to international trade,

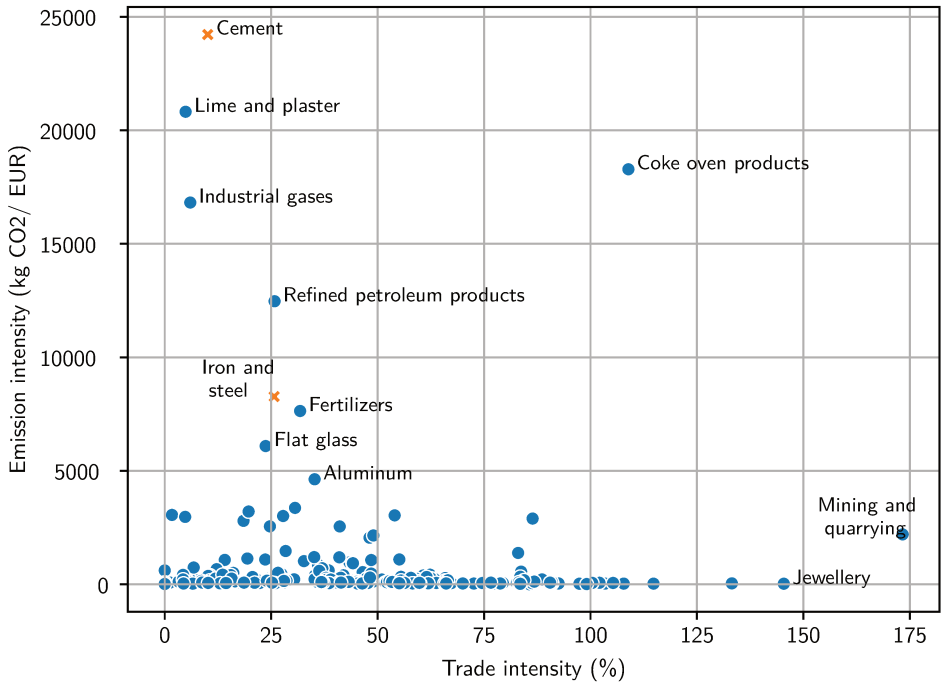
Second, it is interesting to look into these sectors comparatively because they present differing characteristics. Cement production is much more carbon intensive than steel-making, while steel producers have a higher trade intensity than cement. Cement is not traded much over long distances given its heavy weight and resulting high transport costs.

[7]Trade intensity is measured as "the ratio between total value of exports to third countries plus the value of imports from third countries and the total market size for the European Economic Area (annual turnover plus total imports from third countries)" and expressed in percentage (European Commission, 2018).

[8]Emission intensity is measured as "the sum of direct and indirect emissions for the sector concerned, divided by the gross value added" and expressed in kg CO_2 (European Commission, 2018).

Figure 2.1 illustrates this by showing where cement and steel stand compared to other sectors deemed at risk of carbon leakage based on the EU's assessment.

Figure 2.1: European Commission carbon leakage indicator



Source: European Commission

Note: Data from 2013 to 2015, used to determine the carbon leakage list for Phase IV of the EU ETS. See footnotes 7 and 8 for formal definitions of trade and emission intensities.

Finally, these sectors work well with the theoretical underpinning and empirical implementation of the model proposed in this paper. An important characteristic of the model is its Armington trade structure.[9] The products from the cement sector are highly homogeneous, and are therefore substitutable to some extent no matter where they come from. The products from the steel sector are more heterogeneous, but the specialization between different products is country-specific, meaning the Armington structure of trade is also relevant (Carvalho & Sekiguchi, 2015; Herfort et al., 2010; Hourcade et al., 2007). Both industries are also represented by international trade associations that collect and publish data on country-level production.[10] This data is needed for the empirical estimation of the gravity model in this paper. This Section describes each of these sectors in more detail, providing information on their production process and emission patterns.

[9] Armington structures of trade assume that products from different countries are imperfect substitutes. The extent to which products are differentiated by country of origin is measured by Armington elasticities, which are cross-elasticities between two products from different countries (Armington, 1969).

[10] The World Steel Association and the Global Cement and Concrete Association, respectively.

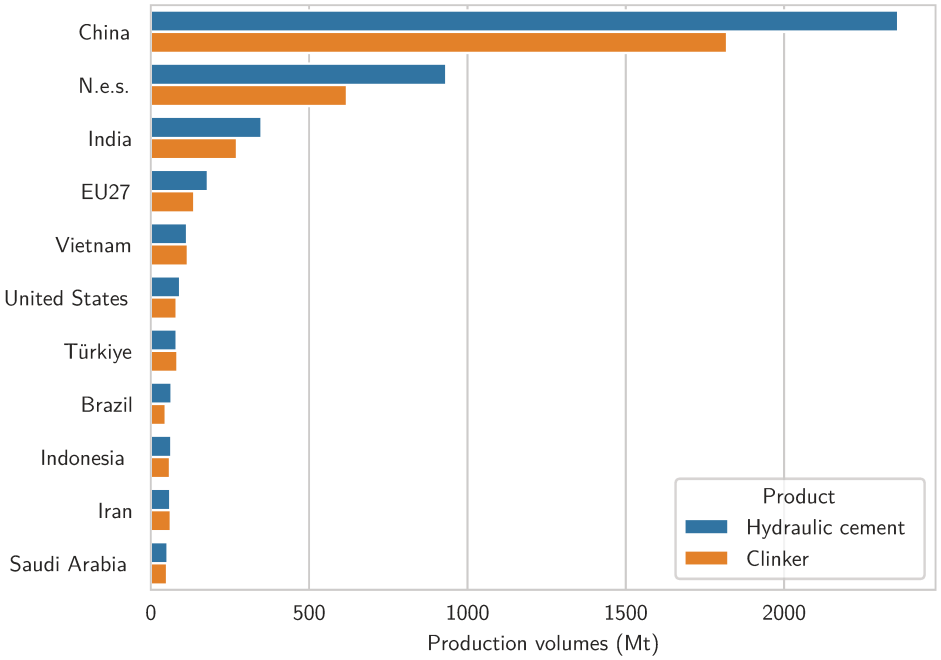
Cement

In this paper, the cement sector is composed of two products: clinker and hydraulic cement. To understand what these products are and what their emission profiles and abatement possibilities are, it is important to have a basic understanding of the cement-making process.

The manufacturing of cement begins with the mining and grinding of raw mineral materials, mostly limestone and clay. The resulting powder is heated to 1450°C. This breaks down and recombines its chemical bonds to create a new compound: clinker. Clinker are nodules that can go from 1 to 25mm in diameter. These are ground into powder to create cement, to which water and other minerals are added to create concrete. Concrete is the material that is used in construction. The most commonly used type of cement is hydraulic cement, defined by its ability to set and harden through a chemical reaction with water. Two-thirds of GHG emissions in cement manufacturing are process emissions caused by the chemical reaction used to produce clinker (Mari et al., 2021). The remaining third originates from energy use.

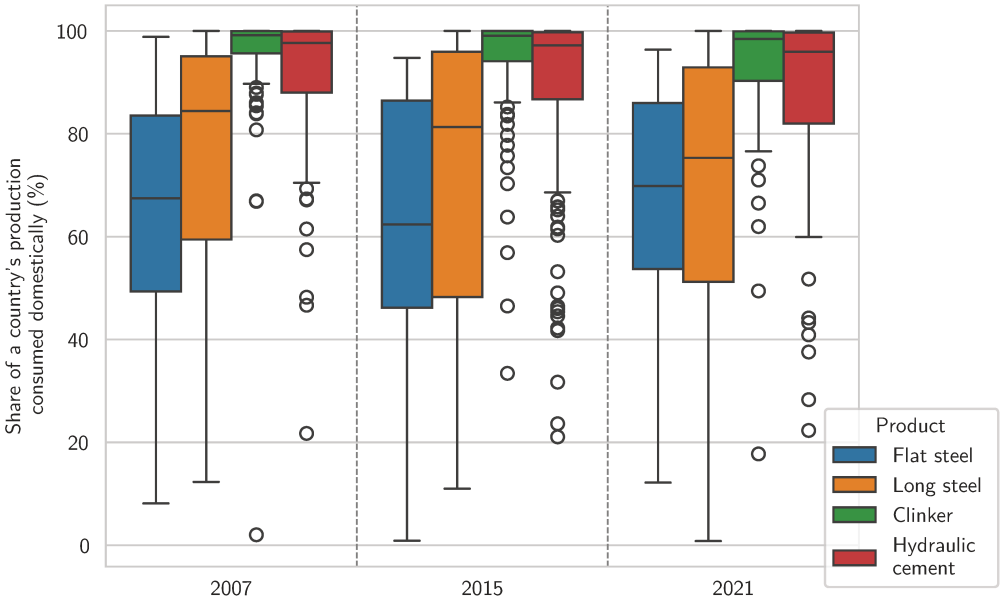
China is by far the largest producer of hydraulic cement and clinker, followed by India, the EU, Vietnam and the USA (Figure 2.2). Due to its high transport costs, most hydraulic cement is produced and consumed domestically, meaning the sector is not very trade intensive. Figure 2.3 shows that for more than half of the countries in the data, 90% of cement products are consumed in the country where they are produced, leaving only a small share to be exported to other countries. Hydraulic cement is slightly more traded than clinker.

Figure 2.2: Top hydraulic cement and clinker producing countries (2021)



Source: United States Geological Survey (2021)
Note: "N.e.s." sums all countries not elsewhere specified

Figure 2.3: Distribution of domestic consumption shares



Sources: Gaulier and Zignago (2010), United States Geological Survey (2021), and WorldSteel (2023)

Steel

The steel industry produces flat and long steel products. These categories of products are used for different types of final products, and have different production requirements that define the ways their production can be decarbonized.

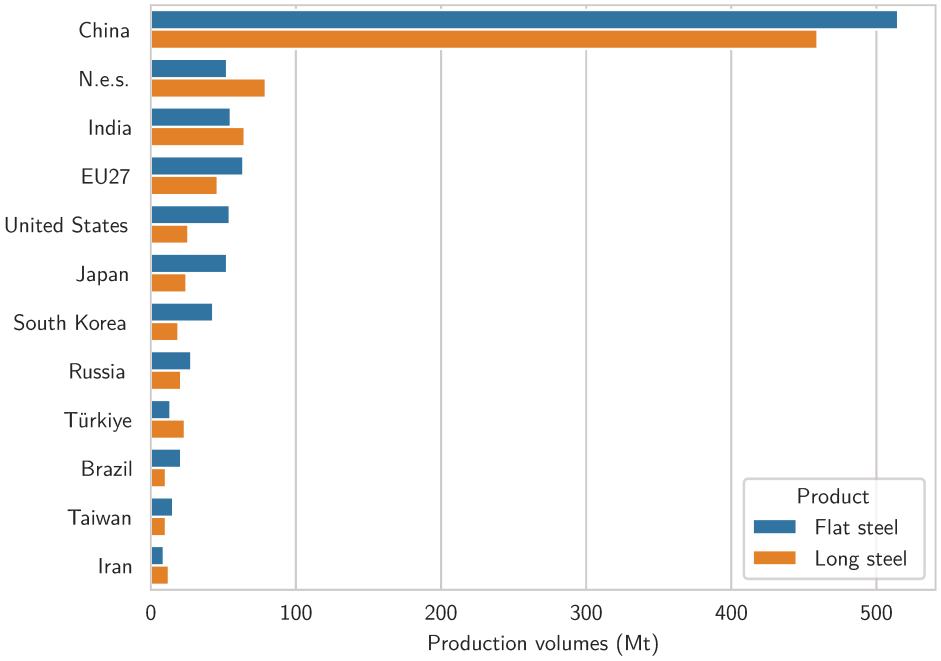
In a schematic sense, the steelmaking process can be split into primary and secondary production. Primary production is based on the mining of iron ore, which is turned into iron either in a blast furnace (BF) or in a direct-reduction iron (DRI) furnace. This iron is then turned into steel either in a basic oxygen furnace (BOF), or in an electric arc furnace (EAF). Direct and indirect emissions related to the production of steel amount to 2 tons of CO2 via the BF-BOF route, or 1 ton of CO2 via the DRI-EAF route. Secondary production is based on the remelting of scrap steel in an EAF. Steel produced via this route directly and indirectly emits only an average of 0.34 tons of CO2 (International Energy Agency, 2020). However, secondary steel production does face a quality issue, as scrap can be mixed with other elements, which prevents its use to create high-quality steel.

While long products can generally be produced with this lower quality steel, some flat products require high-quality steel that can only be produced via the BF-BOF production route today.[11] This might mean these products are not equally sensitive to carbon pricing schemes, since flat products have less options for their decarbonization (Sardain, 2023). In terms of usage, flat and long steel products are also not substitutes. Flat products are generally used in car manufacturing and household appliances, while long steel products are generally used in infrastructure.

Once again, China is unquestionably the largest producer in the world of both products (Figure 2.4). While the EU's production is a lot more restricted, it is the second producer of both flat and long steel products, followed by the USA and Japan for flat steel products, and India and Japan for long steel products. Steel products are traded more than cement (see Figure 2.3) especially flat steel products, but are less carbon intensive (Figure 2.1). Relative to other industrial sectors however, they are still highly carbon intensive.

[11] See the article by an industry specialist on Project Blue, available at https://web.archive.org/web/20240525173158/https://projectblue.com/blue/news-analysis/525/why-could-steel-industry-decarbonisation-be-long-and-difficult

Figure 2.4: Top steel producing countries (2022)



Source: WorldSteel (2023)
Note: "N.e.s." sums all countries not elsewhere specified

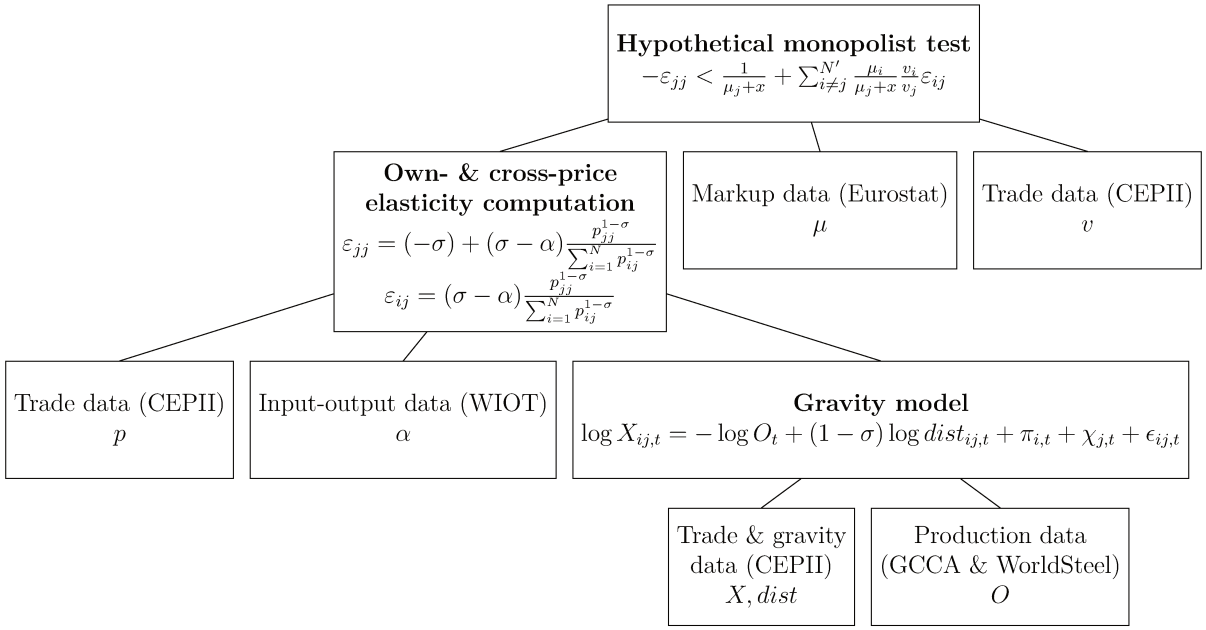
2.4 Model

The model is split into two parts, both of which are anchored in a monopolistic competition framework. There are N countries in the world. There are $2 \times N$ agents in this model: an upstream producer and a downstream producer in each country. The upstream producers use labor and raw materials (such as lime or iron ore) to produce industrial products (such as cement or steel). The downstream producers buy industrial products from the upstream producers and use them as inputs, with labor, to produce final products (such as construction materials or cars). An Armington (1969) structure of international trade for the industrial product (hereafter the product) is assumed, meaning varieties of the product are differentiated by country of origin and each country only produces one variety. In this set-up, indexing by upstream producer, country or product variety is strictly equivalent.

The first part of the model is the hypothetical monopolist test – or SSNIP test (Werden, 2003). This test was developed in competition economics and is generally used at the firm level. In this paper, it is applied at a more aggregated country-product level. The test delineates an upstream producer's relevant market based on information on its margin rates and profit, and on a downstream producer's own- and cross-price elasticities. While it is possible to find data on margin rates and profit at the country-product level, own- and cross-price elasticities must be estimated. These elasticities are therefore derived

from the second part of the model, a gravity model applied at the country-product level. The gravity model is helpful in this setting because it requires relatively little data given that most characteristics are controlled for by fixed effects. Additionally, it is separable both theoretically and empirically (Yotov et al., 2016). The main characteristics of each part of the model are described hereafter, and a full derivation can be found in Appendices 2.A and 2.B. Figure 2.5 summarizes the relationships between the different parts of the model.

Figure 2.5: Model summary



2.4.1 Part one: the Hypothetical Monopolist Test

The hypothetical monopolist test is an iterative method that defines the relevant market for one particular product and country. To define a relevant market, the test finds all the varieties – i.e. country of origin – of a product that consumers consider to be adequate substitutes. These substitutes are defined according to the following rule: if a single entity (the hypothetical monopolist) were producing all of them, it could increase its sales price without reducing its profit because consumers consider all varieties *outside* of those the hypothetical monopolist produces to be inadequate substitutes. This means the relevant market is properly defined, and the products included in the test compete directly with one another. On the other hand, if the test finds that the hypothetical monopolist would reduce its profit if it increased its sales price, then there is at least one variety outside of those produced by the hypothetical monopolist that consumers are switching to.

Taking a country $j \in \{1, ..., N\}$ as a starting point, the test's first iteration checks whether a hypothetical monopolist controlling the production of product j could profitably increase the price of this product. If the result is positive, this means the relevant market for producers in j is only made up of the national market. If the result is negative, this means that there are substitutes outside of j that consumers are turning to following the price increase in j. In this case, the test is run again with a broader definition of the hypothetical monopolist: it does not only include j but also an additional substitute $i \in \{1, ..., N\}$, with $i \neq j$. The specific i that is included in the following iteration of the test is the country that has the highest likelihood of being a competitor to j. This is determined by taking the product of each country's production volume and its cross-price elasticity with j;[12] this measure proxies the magnitude of a potential transfer of consumption from j to i.

If the hypothetical monopolist can impose a price increase on j and capture all substitution to i, without losing out to any other non-i substitutes, then the relevant market has been found. If not, an additional substitute $i + 1$ needs to be added into the definition of the hypothetical monopolist. This will be the country that is the second most likely to be a competitor to j, as defined above. The test is run until it returns a positive result, with an additional substitute added at each iteration. When the test returns a positive result, the hypothetical monopolist controlling the production of product j and its substitutes $i \in \Theta_j = \{1, ..., N'\}$[13] can impose its market power on this market, with Θ_j the subset of products that are adequate substitutes to j. At this point, the test is stopped and the relevant market for j is composed of j and Θ_j.

The test determines whether it is *profitable* for the hypothetical monopolist to increase the price of j by a small but significant amount, set by convention at +5% of the observed price.[14] The observed price is presumed to be the result of a competitive equilibrium. In other words, the test checks whether profits Π made by a hypothetical monopolist controlling the production of j and its substitutes $i \in \Theta_j = \{1, ..., N'\}$ are greater after this monopolist increases the price of j by 5% (post-increase) than in the initially observed situation (pre-increase). By calculating profits made on product j after the price increase, the test captures the price effect of this price increase, while it captures a substitution effect by also including the profit made on substitutes Θ_j. This substitution effect can also be understood as a form of consumption leakage, since it represents the amount of consumption transferred from country j to another country i after a price

[12]The definition and estimation strategy for the cross-price elasticity is described in Section 2.4.2.

[13]Note that i is indexed so that country$_{i=1}$ is the country that is the most likely to be a competitor to j, and may not be the same as country$_{j=1}$.

[14]The threshold of 5% is standard in the literature as it is considered a small but significant price increase. I also include simulations of other levels of price increases in the results.

increase in j. Formally, the condition for the hypothetical monopolist test is written as:

$$\Pi^{post}_{j+\Theta_j} > \Pi^{pre}_{j+\Theta_j} \tag{2.1}$$

$$\Leftrightarrow \Delta\Pi_{j+\Theta_j} > 0 \tag{2.2}$$

At each iteration, this is equivalent to testing for the following condition:

$$-\varepsilon_{jj} < \frac{1}{\mu_j + x} + \sum_{i \neq j}^{N'} \frac{\mu_i}{\mu_j + x} \frac{v_i}{v_j} \varepsilon_{ij} \tag{2.3}$$

Where ε_{jj} is country j's own-price elasticity, ε_{ji} is country j's cross-price elasticity with country i, μ and v are the margin rates and turnover, respectively, and x is the price increase imposed by the hypothetical monopolist.[15] The expression on the right-hand side of the inequality is known as the "critical elasticity". If the opposite of a country's own-price elasticity is smaller than the critical elasticity, then the hypothetical monopolist condition is verified.

If condition 2.3 is not verified, another iteration of the test is run, adding an additional substitute i. If it is verified, then it is profitable for the hypothetical monopolist to impose a price increase on product j, meaning there are no substitutes outside the market. The relevant market for baseline country j is defined at this point.

There is some uncertainty in the data I use for μ because the only data available is for the EU. To mitigate this uncertainty, I run the hypothetical monopolist test in a Monte Carlo simulation. For each iteration of the simulation, I assign a random value of μ to all countries, based on the distribution parameters of the EU's data and run the entire hypothetical monopolist test. The values I report as results of the test are therefore the share of simulation outcomes in which a country appears in the EU's relevant market.

2.4.2 Part two: Gravity model

Gravity model. This paper uses a modified version of the standard gravity model based on micro-founded monopolistic competition (Yotov et al., 2016). It is modified in that the optimizing agent is a downstream producer buying industrial products from an upstream producer rather than a consumer buying consumption products from a producer. The downstream producer has a nested CES production function. For a given country $j \in \{1, ..., N\}$ importing from all other countries, the top level of this production function specifies the substitution between labor and the aggregate industrial product

[15] We take the definition of $\varepsilon_{jj} > 0$.

and is defined as:

$$Y_j = L_j^{\alpha} M_j^{1-\alpha} \tag{2.4}$$

Where L is labor and M is the aggregate industrial product. The aggregate industrial product has N different varieties, one for each country/upstream producer in the world. The lower level of the downstream producer's production function describes how it produces the aggregate industrial product using different varieties of the upstream product as inputs. It is defined by the following CES function:

$$M_j \equiv \left(\sum_{i=1}^{N} m_{ij}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \; ; \; \sigma > 1 \tag{2.5}$$

Where σ is the CES elasticity of substitution between different varieties of the industrial product, m_{ij} is the quantity used in physical units of each variety and $i \in \{1, ..., N\}$ is the exporting country. Setting $\sigma > 1$ implies that varieties of the industrial product are substitutes rather than complements. Downstream producers therefore do not necessarily need to consume all varieties of the industrial product for their production, but could theoretically consume even just one variety. In fact, if a market is purely national, the downstream producer could consume only the variety from the domestic upstream producer.

Solving for the downstream producer's cost minimization problem, the demand for each variety is expressed as:

$$m_{ij}^{*} = p_{ij}^{-\sigma} M_j^{*} \left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{\sigma}{1-\sigma}} \tag{2.6}$$

Where M_j^{*} is the optimal quantity consumed of the aggregate industrial product in country j and p_{ij} is the price of the variety from country i sold in country j. This price is defined as $p_{ij} = p_i t_{ij}$ where p_i is the factory-gate price in country i and t_{ij} are iceberg transport costs from country i to country j.

The trade flow in monetary units X_{ij} of the industrial product exported from country i to country j can be expressed as:

$$X_{ij} = \frac{(p_i t_{ij})^{1-\sigma}}{P_j^{-\sigma}} M_j^{*} \tag{2.7}$$

Where P_j is the price index in country j. The market clearing condition is that production of the product in country i, O_i, is equal to the sum of its exports to all countries ($j \neq i$) and to itself ($j = i$) - i.e., domestic sales, also known as intra-national

trade:

$$O_i = \sum_{j=1}^{N} \frac{(p_i t_{ij})^{1-\sigma}}{P_j^{-\sigma}} M_j^* \tag{2.8}$$

Given that there are no reliable sources of transport cost data for international trade, especially at the product level, trade economists generally use a set of related indicators to proxy for transport costs. A large strand of literature has focused on identifying the determinants of trade costs, a subset of which are now considered as standard proxies and are known as gravity distance variables. The most significant of these is a measure of geographical distance between two trading partners. Even in recent years, a very robust and positive relationship exists between the distance and the transport costs between any two countries. A set of "cultural distance" indicators can also modify transport costs by impacting administrative or regulatory costs for trading partners. The most commonly used cultural distance indicators are contiguity, a common official language between two countries, former colonial ties, and the participation in a common regional trade agreement (Yotov et al., 2016). Given the highly specific nature of the industrial goods covered in this study, the main specification does not include these cultural variables.[16] Transport costs are defined as in equation 2.9 below, with δ_j importer j's distance coefficient and $dist_{ij}$ the geographical distance between countries i and j.

$$t_{ij} = \delta_j dist_{ij} \tag{2.9}$$

From this framework, the gravity equation that is used for estimation is derived. A Poisson Pseudo-Maximum Likelihood estimator with importer-year $\varphi_{i,t}$ and exporter-year $\chi_{j,t}$ fixed effects is used.[17], expressed as:

$$\log X_{ij,t} = -\log O_t + (1-\sigma)\log dist_{ij,t} + \pi_{i,t} + \chi_{j,t} + \epsilon_{ij,t} \tag{2.10}$$

Own- and cross-price elasticities. I derive expressions of country j's own- and cross-price elasticities from the same monopolistic competition framework. These elasticities are dependent on the CES substitution elasticity σ between varieties, the Cobb-Douglas

[16]Trade in industrial goods requires highly specialized equipments and is therefore likely driven more by country specialization than these cultural distance indicators. However, to stay in line with the general gravity literature, I report regression results with these indicators in Appendix 2.C. I use the standard indicators of cultural distance, including whether two countries have a Regional Trade Agreement, whether they have an official language in common, whether they are contiguous and whether they share colonial ties. While the cultural distance indicators have coefficients that are contrary to what is expected, including them does not substantially change the value or significance of the coefficients associated with the log distance between countries.

[17]I use the "ppmlhdfe" command in Stata, developed by Correia et al. (2020).

parameter α for the industrial product and prices of the different varieties:

$$\varepsilon_{jj} = (-\sigma) + (\sigma - \alpha)\frac{p_{jj}^{1-\sigma}}{\sum_{i=1}^{N} p_{ij}^{1-\sigma}} \tag{2.11}$$

$$\varepsilon_{ij} = (\sigma - \alpha)\frac{p_{jj}^{1-\sigma}}{\sum_{i=1}^{N} p_{ij}^{1-\sigma}} \tag{2.12}$$

2.5 Data

As discussed in the previous Section, the model is split into two parts. The first part is the hypothetical monopolist test, which is run using results from the second part, a product-level gravity model. In this Section, I begin by describing the data used in the gravity model. I then turn to the data used for the hypothetical monopolist test, which includes outputs from the gravity model.

2.5.1 Gravity model data

International trade data

The main source of data used for the gravity model is CEPII's BACI dataset (Gaulier & Zignago, 2010).[18] It contains data on quantities and values of international bilateral trade flows for 150 countries between 1995 and 2022. The HS07 version of this dataset is used.[19] This version was last updated in February 2024, and spans from 2007 to 2022.

CEPII's BACI database is drawn from COMTRADE tariff data. While the creators of BACI treat the raw COMTRADE data to have more reliable unit values, there are still some variations in unit values that seem implausible and are likely caused by misreporting in the original data.[20] Tariff data can be unreliable in some cases due to insufficient monitoring from customs administrations and other issues (Yotov et al., 2016). To overcome this issue, I implement a procedure to detect outliers in unit values (defined as the ratio between the value of a trade flow and its quantity), described in Appendix 2.D.

[18] Available at the following URL:
http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37

[19] The Harmonized System (HS) is an internationally standardized nomenclature for traded products. It was developed and is maintained by the World Customs Organization. The HS is updated every few years, generally with added granularity in the nomenclature. Using the 2007 version provides sufficient granularity to perform a highly disaggregated analysis, but it also reduces the sample size since data for this version of the nomenclature only goes back to 2007.

[20] Unit values are defined as the value of a trade flow divided by its quantity.

Finally, the dataset is aggregated to a product level.[21] Cement is classified as either clinker or hydraulic cement and steel products are split into flat or long products.

Intra-national trade data

To be theoretically consistent, gravity models require intra-national trade data. Intra-national trade represents the volume of products that a country both produces and consumes domestically. While most countries do not report direct measures of intra-national trade, a common way to measure this variable is to take the difference between a country's gross production of a product and the sum of its exports of that product to other countries (Yotov et al., 2016).[22]

Some databases use this method to provide intra-national trade data at a relatively aggregated level – generally the 2- or 3-digit level of the Industrial Standard Industrial Classification (ISIC).[23] At the 3-digit level, there are sectors such as "Iron and steel" or "Other non-metallic mineral products". In this paper, more disaggregated production data is used to calculate intra-national trade volumes, thus avoiding – or at least minimizing – the aggregation bias that has been noted in the gravity literature (Anderson & van Wincoop, 2004; Anderson & Yotov, 2010).

For flat and long steel products, data from WorldSteel's online Statistical Yearbooks is used (WorldSteel, 2023).[24] These yearbooks provide data on the gross volume of production of flat and long steel products by country from 2006 to 2022.

For hydraulic cement, data from the United State's Geological Survey's Cement Statistics and Information is used – namely the Minerals Yearbook (United States Geological Survey, 2011, 2016, 2021).[25] This source provides data on the production of hydraulic cement by country between 2004 and 2021.

Comprehensive clinker production data is currently still lacking. The Global Cement and Concrete Association (GCCA) provides this type of data for a selected number of

[21] Appendix 2.E provides a correspondence table between HS codes and the products in this study.

[22] Canada is a notable exception to this. The Government of Canada provides data on trade between provinces that has been used in some of the foundational studies in gravity economics (see McCallum (1995) for example).

[23] See for instance the World Bank's Trade, Production, and Protection Database, the CEPII's TradeProd database, or the United Nations Industrial Development Organization's INDSTAT database.

[24] Available at the following URL:
https://worldsteel.org/steel-topics/statistics/steel-statistical-yearbook/.

[25] Available at the following URL:
https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

countries, but not for the full sample the rest of the data covers.[26] To work around this, I estimate clinker production volumes as the product of hydraulic cement production volumes and a region's clinker-to-cement ratio, to which clinker exports are added and clinker imports removed. A comparison of this proxy to the GCCA's data for available countries shows that it performs relatively well for most countries, with some notable exceptions including Egypt, India and Thailand. Appendix 2.F provides a comparison of the constructed clinker production data with the GCCA's data. For consistency, I use the constructed data for all countries.

This production data was merged with the international trade data from BACI to generate intra-national trade flow volumes, using the product crosswalk shown in Appendix 2.E.

Distance

The data for the geographic distance indicator is taken from the CEPII's Gravity database and is the straight-line geographic distance between the most populated city of each country, in km (Conte et al., 2022).

2.5.2 Hypothetical monopolist test data

Own- and cross-price elasticities

As shown in equations 2.11 and 2.12, own- and cross-price elasticities are computed based on three elements: the CES elasticity of substitution between varieties of a product σ, the Cobb-Douglas parameter α, and prices for each variety.

CES trade elasticity of substitution. Product-specific CES trade elasticities of substitution σ are derived from the gravity model (equation 2.10). Table 2.1 reports the results of the gravity regression. σ is 1 minus the coefficient of the log distance variable. Values of σ are reported in Table 2.2. Figure 2.6 compares this paper's estimates of σ to those found in other papers, showing they are fully in line with existing literature.

[26]The GCCA database provides clinker production data for the following countries and regions: World, Africa, Asia (n.e.c.) + Oceania, Austria, Brazil, Canada, Cembureau members, Central America, China + Korea + Japan, CIS, the Czech Republic, Egypt, EU 28, Europe, France, Germany, India, Italy, Latin America, the Middle East, Morocco + Algeria + Tunisia, North America, the Philippines, Poland, South America ex. Brazil, Spain, Thailand, the United Kingdom, and the United States.

Table 2.1: Gravity regression estimation results

	(1) Hydraulic cement	(2) Clinker	(3) Long steel	(4) Flat steel
Log distance	-4.845***	-5.440***	-3.287***	-2.308***
	(0.697)	(1.296)	(0.331)	(0.237)
Observations	22491	7603	18031	17486
Pseudo R^2	0.98	0.98	0.98	0.95
Fixed effects:				
Exporter-year	Yes	Yes	Yes	Yes
Importer-year	Yes	Yes	Yes	Yes

Note: Standard errors clustered by importer-exporter pair. Standard errors in parenthesis. Estimation through Poisson Pseudo Maximum Likelihood estimator.
* p<0.10, ** p<0.05, *** p<0.01

Table 2.2: Values of σ

	(1) Hydraulic cement	(2) Clinker	(3) Long steel	(4) Flat steel
σ	5.845***	6.440***	4.287***	3.308***

* p<0.10, ** p<0.05, *** p<0.01

Cobb-Douglas alpha parameter. The α parameter is derived from the University of Groeningen's WIOD input-output database.[27] It is calculated as the share of cement or steel consumed by all branches of a country's economy in that country's total costs – which is equated to total production.

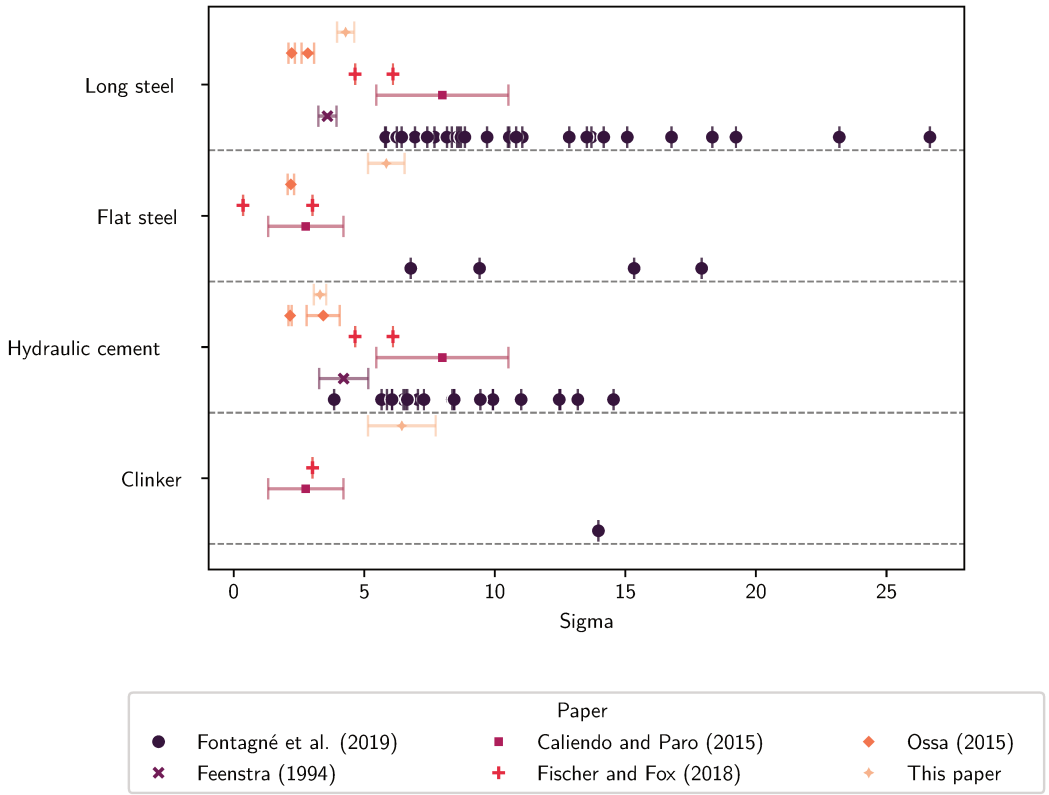
Pricing data. While pricing data is difficult to access directly due to its highly sensitive nature, a proxy value is calculated based on the available trade data. Domestic prices for a country are estimated as the quantity weighted average of this country's export prices.

While it may not perfectly reflect the real domestic prices of the products covered in this paper, this proxy was checked against some steel pricing data made available by the OECD for specific countries. The proxy was found to roughly match the evolution of the OECD's data.[28] An average correlation of 71% and 51% was found between the two datasets for flat and long steel products respectively. There is no reliable data the domestic pricing of hydraulic cement or clinker that could be used to compare with the constructed data.

[27] Available at the following URL:
https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

[28] See Appendix 2.H for a correlation analysis of the constructed data compared to the OECD's data.

Figure 2.6: Comparison of trade elasticities



Note: Some of the elasticities displayed in this graph are estimated at a more aggregated level than those estimated in this paper. In this case, the elasticity is attributed to all the products included in the higher level of aggregation. For example, Caliendo and Parro (2015) estimate elasticities for "Basic metals". This estimate is therefore attributed to both flat and long steel products in this Figure. Appendix 2.G provides all the values used in this graph, as well as the original product level at which each elasticity was estimated.
Source: Author

Turnover and margin rate

Finally, the hypothetical monopolist test requires data on turnover and margin rates for each country included in the test. While it is difficult to recover complete data on margin rates due to its sensitive nature, Eurostat provides values for some countries and industrial sectors in the EU, for selected years.[29] I use this data as a base, and perform a Monte Carlo simulation that assigns a random value to each country at each iteration. The random values is taken from a normal distribution with the parameters of the observed distribution in the EU. This mitigates some of the uncertainty around this parameter. If any bias exists in the EU's data, this bias is applied to all countries equally and therefore should not change the results of the hypothetical monopolist test, which compares countries to each other. Turnover is calculated by multiplying the production data presented in Section 2.5.1 with unit values presented in Section 2.5.1.

[29]The data used from Eurostat is the "sbs_a_ind_r2" series from their Structural Business Statistics series. Specifically, the "Gross operating rate – percentage" indicator from this series is used.

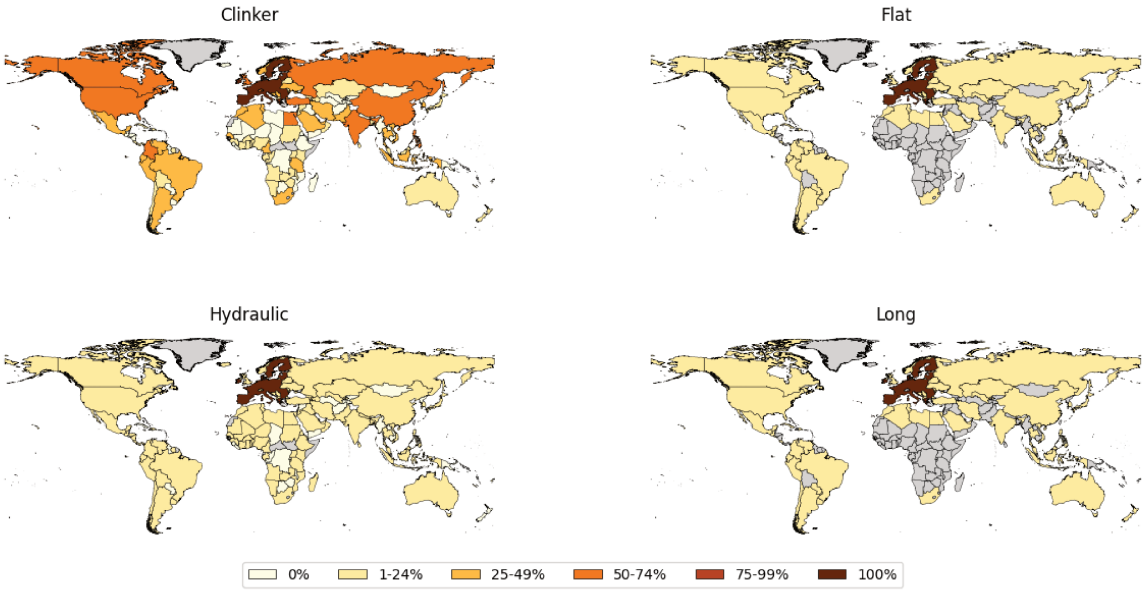
2.6 Results

2.6.1 Presentation of results

This section presents the main results from the hypothetical monopolist test. I first present results showing the EU's relevant market, then turn to results showing countries for which the EU is in the relevant market. All of the results are shown as world maps, with the shade of color representing the share of simulation outcomes in which a country appears. For example, if a country is shaded in the color representing 25-49%, this means that country has appeared in a quarter to half of all results from the Monte Carlo simulation.

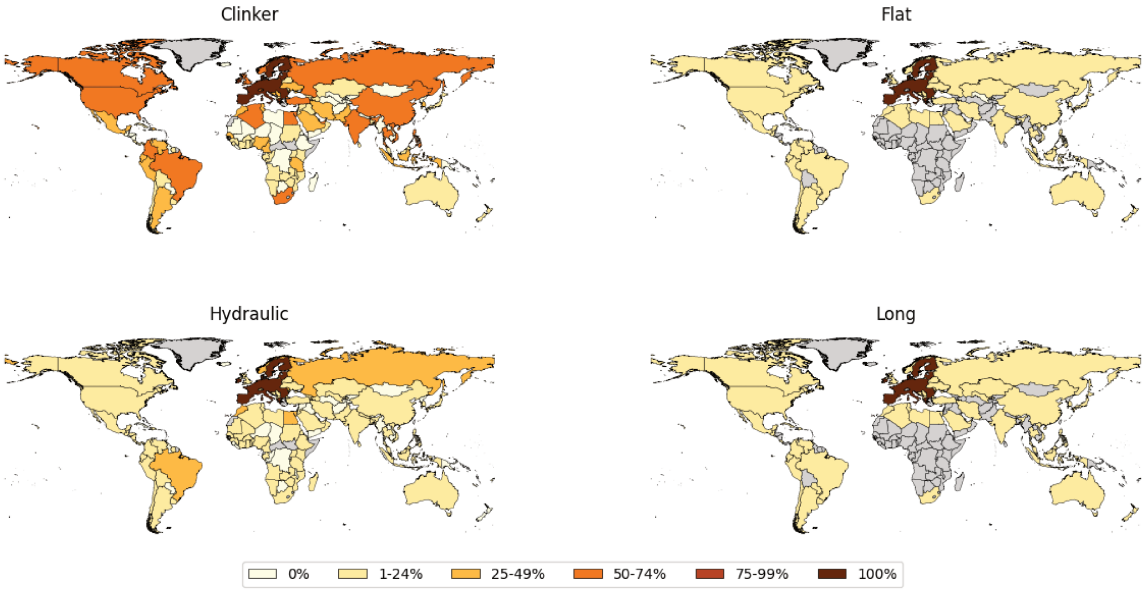
5% price increase. First, I show results with a 5% price increase in the hypothetical monopolist test (Figure 2.7). Among the 4 industrial products that are covered, only clinker appears to face competition from countries outside the EU at this level of price increase. The 11 countries that appear within the EU's relevant market for clinker in more than half of all simulation results are Egypt (60%), Russia (55%), China (55%), Switzerland (55%), Colombia (55%), the UK (55%), India (55%), Türkiye (55%), the US (55%), the Philippines (55%), and Canada (50%). For the other three products that are covered, all other countries outside of the EU appear in less than a quarter of all simulation results.

Figure 2.7: EU relevant market with a 5% price increase



10% price increase. When I change the price increase to 10% in the simulation, results only change in the cement sector (Figure 2.8). For hydraulic cement, some countries begin to appear in more than a quarter of simulation results. These include (in decreasing order of frequency): Egypt, Russia, Moldova, Brazil, Norway and Morocco. For clinker, the same countries appear as they did for the 5% price increase, with the addition of the United Arab Emirates, Thailand, South Africa, Algeria, Norway and Vietnam – all of which appear in around 55% of simulation outcomes. An additional 22 countries appear in 25 to 49% of simulation outcomes, with Serbia, Morocco, Tunisia, Ukraine and Indonesia appearing the most. For steel products, the EU's relevant market remains confined to itself.

Figure 2.8: EU relevant market with a 10% price increase

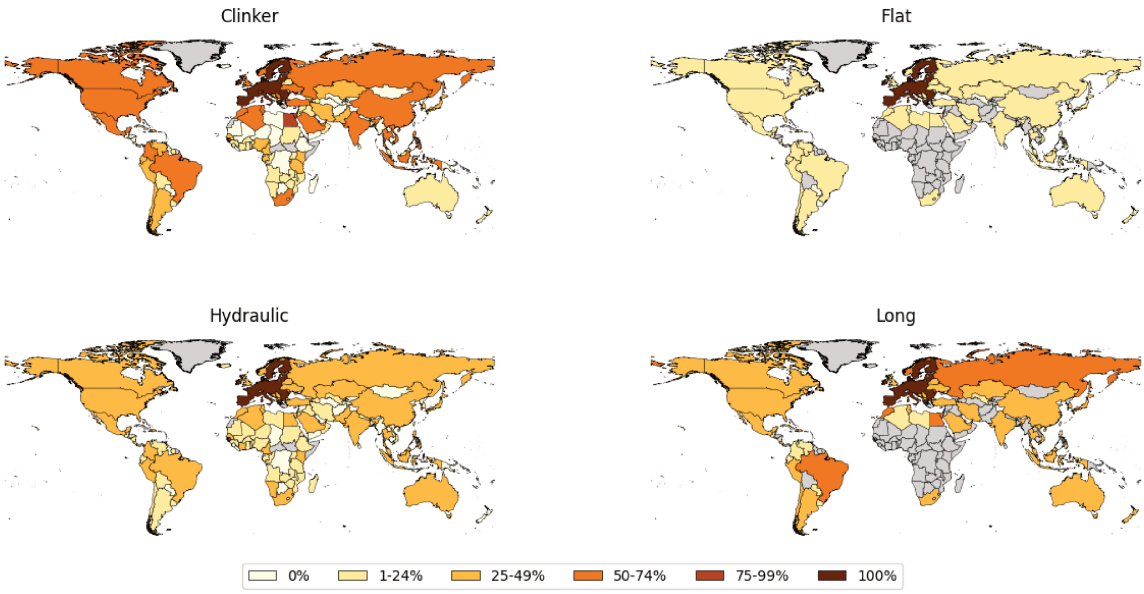


20% price increase. The results for a 20% price increase show a clear shift for long steel products (Figure 2.9). There seems to be a tipping point for long steel between a 10 and 20% price increase that makes the EU's relevant market significantly expand. With a 20% price increase, 7 countries appear in more than 50% of simulation outcomes: Egypt, Morocco, Moldova, Russia, Brazil, Montenegro and Norway. An additional 33 countries now appear in more than a quarter of simulation outcomes. The relevant market for flat steel products remains confined to the EU, even with a 20% price increase.

For clinker, Egypt is the country that appears the most in simulation outcomes (80%). The countries that appear the most frequently after Egypt are Russia, Switzerland, China, Colombia, the UK, India, the Philippines, Türkiye and the US. They appear in around 60% of simulation outcomes. 15 other countries appear in more than half but less than 60% of simulation results for clinker. For hydraulic cement, all countries remain

below the 50% threshold. Egypt also appears the most frequently for this product, followed by Russia, Norway, Brazil, Moldova, Ivory Coast, China, Canada, Mexico, South Africa and Kazakhstan. An additional 31 countries appear in more than 25% but less than 30% of simulation outcomes.

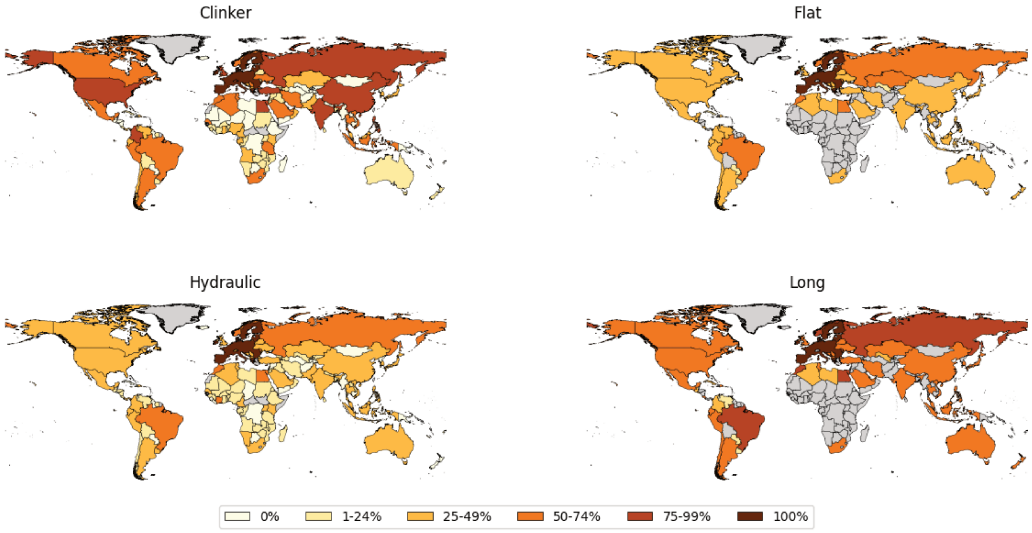
Figure 2.9: EU relevant market with a 20% price increase



50% price increase. Finally, I present the results for the EU's relevant market when the price increase is raised to 50% (Figure 2.10). While this represents a fairly implausible scenario, it is useful to illustrate the upper bounds of the EU's relevant market. Indeed, if a country is not in the EU's relevant market when the bloc experiences a 50% unilateral price increase, there is probably a reason for this. The variety that specific country produces may be too different from the EU's for EU consumers to ever consider it a relevant alternative, no matter the price differential.

For clinker, hydraulic cement and long steel products, results with a 50% price increase are in line with those presented with lower levels of price increases. The same countries appear most frequently in the EU's relevant market – although this frequency has itself increased. At this level, flat steel products also seem to have gone past a tipping point after which countries outside the EU enter the relevant market. The countries that appear in more than 50% of simulation outcomes are Egypt, Morocco, Russia, Brazil, Montenegro, Norway, Kazhakstan and Moldvoa, in decreasing order of frequency.

Figure 2.10: EU relevant market with a 50% price increase



EU exporters. The methodology used in this paper also gives insights on the relevant markets that EU exporters operate in. By applying the hypothetical monopolist test to different base countries (replacing the EU in previous results), I can determine their respective relevant markets. If the EU is included in this relevant market at low levels of a price increase, this indicates the competitiveness of the EU on the market as it is able to provide a suitable substitute to consumers. On the other hand, if the EU does not appear in the new base country's relevant market, this indicates that the EU's product is not sufficiently substitutable to be competitive.

With a 5% price increase in the hypothetical monopolist test for clinker, the EU is in more than a quarter of simulation outcomes for a number of countries, mostly on the African continent – including in more than 50% of simulation outcomes for Mali and Cameroon (Figure 2.11). As the price increase is raised to 20% (Figure 2.12) and 50% (Figure 2.13), this remains fairly consistent – most countries that have the EU in their relevant market are in Africa – with the addition of Russia, Myanmar, Australia and Brazil. Hydraulic cement shows similar patterns for these three levels of price increases, with the difference that the EU begins to appear in other countries' relevant markets at a higher level of price increase.

Turning to steel products, results for both flat and long products are similar to each other. With a 5% price increase, almost no countries have the EU in their relevant market in more than 25% of simulation outcomes – except Algeria for long steel products (Figure 2.11). At the 20% level, a few more countries appear, namely China, the US and Colombia (Figure 2.12). Finally, with a 50% price increase, the EU appears in more than 90% of the US's simulation outcomes for flat products, 80% of India's. It also appears in nearly 60% of simulation outcomes for China, the UK, Vietnam, Canada and Korea

(Figure 2.13). This indicates that there is a threshold between 20 and 50% where the EU becomes significantly more competitive on international flat steel markets. For long products, the same countries appear as in the 20% price increase results: China, the US and Colombia are the countries for which the EU appears the most frequently – 66, 62 and 50% respectively.

Figure 2.11: Countries where EU is in relevant market with a 5% price increase

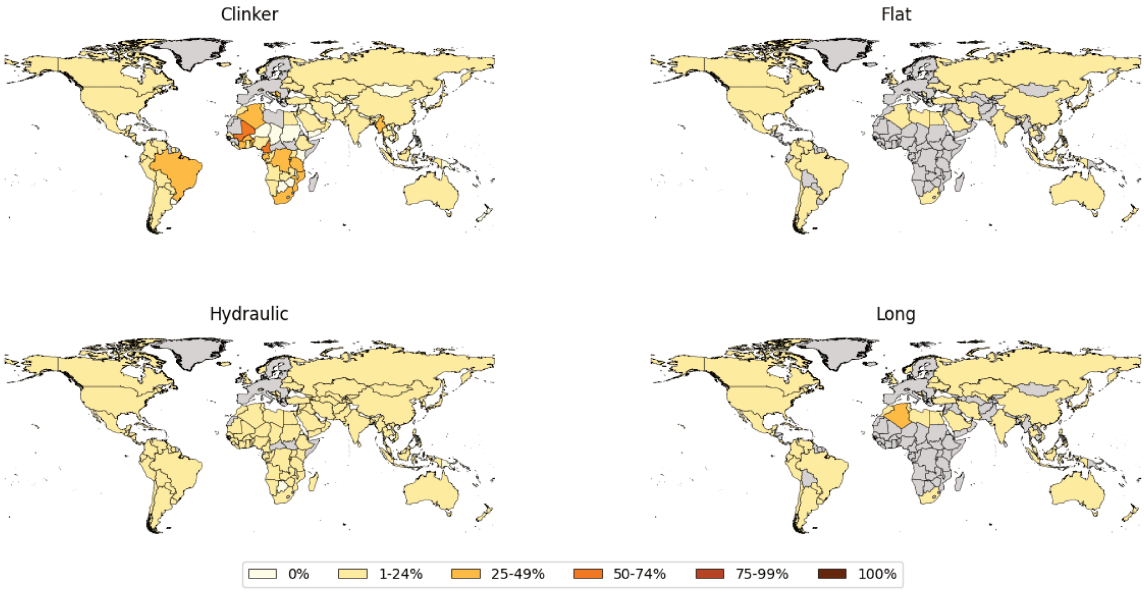


Figure 2.12: Countries where EU is in relevant market with a 20% price increase

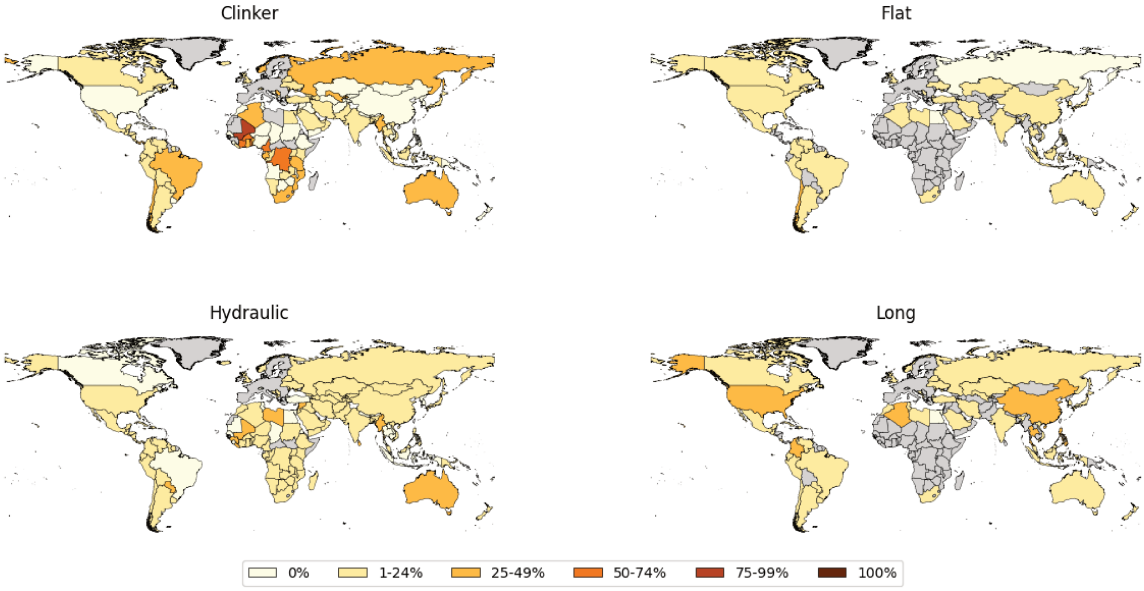
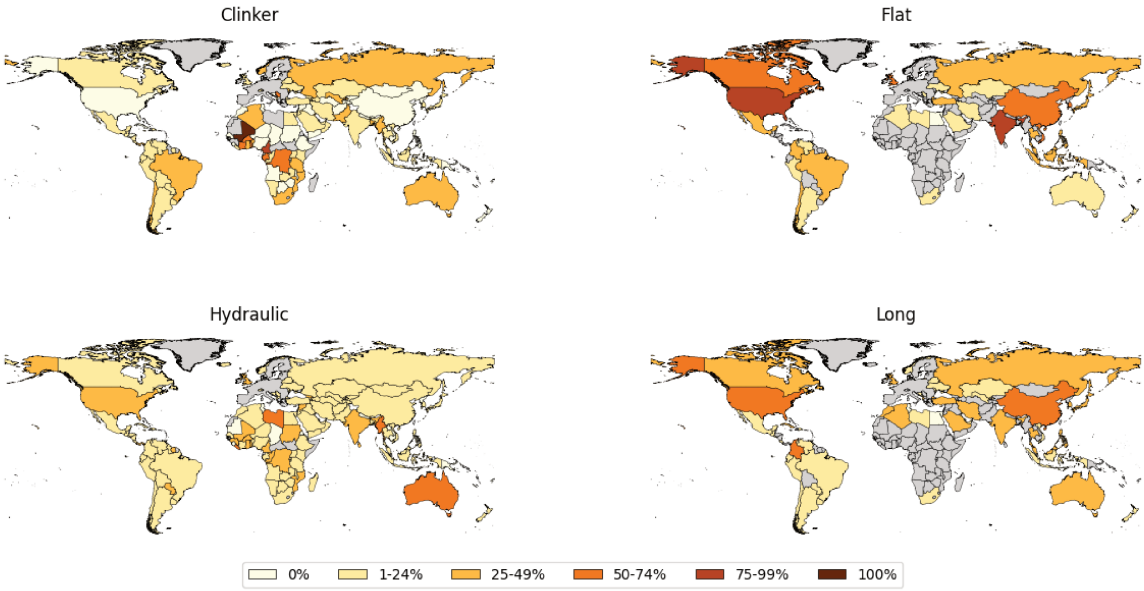


Figure 2.13: Countries where EU is in relevant market with a 50% price increase



2.6.2 Discussion and policy implications

This subsection discusses the results presented above and their policy implications. This study's results underscore notable differences in the market structure of clinker, hydraulic cement, and steel products. Three important policy implications can be drawn from these findings. First, when measuring carbon leakage risk, the following elements should be accounted for: the level of product homogeneity, regional specialization and trade *potential*. Second, this measure should be as granular as possible as products within the same sector can have very different levels and types of risk. Third, there may not be a strong risk of climate policy impacts on exporters and the risk that does exist could be alleviated by elaborating common carbon standards and policies at the product level with strategically selected countries.

Among the four industrial products covered by this study, clinker emerges as the product with the highest level of carbon leakage risk in the EU, followed by hydraulic cement, long steel, and flat steel products. Clinker has the most countries in the EU's relevant market at the lowest level of a price increase (5%). Hydraulic cement begins to have more countries in the EU's relevant market at the 10% level, while the threshold for long steel products is between 10 and 20%, and is above 20% for flat steel products. This ranking reflects differences in product homogeneity, regional specialization and trade potential.

In the EU's current methodology to determine carbon leakage risk, the level of product homogeneity and market specialization are not taken into account. In this methodology, these elements are captured by the Armington elasticity – which represents the cross-price elasticity between two specific countries. This type of indicator could be included in the EU's methodology to better reflect carbon leakage risk based on each product's characteristics.

Product homogeneity. Clinker is the most homogeneous product of all four products analyzed in this paper. Since the 2000s, the chemical composition of this material has been stabilized, making it highly homogeneous across different countries (Herfort et al., 2010). Hydraulic cement is more homogeneous than steel, but less than clinker. Depending on their composition, different types of cement will have different applications and qualities (Kurdowski, 2014). The HS codes associated with these products perfectly show their different levels of homogeneity: clinker is only associated with one 8-digit code, while cement is associated with three, and flat and long steel products are each associated with five 4-digit codes, themselves each made up of two to eight 8-digit codes (see Appendix 2.E).

A product's level of homogeneity can significantly impact its carbon leakage risk. It is more likely that EU consumers find acceptable alternatives outside of the EU for a homogeneous product like clinker than for highly differentiable products like steel. This makes it easier for foreign clinker producers to enter or increase their presence on the EU market if domestically-produced products become relatively more expensive.

Regional specialization. Since clinker is highly homogeneous, it is not possible for individual producers to specialize in significant ways to cater to specific markets. Specialization is slightly more prevalent in hydraulic cement, and is especially notable in the production of steel. Different countries and regions of the world have specialized in the production of different types and grades of steel (Carvalho & Sekiguchi, 2015; Steel Plate & Sections, 2024).[30] Flat steel products require higher-quality grades of steel than long products do.[31] As a result, flat steel products can almost only be produced via a Blast Furnace – Basic Oxygen Furnace (BF-BOF) route while long steel products can be produced via the BF-BOF route as well as the Electric Arc Furnace (EAF) route.[32] This means that countries that have specialized more in EAF technologies would have to switch to BF-BOF if they want to compete on flat steel markets.

Observed trade versus trade potential. The EU's measure of carbon leakage relies on a measure of trade intensity as a proxy of the international competition a sector faces. However, this indicator is backward-looking and does not represent *potential* competition that a sector could realistically face given slight changes in prices or other circumstances. The methodology presented in this paper can complement the EU's measure by providing indications on trade and competition *potential*.

Using the hypothetical monopolist methodology reveals that clinker has a larger relevant market than hydraulic cement. However, using the EU's indicator of trade intensity puts hydraulic cement in front of clinker. This illustrates the fact that while hydraulic cement is currently more traded than clinker (relative to the amount produced), clinker has a higher potential for trade expansion due to its higher levels of homogeneity

[30]See also the blogpost entitled "Green steel transition in focus: Key takeaways from Eurometal Steel Day in Zurich" by Fastmarkets, available at https://www.fastmarkets.com/insights/green-steel-transition-in-focus-key-takeaways-from-eurometal-steel-day-in-zurich/ and the webpage entitled "Steel from Around the World: Types of Steel" from Steel Plate & Sections available at https://sps-bmsteel.co.uk/article/steel-from-around-the-world.

[31]See the article by an industry specialist on Project Blue, available at https://web.archive.org/web/20240525173158/https://projectblue.com/blue/news-analysis/525/why-could-steel-industry-decarbonisation-be-long-and-difficult.

[32]The BF-BOF production route allows for a higher level of purification of iron ore than the EAF production route does. This means that it can produce higher-quality grades of steel from iron ore with low levels of purity (International Energy Agency, 2020).

and lower trade costs.[33] Without measuring *potential* trade, the relatively lower clinker trade levels currently observed may obscure its true market size. Policymakers should therefore take this parameter into account when measuring carbon leakage risk.

Importance of product-level market definitions. The results of this paper's analysis reveal significant differences in the market definitions of each specific product. Differences are apparent in terms of the price increase needed for a significant market expansion and in terms of the specific countries included in each country's relevant market. The countries included in each product's relevant market reflect the specialization discussed above, but also the trade costs associated with reaching the EU's market. For instance, clinker is lighter and therefore easier and cheaper to transport than hydraulic cement.[34] This can also explain why this product has a larger relevant market at lower levels of a price increase.

The fact that results differ substantially by product is in line with the rest of the literature that highlights that aggregating products or sectors too much may create a bias in the measure of carbon leakage risk (Fischer & Fox, 2018). The policy implication of this finding is that all assessments of carbon leakage should be conducted at the lowest possible level of disaggregation. This can help to prioritize the products that are the most at risk. Additionally, studying products within a common value chain, like clinker and hydraulic cement, can help to highlight risks of reshuffling.[35] Identifying specific countries that produce the closest substitute products to the EU's can also help policymakers to strategically target these countries for partnerships aimed at fostering common climate standards and policies.

Impacts on exporters. One of the issues around carbon leakage is whether anti-leakage measures should be applied to all producers, only importers or only exporters (Ambec et al., 2024; Fischer & Fox, 2012). This stems from the fact that there may be legal challenges to implementing anti-leakage measures for exporters as they may be seen as export subsidies, which are outlawed by international trade law (Cameron & Baudry, 2023). The results indicate that for certain products, there may be minimal risk of competitiveness losses for exporters, as they are already absent from many countries' relevant markets.

[33]See the note prepared by PEC Consulting Group, available at https://pecconsultinggroup.com/grinding-plant-utilizing-imported-clinker/.

[34]See the note prepared by PEC Consulting Group, available at https://pecconsultinggroup.com/grinding-plant-utilizing-imported-clinker/

[35]Reshuffling refers to companies intentionally exporting their cleanest products to countries with stringent policies and their dirtiest products to other countries. This allows them to avoid true carbon reductions, and is a risk often highlighted in the literature (Böhringer et al., 2022; Grubb et al., 2022).

EU producers of hydraulic cement and flat steel are not on any non-EU country's relevant market even when these countries increase their prices by 5 to 20%. A 50% price increase is required for the EU to appear in more than 50% of some countries' relevant market simulation outcomes. EU producers of clinker and long steel products appear to be in a few countries' relevant market at lower levels of a price increase.

Additionally, it is clear in the results with the 50% price increase that EU hydraulic cement and clinker exporters do not operate on the same markets as EU steel exporters. In the cement sector, the countries that appear the most are on the African continent – with the addition of Myanmar and Australia for hydraulic cement. On the other hand, for steel, the USA, Canada, China, India and Colombia appear as important markets that EU producers can compete on. This seems to indicate that EU hydraulic cement producers are only competitive on their own regional market, while for steel, they can be competitive globally – in the case of a 50% price increase in foreign countries.

The EU's CBAM will only cover products imported into the bloc, not those exported by its own producers. The results suggest that impacts on exporters may be fairly limited, as they are already not very competitive on many foreign markets. Targeting specific countries to establish bilateral climate standards and policies in markets that are the most relevant by product may be effective to alleviate impacts on exporters without resorting to distortionary measures such as export subsidies.

2.6.3 Limitations

Several limitations of this work need to be highlighted. First, the data available for the different steps in the analysis are sometimes limited both in terms of their quality and their range. There is a scope for improvement using more precise and comprehensive data that may be available in the future, namely for margin rates. Additionally, this analysis would have to be extended to many more sectors and products in order to be used in a policymaking context.

Second, because the margin rates that I use for all countries are based on the distribution from EU margin rates, they are entirely based on real market conditions. This may induce a bias since low observed margin rates would lead the hypothetical monopolistic test to show that the relevant market is very small, but could actually reflect an already competitive market and therefore induce a fallacy. The risk of this happening in the analysis is mitigated by the Monte Carlo simulation that is applied and the fact that I find that the relevant market is not only composed of the EU for all of the products covered. To fully measure and remove this bias, further research could compare observed

margin rate values with margin rates derived from a counterfactual analysis where no competition is observed.

2.7 Conclusion

This paper has proposed a new approach to measure the risk of carbon leakage in the cement and steel sectors, looking in particular at the competitive market conditions for both of these heavy industries. Applying the hypothetical monopolist test to EU heavy industry producers, this study highlights significant variation in carbon leakage risks across clinker, hydraulic cement, and flat and long steel products. This variation is driven by differences in homogeneity, trade costs, and regional specialization. Clinker consistently exhibits the largest relevant market, even at low levels of price increases, while steel products show significant market expansion only at higher thresholds of price increases. These findings emphasize the need for targeted, product-specific climate and trade policies to address carbon leakage effectively.

Future research could expand this study by incorporating more industrial sectors and products – this would bolster the policy relevance of the methodology proposed. On the data side, it would be particularly useful to include more granular and comprehensive data on margin rates. Exploring dynamic models that account for innovation and potential changes in trade and production patterns globally could also further refine estimates of carbon leakage risks. Finally, comparative studies across regions beyond the EU could inform about risks of carbon leakage in different jurisdictions and help countries to develop strategic partnerships on climate policies and standards.

Appendix

2.A Part one: the Hypothetical Monopolist Test

The hypothetical monopolist test determines whether it is *profitable* for a hypothetical monopolist controlling the production of good j and of its substitutes $i \in \Theta_j = \{1, ..., N'\}$ to increase the price of j by a small but significant amount - set by convention at +5%. Formally, this means testing whether profits made by this hypothetical monopolist are greater before or after the price increase. If they are greater before, then the relevant market has been identified.[36]

$$\Pi^{post}_{j+\Theta_j} > \Pi^{pre}_{j+\Theta_j} \tag{2.1}$$

$$\Leftrightarrow \Delta\Pi_{j+\Theta_j} > 0 \tag{2.2}$$

By definition, we have the following own- and cross-price elasticity formulations:

$$\varepsilon_{jj} = \frac{\Delta q_j/q_j}{\Delta p_j/p_j} \quad \Leftrightarrow \quad \Delta q_j = \varepsilon_{jj}\frac{\Delta p_j}{p_j}q_j$$

$$\varepsilon_{ij} = \frac{\Delta q_i/q_i}{\Delta p_j/p_j} \quad \Leftrightarrow \quad \Delta q_i = \varepsilon_{ij}\frac{\Delta p_j}{p_j}q_i$$

p_j is the good j's unit price and q_j is the quantity produced. The quantities of j and i that are sold both before and after the price increase are respectively given by:

$$q_j + \Delta q_j = q_j + (\varepsilon_{jj} x q_j) = q_j(1 + \varepsilon_{jj}x)$$

$$q_i + \Delta q_i = q_i + (-\varepsilon_{ij} x q_i) = q_i(1 + \varepsilon_{ij}x)$$

With $x = \frac{\Delta p_j}{p_j}$. Pre- and post-price increase profits are defined as follows:

$$\Pi^{pre}_{j+\Theta_j} = (p_j - c_j)q_j + \sum_{j\neq i}^{N'}(p_i - c_i)q_i$$

$$\Pi^{post}_{j+\Theta_j} = (p_j(1+x) - c_j)(q_j + \Delta q_j) + \sum_{j\neq i}^{N'}(p_i - c_i)(q_i + \Delta q_i)$$

[36] All equations in this appendix are numbered as in the main text so they can easily be matched up.

I substitute Δq_j and Δq_i in the definition of post-price increase profits:

$$\Pi^{post}_{j+\Theta_j} = (p_j + p_j x - c_j)(q_j(1 + \varepsilon_{jj}x)) + \sum_{j \neq i}^{N'}(p_i - c_i)q_i(1 + \varepsilon_{ij}x)$$

c_j is the good j's ex ante unit cost and x is the percentage price increase imposed on j by the hypothetical monopolist, which is set at 5% by convention.

This gives us the following value for the change in profit:

$$\Delta\Pi_{j+\Theta_j} = \Pi^{post}_{j+\Theta_j} - \Pi^{pre}_{j+\Theta_j}$$

$$\begin{aligned}\Leftrightarrow \Delta\Pi_{j+\Theta_j} =&(p_j + p_j x - c_j)(q_j(1 + \varepsilon_{jj}x)) + \sum_{j \neq i}^{N'}(p_i - c_i)(q_i(1 + \varepsilon_{ij}x)) \\ &- (p_j - c_j)q_j - \sum_{j \neq i}^{N'}(p_i - c_i)q_i\end{aligned}$$

$$\begin{aligned}\Leftrightarrow \Delta\Pi_{j+\Theta_j} =&(p_j - c_j)q_j\varepsilon_{jj}x + xp_jq_j(1 + \varepsilon_{jj}x) \\ &+ \sum_{j \neq i}^{N'}(p_i - c_i)q_i\varepsilon_{ij}x\end{aligned}$$

I divide and multiply by prices p_j and p_i to make margin rates μ and turnover v apparent:

$$\Delta\Pi_{j+\Theta_j} =\varepsilon_{jj}x * \underbrace{\frac{p_j - c_j}{p_j}}_{\mu_j} * \overbrace{p_jq_j}^{v_j} + x * \overbrace{p_jq_j}^{v_j} * (1 + \varepsilon_{jj}x)$$

$$+ \sum_{j \neq i}^{N'} \underbrace{\frac{p_i - c_i}{p_i}}_{\mu_i} * \overbrace{p_iq_i}^{v_i} * \varepsilon_{ij}x$$

Adding the condition that $\Delta\Pi_{j+\Theta_j} > 0$:

$$\Delta\Pi_{j+\Theta_j} > 0$$

$$\Leftrightarrow \varepsilon_{jj}x\mu_jv_j + xv_j(1 + \varepsilon_{jj}x) + \sum_{j \neq i}^{N'} \mu_iv_i\varepsilon_{ij}x > 0$$

Finally, factorizing by ε_{jj} and dividing by x yields the following condition, which is used as the empirical application of the hypothetical monopolist test:

$$-\varepsilon_{jj} < \frac{1}{\mu_j + x} + \sum_{j \neq i}^{N'} \frac{\mu_i}{\mu_j + x} \frac{v_i}{v_j} \varepsilon_{ij} \tag{2.3}$$

2.B Part two: Gravity model

Gravity model. The downstream producer of industrial goods has a two-level nested production function. For a given country $j \in \{1, ..., N\}$ buying from all other countries, the top level of the production function specifies the substitution between labor and primary industrial goods. This relationship is characterized by a Cobb-Douglas production function, defined as:

$$Y_j = L_j^{\alpha} M_j^{1-\alpha} \tag{2.4}$$

Where L_j denotes labor employed in country j and M_j represents the aggregate industrial good used in production. The parameter α $(0 < \alpha < 1)$ reflects the share of labor in production.

The industrial good M_j comprises N distinct varieties, with each variety produced by one of N countries (including country j itself). Thus, country j has access to its own variety, as well as varieties imported from all other countries $i \in \{1, ..., N\}$. Each variety is defined as a good exported from country i and imported by country j. The production function for aggregating these varieties into the composite industrial good M_j is specified as a constant elasticity of substitution (CES) function:

$$M_j \equiv \left(\sum_{i=1}^{N} m_{ij}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \; ; \; \sigma > 1 \tag{2.5}$$

Where σ is the CES elasticity of substitution between different varieties of a good and m_{ij} is the quantity of each variety that is used in physical units. The downstream producer's cost minimization problem is defined as:

$$\begin{aligned} \min \quad & w_j L_j + P_j M_j \\ \text{s.t.} \quad & L_j^{\alpha} \left[\left(\sum_{i=1}^{N} m_{ij}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \right]^{1-\alpha} = Y_j \end{aligned}$$

Where w_j are wages and P_j is the price index in country j.

Solving for this gives the following minimized demand function for the aggregate industrial good M_j:

$$M_j^* = Y_j \left(\frac{\alpha}{1-\alpha}\right)^{-\alpha} P_j^{-\alpha} w_j^{\alpha}$$

Next, I minimize the cost of all varieties subject to the production function to obtain the aggregate industrial good, where M_j^* is the targeted amount of the aggregate industrial good obtained in the previous equation:

$$\begin{aligned} \min_{(m_{ij},\ldots,m_{Nj})} \quad & \sum_{i=1}^{N} p_{ij} m_{ij} \\ \text{s.t.} \quad & \left(\sum_{i=1}^{N} m_{ij}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} = M_j^* \end{aligned}$$

Minimizing for a single variety $m_{ij'}$ gives the following first order condition:

$$p_{ij'} - \lambda \left(\sum_{i=1}^{N} m_{ij}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}-1} m_{ij'}^{\frac{\sigma-1}{\sigma}-1} = 0$$

This implies:

$$m_{ij'} = p_{ij'}^{-\sigma} \lambda^{\sigma} M_j^{*\,-\alpha}$$

Substituting this back into the constraint yields:

$$\lambda^{\sigma} M_j^{*\,-\alpha} = M_j^* \left(\sum_{i=1}^{N} p_{ij'}^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}}$$

Substituting this back into the above expression of $m_{ij'}$ and taking the more generic case for m_{ij} gives us the demand for a good m_{ij} conditional on consumption of the aggregate industrial good M_j^* and price p_{ij}:

$$m_{ij} = p_{ij}^{-\sigma} M_j^* \left(\sum_{i=1}^{N} p_{ij}^{1-\sigma}\right)^{\frac{\sigma}{1-\sigma}} \tag{2.6}$$

To get to the price index, we start from:

$$\underbrace{\sum_{i=1}^{i} p_{ij} m_{ij}}_{\substack{\text{sum of demand for all} \\ \text{varieties of the industrial good} \\ \text{in country } j}} = \overbrace{P_j M_j^*}^{\substack{\text{aggregate demand for} \\ \text{the industrial good} \\ \text{in country } j}}$$

Substituting equation (2.6) into this yields the following price index P_j, which coincides with the price index found in the standard consumer maximization-based gravity model:

$$P_j = \left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}}$$

Given this expression of the price index, the conditional expression of m_{ij} can be rewritten:

$$m_{ij} = M_j^* \frac{p_{ij}^{-\sigma}}{P_j^{-\sigma}}$$

Assuming iceberg transport costs defined as $p_{ij} = p_i t_{ij}$ with t_{ij} transport costs between i and j and p_i the factory-gate price in country i, the price index can be expressed as:

$$P_j = \left(\sum_{i=1}^{N} (p_i t_{ij})^{1-\sigma} \right)^{\frac{1}{1-\sigma}}$$

From this we can get the trade flow X_{ij} of a good from country i to country j:

$$X_{ij} = p_{ij} m_{ij} = p_{ij} \frac{(p_{ij})^{-\sigma}}{P_j^{-\sigma}} M_j^*$$

$$\Leftrightarrow X_{ij} = \frac{(p_i t_{ij})^{1-\sigma}}{P_j^{-\sigma}} M_j^* \tag{2.7}$$

This is the theoretical equation from which I derive the gravity model used in estimations. Finally, market clearing is imposed for goods from each origin, with O_i country i's production of the good:

$$O_i = \sum_{j=1}^{N} \frac{(p_i t_{ij})^{1-\sigma}}{P_j^{-\sigma}} M_j^* \tag{2.8}$$

Following Yotov et al. (2016), I define world output $O = \sum_{i=1}^{N} O_i$ and divide (2.8) by O:

$$p_i^{1-\sigma} = \frac{O_i / O}{\sum_{j=1}^{N} \frac{t_{ij}^{1-\sigma}}{P_j^{-\sigma}} \frac{M_j^*}{O}}$$

Following Anderson and van Wincoop (2003) and Yotov et al. (2016), the structural term Ω_i is defined as $\Omega_i = \left(\sum_{i=1}^{N} \frac{t_{ij}^{1-\sigma}}{P_j^{-\sigma}} \frac{M_j^*}{O} \right)^{\frac{1}{1-\sigma}}$. It can be substituted back into the previous equation:

$$p_i^{1-\sigma} = \frac{O_i / O}{\Omega_i^{1-\sigma}}$$

Substituting this into the equations respectively defining X_{ij} and P_j yields:

$$X_{ij} = \frac{O_i M_j^*}{O} \left(\frac{t_{ij}}{\Omega_i P_j^{\frac{-\sigma}{1-\sigma}}} \right)^{1-\sigma}$$

$$P_j^{1-\sigma} = \sum_{i=1}^{N} \left(\frac{t_{ij}}{\Omega_i} \right)^{1-\sigma} \frac{O_i}{O}$$

I suppose that transport costs are defined as in equation (2.9) below, with δ_j importer j's distance elasticity and $dist_{ij}$ the geographical distance between countries i and j:

$$t_{ij} = \delta_j dist_{ij} \tag{2.9}$$

Log-linearizing the expression of X_{ij} above, adding distance as defined in equation (2.9) and a time index t yields the gravity equation used for estimation:

$$\begin{aligned} \log X_{ij,t} = & \log M_{j,t}^* + \log O_{i,t} - \log O_t + (1-\sigma) \log dist_{ij,t} + (1-\sigma) \log \delta_{j,t} \\ & - (1-\sigma) \log \Omega_{i,t} - \sigma \log P_{j,t} + \epsilon_{ij,t} \end{aligned}$$

I use a PPML estimator with importer-year and exporter-year fixed effects, $\pi_{i,t}$ and $\chi_{j,t}$ respectively. I estimate the following gravity equation, in which the terms $\log M_{j,t}^*$, $\log O_{i,t}$, $(1-\sigma) \log \delta_{j,t}$, $(1-\sigma) \log \Omega_{i,t}$, and $\sigma \log P_{j,t}$ are captured by the fixed effects:

$$\log X_{ij,t} = -\log O_t + (1-\sigma) \log dist_{ij,t} + \pi_{i,t} + \chi_{j,t} + \epsilon_{ij,t} \tag{2.10}$$

Own- and cross-price elasticities. Going back to the price index defined above, and substituting it into the minimized demand function for the aggregate industrial good M_j^*:

$$M_j^* = Y_j \left(\frac{\alpha}{1-\alpha} \right)^{-\alpha} \left[\left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \right]^{-\alpha} w_j^{\alpha}$$

Substituting this into the expression of demand for a variety ij:

$$m_{ij} = p_{ij}^{-\sigma} Y_j \left(\frac{\alpha}{1-\alpha} \right)^{-\alpha} \left[\left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \right]^{-\alpha} w_j^{\alpha} \left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{\sigma}{1-\sigma}}$$

$$m_{ij} = \left(\frac{\alpha}{1-\alpha} \right)^{-\alpha} w_j^{\alpha} Y_j \frac{p_{ij}^{-\sigma}}{\left(\sum_{i=1}^{N} p_{ij}^{1-\sigma} \right)^{\frac{\alpha-\sigma}{1-\sigma}}}$$

From this we can derive the expressions for country j's own- and cross-price elasticities, respectively ε_{jj} and ε_{ij}, defined as:

$$\varepsilon_{jj} = \frac{\partial m_{jj}}{\partial p_{jj}} \frac{p_{jj}}{m_{jj}} \quad \text{and} \quad \varepsilon_{ij} = \frac{\partial m_{ij}}{\partial p_{jj}} \frac{p_{jj}}{m_{ij}}$$

$$\varepsilon_{jj} = (-\sigma) + (\sigma - \alpha) \frac{p_{jj}^{1-\sigma}}{\sum_{i=1}^{N} p_{ij}^{1-\sigma}} \tag{2.11}$$

$$\varepsilon_{ij} = (\sigma - \alpha) \frac{p_{jj}^{1-\sigma}}{\sum_{i=1}^{N} p_{ij}^{1-\sigma}} \tag{2.12}$$

2.C Gravity regression with cultural distance controls

Table 2.3: Gravity regression results with cultural distance controls

	(1) Hydraulic cement	(2) Clinker	(3) Long steel	(4) Flat steel
Log distance	-4.759***	-5.898***	-2.988***	-2.151***
	(0.316)	(0.547)	(0.322)	(0.144)
RTA	-2.371***	-4.423***	-1.683***	-1.658***
	(0.653)	(0.906)	(0.533)	(0.275)
Common language	-1.245	-1.864***	-0.354	-0.531
	(0.823)	(0.712)	(0.565)	(0.554)
Contiguous	-2.885***	-4.670***	-2.229***	-1.833***
	(0.682)	(0.689)	(0.506)	(0.348)
Former colonial tie	-0.210	2.054***	1.344*	2.207***
	(0.596)	(0.677)	(0.790)	(0.557)
Observations	22491	7603	18031	17486
Pseudo R^2	0.99	0.99	0.99	0.97
Fixed effects:				
Exporter-year	Yes	Yes	Yes	Yes
Importer-year	Yes	Yes	Yes	Yes

2.D Treatment of outliers in international trade data

Following Berthou and Emlinger (2011) who use a similar procedure on the United Nations Statistical Division's "Tariff Line" database, the procedure aims to capture outliers based on two dimensions: temporal and geographical.

I apply the following criteria to identify outliers:

- Unit values that are 100 times greater or 100 times smaller than the median unit value for each product-importer-exporter grouping;
- Unit values that are 100 times greater or 100 times smaller than the median unit value for each product-importer or product-exporter grouping;
- Unit values that are 1000 times greater or smaller than the value of the immediately preceding or following year;
- Quantities that are less than 0.1 ton (these are generally very close to 0 and seemingly included as placeholders rather than real values).

This method identifies roughly 10% of outliers in cement trade flows and 12% in steel trade flows. However, these are generally very small trade flows, which make up 0.48% and 0.39% of quantities traded for cement and steel respectively.

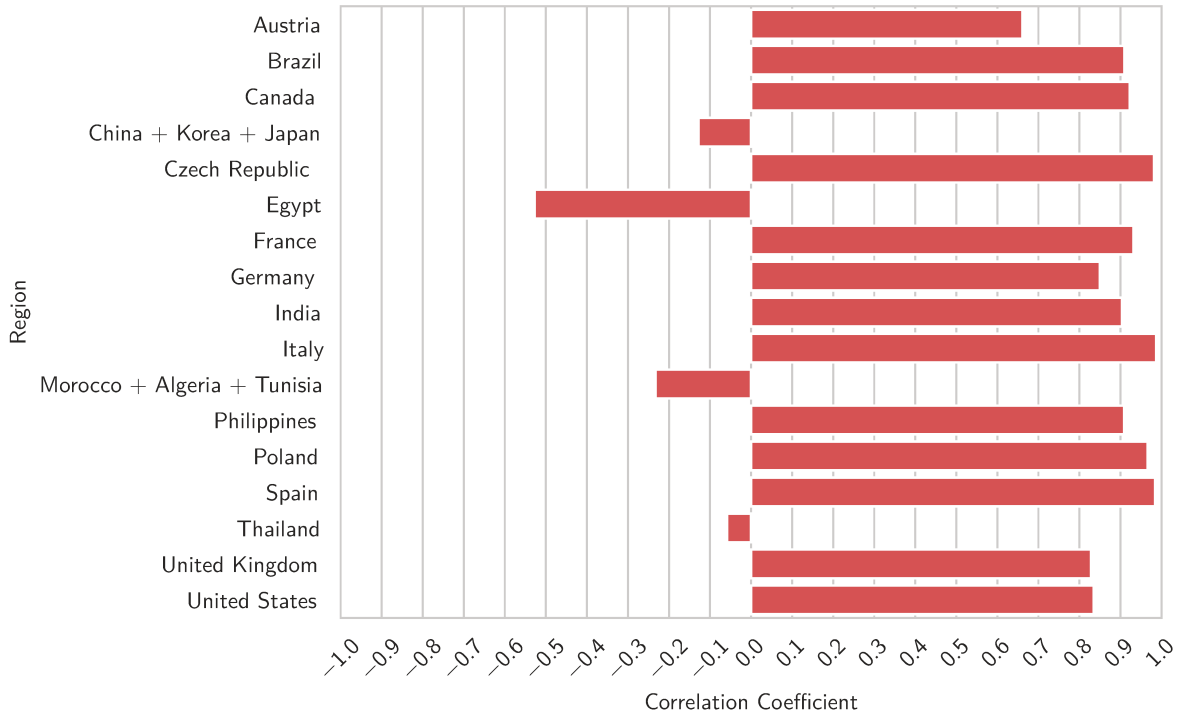
The unit value and the quantity of flagged trade flows are dropped. The unit value is replaced by the importer-exporter median unit value if it is available, or the importer (or exporter) median unit value if it is not. Missing quantity values are then replaced with the ratio between the value of the flow and the updated unit value.

2.E Table of products

HS code	HS description	Product
252310	Cement clinkers	Clinker
252321	Portland cement - White cement, whether or not artificially colored	Hydraulic cement
252329	Portland cement - other	Hydraulic cement
252330	Aluminous cement	Hydraulic cement
252390	Other hydraulic cements	Hydraulic cement
7208xx	Flat-rolled products of iron or nonalloy steel, of a width of 600 mm (23.6 in.) or more, hot-rolled, not clad, plated or coated	Flat steel products
7209xx	Flat-rolled products of iron or nonalloy steel, of a width of 600 mm (23.6 in.) or more, cold-rolled (cold-reduced), not clad, plated or coated	Flat steel products
7210xx	Flat-rolled products of iron or nonalloy steel, of a width of 600 mm (23.6 in.) or more, clad, plated or coated	Flat steel products
7211xx	Flat-rolled products of iron or nonalloy steel, of a width of less than 600 mm (23.6 in.), not clad, plated or coated	Flat steel products
7212xx	Flat-rolled products of iron or nonalloy steel, of a width of less than 600 mm (23.6 in.), clad, plated or coated	Flat steel products
7213xx	Bars and rods, hot-rolled, in irregularly wound coils, of iron or nonalloy steel (long products)	Long steel products
7214xx	Other bars and rods of iron or nonalloy steel, not further worked than forged, hot-rolled, hot-drawn or hot-extruded, but including those twisted after rolling	Long steel products
7215xx	Other bars and rods, of iron or nonalloy steel	Long steel products
7216xx	Angles, shapes and sections of iron or nonalloy steel	Long steel products
7217xx	Wire of iron or nonalloy steel	Long steel products

2.F Clinker production data verification

Figure 2.14: Correlation between computed clinker production data and Global Concrete and Cement Association clinker production data



2.G Comparison of trade elasticities of substitution

Table 2.4: Estimates of trade elasticities of substitution

Paper	Sigma	S.E.	Original product	Attributed product
Fontagné et al. (2019)	13.9688	-	HS 252310	Clinker
Fontagné et al. (2019)	9.417004	-	HS 252321	Hydraulic cement
Fontagné et al. (2019)	17.92119	-	HS 232529	Hydraulic cement
Fontagné et al. (2019)	15.33466	-	HS 232530	Hydraulic cement
Fontagné et al. (2019)	6.78148	-	HS 252390	Hydraulic cement
Fontagné et al. (2019)	9.927554	-	HS 720810	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720825	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720826	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720827	Flat steel
Fontagné et al. (2019)	7.054688	-	HS 720836	Flat steel
Fontagné et al. (2019)	3.850092	-	HS 720837	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720838	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720839	Flat steel
Fontagné et al. (2019)	11.00852	-	HS 720840	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720851	Flat steel
Fontagné et al. (2019)	9.927554	-	HS 720852	Flat steel
Fontagné et al. (2019)	14.54622	-	HS 720853	Flat steel
Fontagné et al. (2019)	13.17825	-	HS 720854	Flat steel

Continued on next page

Table 2.4 continued from previous page

Paper	Sigma	S.E.	Original product	Attributed product
Fontagné et al. (2019)	9.927554	-	HS 720890	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720915	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720916	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720917	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720918	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720925	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720926	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720927	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720928	Flat steel
Fontagné et al. (2019)	12.5062	-	HS 720990	Flat steel
Fontagné et al. (2019)	8.44384	-	HS 721011	Flat steel
Fontagné et al. (2019)	7.285771	-	HS 721012	Flat steel
Fontagné et al. (2019)	8.44384	-	HS 721020	Flat steel
Fontagné et al. (2019)	8.44384	-	HS 721030	Flat steel
Fontagné et al. (2019)	12.46808	-	HS 721041	Flat steel
Fontagné et al. (2019)	6.586295	-	HS 721049	Flat steel
Fontagné et al. (2019)	8.373048	-	HS 721050	Flat steel
Fontagné et al. (2019)	6.50311	-	HS 721061	Flat steel
Fontagné et al. (2019)	8.44384	-	HS 721069	Flat steel
Fontagné et al. (2019)	9.446736	-	HS 721070	Flat steel
Fontagné et al. (2019)	8.44384	-	HS 721090	Flat steel
Fontagné et al. (2019)	6.062273	-	HS 721210	Flat steel
Fontagné et al. (2019)	6.062273	-	HS 721220	Flat steel
Fontagné et al. (2019)	5.871687	-	HS 721230	Flat steel
Fontagné et al. (2019)	6.652194	-	HS 721240	Flat steel
Fontagné et al. (2019)	5.662936	-	HS 721250	Flat steel
Fontagné et al. (2019)	6.062273	-	HS 721260	Flat steel
Fontagné et al. (2019)	26.66272	-	HS 721310	Long steel
Fontagné et al. (2019)	13.70141	-	HS 721320	Long steel
Fontagné et al. (2019)	8.350808	-	HS 721391	Long steel
Fontagné et al. (2019)	5.801511	-	HS 721399	Long steel
Fontagné et al. (2019)	23.19176	-	HS 721410	Long steel
Fontagné et al. (2019)	15.07419	-	HS 721420	Long steel
Fontagné et al. (2019)	14.17237	-	HS 721430	Long steel
Fontagné et al. (2019)	7.690362	-	HS 721491	Long steel
Fontagné et al. (2019)	5.825302	-	HS 721499	Long steel
Fontagné et al. (2019)	19.23537	-	HS 721510	Long steel
Fontagné et al. (2019)	11.05093	-	HS 721550	Long steel
Fontagné et al. (2019)	8.167645	-	HS 721590	Long steel
Fontagné et al. (2019)	6.245874	-	HS 721610	Long steel
Fontagné et al. (2019)	6.942575	-	HS 721621	Long steel
Fontagné et al. (2019)	10.50129	-	HS 721622	Long steel
Fontagné et al. (2019)	13.52268	-	HS 721631	Long steel
Fontagné et al. (2019)	8.628777	-	HS 721632	Long steel
Fontagné et al. (2019)	6.433973	-	HS 721633	Long steel
Fontagné et al. (2019)	8.562211	-	HS 721640	Long steel
Fontagné et al. (2019)	8.704834	-	HS 721650	Long steel
Fontagné et al. (2019)	18.33108	-	HS 721661	Long steel
Fontagné et al. (2019)	10.55549	-	HS 721669	Long steel
Fontagné et al. (2019)	16.76702	-	HS 721691	Long steel
Fontagné et al. (2019)	10.81971	-	HS 721699	Long steel
Fontagné et al. (2019)	12.85082	-	HS 721710	Long steel
Fontagné et al. (2019)	7.412021	-	HS 721720	Long steel
Fontagné et al. (2019)	9.705378	-	HS 721730	Long steel
Fontagné et al. (2019)	8.853293	-	HS 721790	Long steel
Feenstra (1994)	4.21	0.94	Flat steel	Flat steel

Continued on next page

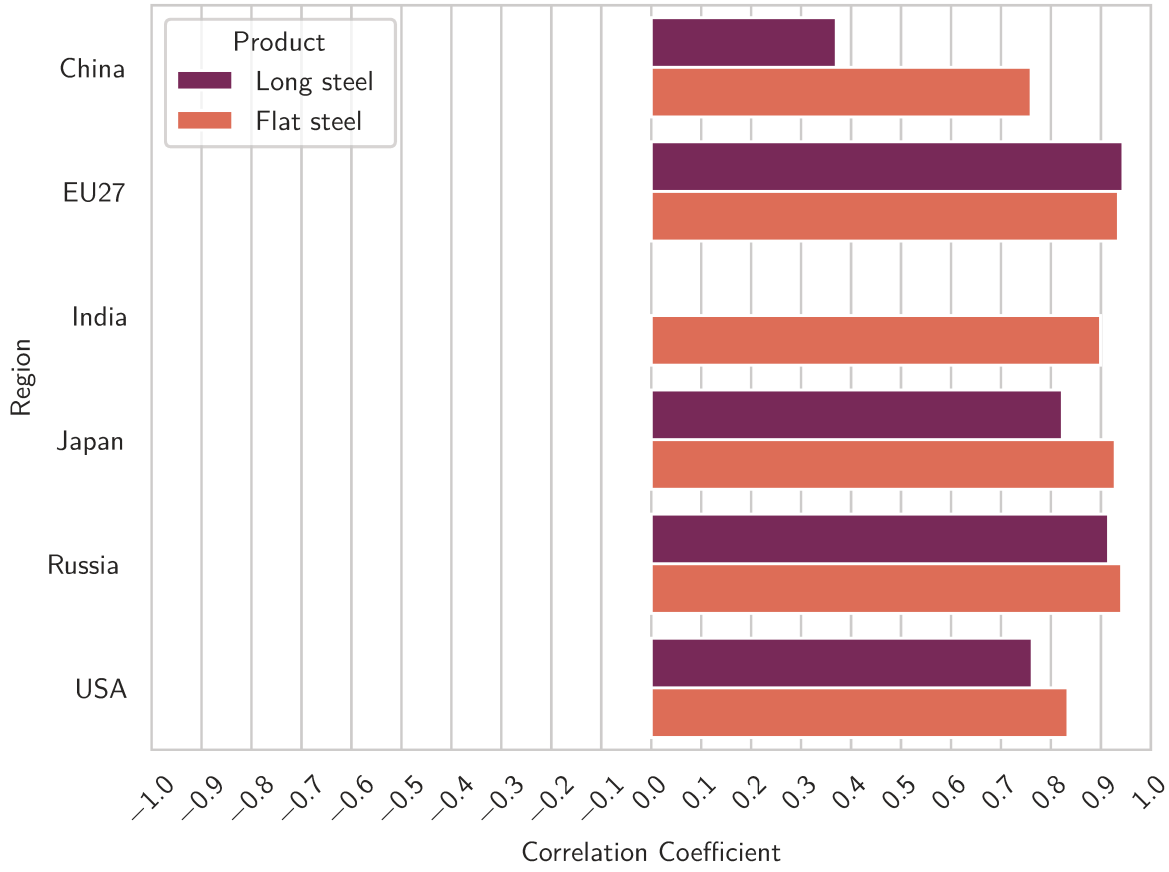
Table 2.4 continued from previous page

Paper	Sigma	S.E.	Original product	Attributed product
Feenstra (1994)	3.59	0.35	Long steel	Long steel
Caliendo and Paro (2015)	7.99	2.53	Basic metals	Flat steel
Caliendo and Paro (2015)	7.99	2.53	Basic metals	Long steel
Caliendo and Paro (2015)	2.76	1.44	Non metallic minerals	Clinker
Caliendo and Paro (2015)	2.76	1.44	Non metallic minerals	Hydraulic cement
Fischer and Fox (2018)	6.1	-	Iron and Steel	Flat steel
Fischer and Fox (2018)	6.1	-	Iron and Steel	Long steel
Fischer and Fox (2018)	4.65	-	Iron and Steel and Ferroalloy Steel Products	Flat steel
Fischer and Fox (2018)	4.65	-	Iron and Steel and Ferroalloy Steel Products	Long steel
Fischer and Fox (2018)	3.02	-	Non metallic minerals	Clinker
Fischer and Fox (2018)	3.02	-	Non metallic minerals	Hydraulic cement
Fischer and Fox (2018)	0.36	-	Cement	Hydraulic cement
Ossa (2015)	2.16	0.065	SITC 673	Flat steel
Ossa (2015)	2.19	0.125	SITC 661	Hydraulic cement
Ossa (2015)	2.22	0.12	SITC 679	Long steel
Ossa (2015)	2.84	0.24	SITC 676	Long steel
Ossa (2015)	3.43	0.635	SITC 674	Flat steel
This paper	5.845	0.697	Hydraulic cement	Hydraulic cement
This paper	6.44	1.296	Clinker	Clinker
This paper	4.287	0.331	Long steel	Long steel
This paper	3.308	0.237	Flat steel	Flat steel

Note: "Original product" is the product categorization provided in the source paper. "Attributed product" is the product categorization attributed in this paper.

2.H Steel price data verification

Figure 2.15: Correlation between computed steel price data and OECD steel price data



Chapter 3

Carbon intensity and corporate performance: A micro-level study of EU ETS industrial firms

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Abstract

EU industrial firms are increasingly establishing strategies to decarbonize their production processes. Existing literature debates whether investing in decarbonization increases firms' production costs, thus hindering their competitiveness, or generates cost reductions through short-term efficiency improvements and long-term investments. Understanding how decarbonization affects overall firm performance is crucial as EU policymakers aim to reach the 2050 objective of carbon neutrality. This paper examines how changes in industrial firms' emission intensity affects their economic and financial performance. We construct a dataset covering around 1,200 industrial firms regulated under the third phase of the EU's carbon market (2012-2019) and estimate a novel indicator of volume-based emission intensities. Applying an IV approach to a within-firm panel model, we find that firms' emission intensity inversely affects their corporate performance, meaning that firms who decarbonize do not harm their economic and financial results. This should encourage policymakers to keep supporting industries in their decarbonization process, as it has so far not come at the cost of their competitiveness.

***

This chapter was co-authored with Maria Garrone.

Chapter dissemination

This chapter was published as a Conference Working Paper after being presented at the 2024 edition of the European Commission's Single Market Conference.

Citation:

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This chapter also resulted in the publication of a Technical Report on the matching produced between the European Union Transaction Log and ORBIS. The resulting correspondence table, the script used to produce it, and related documentation have all been made publicly available by the author, in collaboration with the European Commission.

Citation:

Cameron, A., & Ho, V. (2024). *Matching the EU Transaction Log and ORBIS: A Natural Language Processing approach. Working paper.* (tech. rep.). European Commission, DG GROW, Chief Economist Team. Brussels

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- 2024 EAERE conference
- 2024 Research Conference on the Single Market, European Commission, DG GROW
- 2024 Annual Conference of French Economists (AFSE)
- 2024 Public Policy Analysis Seminar at the University of Le Havre
- 2023 ISEFI (Ipag Business School, Paris)
- 2023 Florence School of Regulation (European University Institute) Doctoral School

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3.1 Introduction

To reach carbon neutrality by 2050, the European Union (EU) must undertake a systemic transformation across its economy. One of the key sectors in this transformation is industry, which generates nearly 750 megatonnes of yearly greenhouse gas (GHG) emissions, or 22% of the bloc's total emissions (EEA, 2024a). Current policies aimed at industrial decarbonization are progressing, but are still projected to miss the mark on the EU's 2030 and 2050 climate targets (Climate Action Tracker, 2024; EEA, 2024b; European Commission, 2023b). One significant blocking factor in intensifying efforts are concerns about the risk of competitiveness losses and carbon leakage (IPCC, 2023), a mechanism through which domestic producers lose out to unregulated foreign competition and decide to relocate - and therefore pollute - elsewhere (Markusen et al., 1993).

The argument of carbon leakage and competitiveness losses is underpinned by the notion that climate regulation is cost-imposing for regulated firms since they have to either pay the cost of the regulation (as with a price on carbon) or invest in a costly decarbonization of their production processes (Levinson & Taylor, 2008). However, this argument that decarbonization is obviously detrimental for firms has been debated for decades in the economic literature (see Jaffe et al. (1995) for an early review of the literature and Dechezleprêtre and Kruse (2018) for a recent one). On the one hand, decarbonization can increase production costs - we call this the cost-imposing hypothesis. This can be a direct effect as firms invest to reduce their emission levels, which diverts resources away from other more productive investments, or an indirect effect because factors of production become more expensive when they are less carbon intensive (Jaffe et al., 1995; Schmalensee, 1993; Walley & Whitehead, 1994). On the other hand, firms can decarbonize by becoming more efficient in their material input and energy usage (Busch & Lewandowski, 2018), as well as by investing in innovations which jointly improve their environmental performance and overall productivity (Porter, 1991; Porter & van der Linde, 1995). Both of these effects would improve their competitiveness - we call this the win-win hypothesis.

This paper examines whether firm-level decarbonization changed the economic and financial results of industrial firms regulated under the EU's Emission Trading System (ETS). It is particularly important to understand whether decarbonization helps or harms firms' competitiveness as the EU works to increase the stringency of its climate policies to reach its objective of carbon neutrality, with carbon leakage as a central consideration.[1]

[1]See the European Commission's web page on carbon leakage: "European Commission - Carbon Leakage"

The main policy tool aimed at EU industrial decarbonization is the EU Emission Trading System (ETS), launched in 2005 (European Parliament and Council, 2003). This system creates a financial incentive for firms to decarbonize, both through short-term abatements and long-term innovation and investments. Policymakers have reformed the EU ETS throughout its different phases, gradually expanding its scope and increasing its stringency.[2] Today, it covers around 2,000 industrial firms and 4,000 energy firms and has one of the world's highest carbon prices, fluctuating between 60 and 100 euros per tCO_2e in the past years (International Carbon Action Partnership, 2023).

To mitigate the risk of carbon leakage, "anti-leakage" measures were adopted hand-in-hand with the EU ETS' implementation, including the free allocation of allowances (European Parliament and Council, 2013), indirect cost compensations (European Commission, 2012), and more recently, a Carbon Border Adjustment Mechanism (CBAM; European Parliament and Council, 2023). The joint development of these policies requires finding a difficult balance between creating a real incentive for firms to decarbonize while avoiding carbon leakage. Understanding how firms' decarbonization decisions affect their competitiveness is a key input to find this balance.

Existing literature has generally found mixed and heterogeneous evidence on the relationship between environmental performance and corporate performance. Several meta-analyses and literature reviews show a positive average relationship in studies on this topic (Albertini, 2013; Busch & Lewandowski, 2018; Dechezleprêtre & Kruse, 2018; Horváthová, 2010), but which appears to be weaker in studies focused on Europe (Albertini, 2013; Horváthová, 2010). Dechezleprêtre and Kruse (2018) also show that the positive relationship between environmental and economic performance is mostly explained by reduced material and energy costs. Some country-level studies within the EU demonstrate some dimensions of heterogeneity in this effect, in particular depending the time lag considered and firms' initial performance Horváthová (2012) and Wagner and Blom (2011). To our knowledge, no study has yet looked into the question of the effect of environmental performance on economic performance looking specifically at the context of the EU ETS. This provides a wider geographical scope of analysis than previous country-level studies, while taking into account the specific regulatory context of the EU's carbon market.

The main contribution of this paper is to provide an ex-post study of the short-term relationship between climate and corporate performance in the context of the EU ETS' third phase. We do not directly isolate the policy effect of the EU ETS - given that the majority of large industrial installations are regulated after the first two phases, a differences-in-differences design is no longer possible. Instead, we apply a fixed-effects panel model using a within-firm estimator. Our dependent variables are a range of indi-

[2]This is discussed in section 3.2.2

cators on economic and financial performance, including return on assets, profit margins, EBITDA[3] margins, the ratio of turnover over costs, and labor productivity. To avoid issues of endogeneity, we employ an Instrumental Variable (IV) strategy following the approach proposed by Fontagné et al. (2023), namely using a Bartik sectoral shift-share instrument.

A second contribution concerns the data we use. We have extended and improved the matching of two firm-level databases: the EU Transaction Log (EUTL) and Bureau van Dijk's ORBIS database using Natural Language Processing methods, as detailed in Cameron and Ho. This dataset provides climate and financial data for the entirety of the EU ETS' third phase.

As a third contribution, this work introduces a new, volume-based measure of emission intensity, measured as the ratio between a firm's emissions and the volume of its industrial production. This moves away from the traditionally used value-based measure of emission intensity, which can take into account activities other than industrial production, such as services or marketing. To retrieve information of production volume, we exploit data from the EUTL on the volume of free allowances that installations receive and information on benchmarks and other relevant parameters reported in EU legislation. We address potential measurement errors due to lack of data availability at the sub-installation level by using a Monte Carlo process based on benchmark distribution parameters to generate corrected production values.

Finally, this paper also contributes to the literature by explicitly studying the role of the international competition setting that EU ETS firms operate in. A significant factor that affects how firms respond to carbon pricing is the exposure of their final goods to international trade and competition (Fischer & Fox, 2018). We formulate an empirical specification that explicitly controls for this crucial aspect. To do this, we compute two metrics at the product level to gauge firms' exposure to international competition: the first assesses import competition intensity, while the second measures intra-branch trade intensity, as defined by Gruebel and Lloyd (1975), and provides insights into the level of differentiation of a good.

Overall, our findings align with existing literature, indicating that changes in firms' emission intensity are either not affecting their economic and financial performance, or that they are driving inverse changes. This means that reductions in emission intensity drive increases in corporate performance, and vice-versa. This effect is slightly stronger when controlling for the competitive environment that firms operate in. Our results imply that firms that have decarbonized within the EU ETS have not been negatively affected by this decision; if anything, they have even slightly improved their corporate

[3]Earnings Before Interest, Taxes, Depreciation, and Amortization

performance. This is an encouraging signal suggesting that firms may enhance their economic and financial viability by transitioning to cleaner production methods.

While marginal reductions in carbon emissions could potentially boost energy or intermediate input efficiency, heavy industry sectors require substantial investments to develop entirely new production processes for full or significant decarbonization. Our results do not capture these dynamics which have yet to materialize in the EU. This study also does not capture the EU's most recent regulatory changes including the fourth phase of the EU ETS and the implementation of a CBAM in its initial transitory phase. Further research should be conducted to understand the underlying mechanisms of this relationship, particularly regarding the role of innovation in green or general technology.

The remainder of this paper is structured as follows. Section 3.2 reviews existing literature on the relationship between environmental and corporate performance and describes the policy context of our study, namely the EU ETS. Section 3.3 describes our data and the construction of our variables. Section 3.4 details our empirical specifications and expectations about the relationship between firms' emission performance and their economic outcomes. Section 3.5 presents and discusses our results, also providing avenues for future research. Section 3.6 concludes and draws policy implications.

3.2 Context and related literature

3.2.1 Related literature: climate versus corporate performance?

As the EU increases the stringency of its climate policy to reach climate neutrality, it is more crucial than ever to understand how firms' environmental performance impacts their economic and financial performance. The economic literature exploring this topic is rich, and is generally structured around two opposing hypotheses: the cost-imposing hypothesis and the win-win hypothesis.

The cost-imposing hypothesis states that decarbonization is costly to firms, and forces them to redirect resources away from more productive uses (Jaffe et al., 1995; Schmalensee, 1993; Walley & Whitehead, 1994). Costs may also be indirect, resulting from input-output relationships between industries, such as when industrial sectors pay higher energy costs due to the power sector's full pass-through of EU ETS costs (Dagoumas & Polemis, 2020; Sijm et al., 2006).[4]

[4]The extent to which these costs can be passed down to the consumers depends on a number of factors such as the price responsiveness of demand, competition dynamics – or lack thereof – and market geography (Clò, 2010; De Bruyn et al., 2010; Fabra & Reguant, 2014; Veith et al., 2009).

On the other hand, the win-win hypothesis states that environmental and economic performance go hand in hand since decarbonization decisions can improve firms' overall competitiveness through reduced material input and energy costs (Busch & Lewandowski, 2018), as well as through environmental and productivity-enhancing innovation. This latter argument is closely related to the strong version of the Porter hypothesis (Porter, 1991; Porter & van der Linde, 1995), which states that environmental policies drive firms to reduce their environmental impacts and incentivizes them to solve their technical inefficiencies, which also increases their overall productivity. In line with this, one of the objectives of the EU ETS is to provide economic incentives for companies to innovate and use "more energy-efficient technologies" (European Parliament and Council, 2003). The strong Porter hypothesis implies that environmental policies, especially those that are market based, increase firms' profitability.

The literature related to our study can be split into two main strands. The first strand is made up of research which studies the direct relationship between environmental and economic performance at the firm level. Busch and Lewandowski (2018) perform a meta-analysis on studies which look at the impact of firms' CO_2-equivalent (CO_2e) emission levels on their financial results. They find a significantly positive mean correlation between these two factors across the 68 studies included in their sample, with some heterogeneity depending on the type of emission and financial indicators used. Another review of the literature is provided by Dechezleprêtre and Kruse (2018), who widen the scope of environmental and economic indicators they include in their analysis. Overall, they also find that with a few exceptions, evidence converges towards there being no competitiveness penalty for "being green" - evidence for there being an outright benefit to improving environmental performance is more mixed. They also look into the possible drivers of this relationship and argue that reduced material and energy costs are the main reason for environmental benefits improving economic performance. However, the authors note that most of the evidence on this topic is based on correlations and does not argue for a causal impact of environmental performance on economic performance. More recently, Trinks et al. (2020) have provided a wide-spanning study of the effect of carbon efficiency on financial performance on an international sample of firms. They find that carbon efficiency has a significantly positive relationship with firms' profitability.

Looking more specifically at the context of the EU, the picture is more mixed. Some meta-analyses have found a weaker link between environmental and economic performance in Europe, compared mostly to the US, Canada and the UK (Albertini, 2013; Horváthová, 2010). A few country-level studies have also explored different aspects of this relationship. Horváthová (2012) studies firm-level data from Czechia and finds that environmental performance negatively affects economic performance in the short run, but that this effect changes to being positive in the long run. Looking at firms in Germany and

the UK, Wagner and Blom (2011) show evidence that the initial financial performance of a firm determines whether the relationship between its environmental and financial performance is positive or negative.

The second strand of related literature is made up of studies which study the effect of the EU ETS on firms' environmental and economic performance, without digging into the direct relationship between these variables. This literature has found that the EU ETS induced emission reductions in the firms it covers (Colmer et al., 2023; Dechezleprêtre et al., 2023). From an economic perspective, current evidence converges towards the EU ETS having had either no effect or a small but positive effect on firms' economic performance. Verde (2020) and Joltreau and Sommerfeld (2019) review early literature on this topic and find that no significant effect is associated to firms being regulated by the EU ETS. They point to the over-allocation of allowances and the ability for firms to pass through their costs and generate windfall profits (Cludius et al., 2020) as explanations for these results. More recent evidence indicates that the EU ETS led to statistically significant increases in firm revenue and fixed assets (Dechezleprêtre et al., 2023). Additional evidence shows that carbon pricing tends to have an effect on investment decisions for manufacturing industries in Europe, although this effect is small and heterogeneous across countries (Borghesi et al., 2020; Koch & Mama, 2019), firms and sectors (D'Arcangelo & Galeotti, 2022; D'Arcangelo et al., 2023). Existing research supports the weak version of the Porter hypothesis, namely that the EU ETS has incentivized regulated firms to invest in green innovation (Borghesi et al., 2015; Calel, 2020; European Investment Bank, 2024; Teixidó et al., 2019).

Most of this evidence focuses on the first two phases of the EU ETS, which were less stringent than later phases. Additionally, these papers do not explicitly study the relationship between firms' decarbonization dynamics and their competitiveness, but instead look at the average across-firm effect of the EU ETS. Overall, it appears that the average effect has been to slightly reduce emissions, without negatively impacting firms' economic performance, which could support the win-win hypothesis.

Based on this review of the literature, evidence is still mixed between the win-win hypothesis and the cost-imposing hypothesis. While some literature points to the former, this effect is heterogeneous depending on firms' sector and characteristics, as well as depending on the specific indicator which is studied. This paper complements existing literature by exploring the link between climate performance and economic and financial performance during the EU ETS' third phase.

3.2.2 Policy context: the EU Emissions Trading Scheme

The EU ETS was introduced in 2005 as a central pillar of the EU's climate strategy to comply with its commitment to the Kyoto Protocol. The system sets a yearly absolute cap on GHG emissions, which determines the number of allowances on the market. Allowances are then freely allocated or auctioned to participants, who can trade them throughout the regulatory period depending on their abatement decisions. At the end of this period, participants must surrender enough allowances to cover their emissions. They can decide to keep their permits for the future, allowing for inter-temporal arbitrage.

Since its implementation, the EU ETS has gone through four phases, each progressively tightening its regulation to align the system with the EU's climate targets. Phase 1 (2005-2007) was a 3-year pilot phase during which allowances were freely allocated based on a grandfathering approach and the overall cap was set based on the sum of national estimates provided by Member States.

Phase 2 (2008-2012) saw a 6.5% cap reduction compared to 2005, with around 10% of allowances auctioned - the rest remained freely allocated based on grandfathering. As shown in Figure 3.1, most sectors received more free allowances than their ex-post verified emissions, and an oversupply was observed on the market by the end of Phase 2.[5] This is in part due to the 2008 financial crisis which cut down production, and in part due to the use of offsets from the UNFCCC's Clean Development Mechanism (Trotignon, 2011). These elements put a downward pressure on the price of carbon during the first two phases of the EU ETS (Figure 3.2).

In phase 3 (2013-2020), the EU ETS was overhauled and strengthened. The cap was set for the EU as a whole, rather than as the sum of nationally determined caps, and an annual linear factor of 1.74% was applied. More sectors were included, namely aluminum, lime, mineral wool, gypsum and chemicals production, as well as metal refining and rolling. Free allowances were allocated based on an emission intensity benchmark rather than grandfathering and the scheme was extended to additional sectors. To address allowance oversupply, the European Commission "back-loaded" 900 million allowances, meaning it postponed their auctioning from the beginning to the end of the phase. As a more long-term response, the Market Stability Reserve (MSR) was established in January 2019 (European Parliament and Council, 2015). The 900 million allowances that were initially back-loaded were transferred to the MSR. Every year, allowances are transferred to or released from the MSR based on predefined rules to avoid any surplus or lack

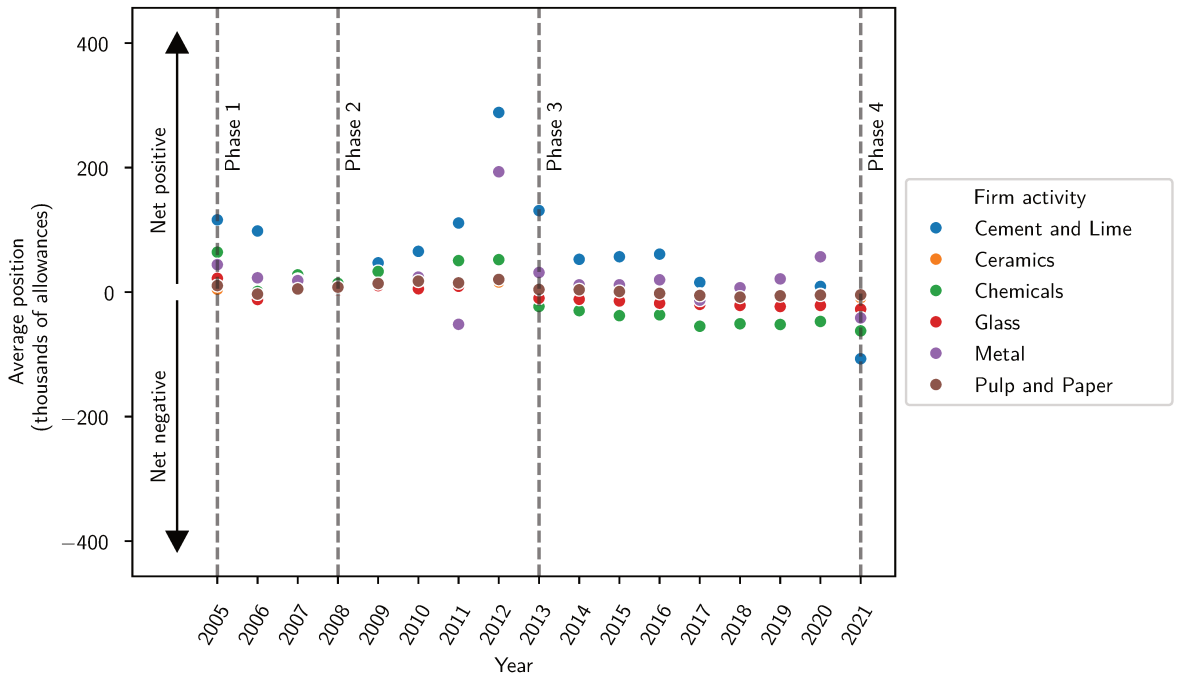
[5]Ex-post estimates point to a surplus of 2 billion allowances at the start of phase 3 (Market Stability Reserve| europa.eu).

of allowances on the market.[6] Another strong signal was sent to EU ETS participants through the European Green Deal (European Commission, 2019), an economic growth strategy set out in December 2019 whose primary objective is for the EU to reach carbon neutrality by 2050.

All of these policy developments make phase 3 of the EU ETS particularly interesting to study, as it represents the first truly constraining phase of the market for regulated firms. This is especially true starting in 2018 when a hike in prices can be observed.

In Phase 4 (2021-2030), the EU ETS saw further reforms with a faster emission cap reduction (4.3% until 2027, then 4.4%). Free allowances for sectors at risk of carbon leakage remain, but will be gradually phased out starting in 2026 when the EU's CBAM becomes fully operational. Amendments to the MSR invalidated excess allowances from previous years and increased the amount of allowances stored in the reserve.[7] In recent years, and especially since the beginning of the fourth phase in 2021, the carbon price has increased exponentially (figure 3.2). This paper does not cover this phase partly due to data limitations, as well as changes in the allocation parameters resulting from recent changes in legislation. The latter prevents us from having comparable emission-based indicators across both phases 3 and 4.

Figure 3.1: Average net position by sector in the EU ETS

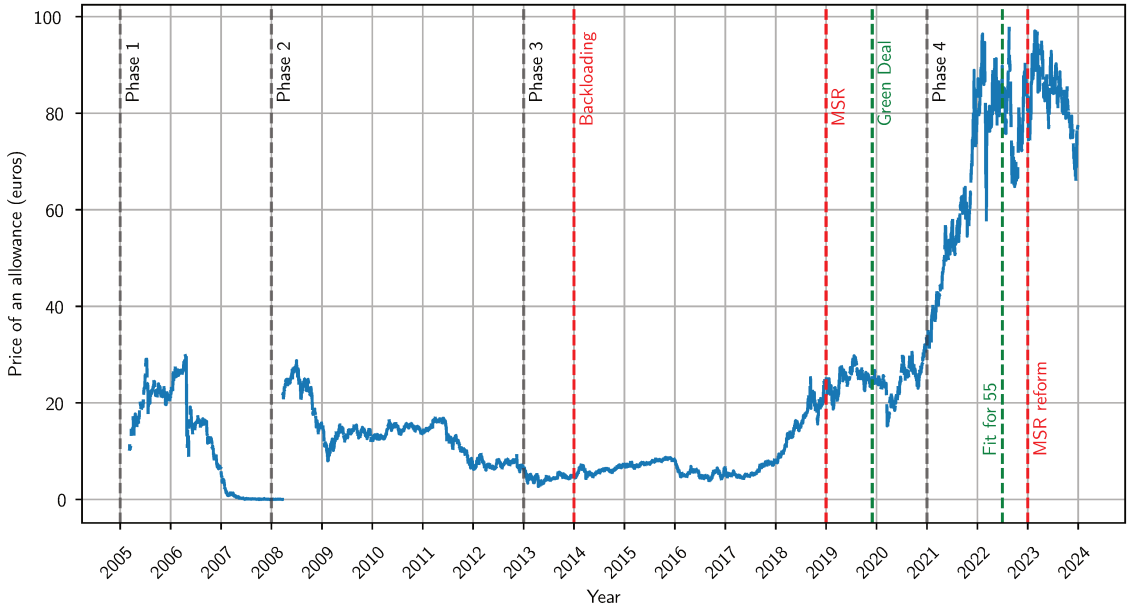


Source: Authors based on the EUTL.

[6]Every year, the MSR required that 12 percent of the total number of allowances in circulation be added to its stock instead of being auctioned, unless this percentage represented 100 million allowances or less, in which case they would have been auctioned.

[7]The percentage of allowances to be stored in the reserve was doubled to 24%, and the threshold for the auctioning of these allowances was also doubled to 200 million allowances.

Figure 3.2: Evolution of the price of carbon in the EU ETS



Source: Authors based on International Carbon Action Partnership.

3.3 Data and descriptive statistics

3.3.1 Data overview

Two main databases were merged to provide data on firm-level climate and economic variables: Bureau van Dijk's ORBIS database,[8] and the European Union Transaction Log (EUTL).[9]

ORBIS is a commercial dataset encompassing approximately 40 million global companies. It standardizes financial data into a global format, facilitating cross-country comparisons. From this dataset we extract data on economic performance, which we complement with some computed variables. The following variables have been extracted or constructed: return on assets, profit margins, EBITDA margins, labor productivity and turnover over costs. Table 3.1 below provides details on how each of these variables is defined and computed.

The EUTL is the central reporting and monitoring tool run by the European Commission that lists all transactions taking place within the EU ETS. It contains public information on the GHG emission compliance of the entities covered by the scheme.

[8]Orbis | Compare Private Company Data | Bureau van Dijk (bvdinfo.com)
[9]EU Emissions Trading System (ETS) data viewer — European Environment Agency (europa.eu).

Table 3.1: Definition of outcome variables

	Indicator	Definition
Financial indicators	Return on assets	$\frac{Turnover}{Assets}$
	Profit margin	$\frac{Profit\ before\ tax}{Operating\ revenue}$
	EBITDA margin	*Operating profit + depreciation*
Economic indicators	Labor productivity	$\frac{Turnover}{N° employees}$
	Material input productivity	$\frac{Turnover}{Material\ costs}$

The merged EUTL-ORBIS database provides firm-level data on verified CO_2 emissions and a range of financial indicators. While the EUTL does cover a few countries outside the EU, we have chosen to restrain our analysis to firms in the EU's 27 Member States. All data provided hereafter is for these 27 countries only. These two databases were merged through a matching procedure described in Cameron and Ho which utilizes Natural Language Processes and expands on the previous work done by Letout (2021). Appendix 3.A describes our data cleaning procedure.

3.3.2 Data coverage

The EU ETS regulates around 10,000 energy and industrial installations. Each of these installations is associated to an account run by its parent company - one company may report emissions for several installations. Companies submit an annual report to the national Union Registry where they are registered. Data from all EU national Union Registries is then aggregated in the EUTL. This means that multinational companies must have one account for each country in which they have a regulated installation, with no fully satisfactory way to link several national accounts owned by a single parent company.

With this in mind, between 5,000 and 6,000 'national' firms report verified emissions in the EUTL every year. Of these, only about 2,000 firms are classified in an industrial sector (blue line in figure 3.3). The rest operate in the energy sector, which we do not include in this paper. We find a match in ORBIS for 65-80% of industrial firms between 2013 and 2021 (orange line in figure 3.3). The final sample is made up of firms that have a match in ORBIS and for which financial data is available and of sufficient quality in ORBIS (green line in figure 3.3) - totaling around 1,200 firms during phase 3 of the EU ETS. We drop the year 2020 to avoid data issues linked to the COVID crisis, as well as the year 2021 because the rules changed for the free allocation of allowances and the

estimates of emission intensity would not be valid. The sample is too restricted in the first phases of the EU ETS, so we do not include these years in the analysis.[10]

The firms covered in our sample represent the largest and most emission-intensive industrial firms in the EU, but are not representative of the much vaster industrial sector in the EU. The EU ETS covers only about 2-3% of all industrial firms in the EU. However, these firms are responsible for 30-40% of the bloc's industrial emissions.[11]On average, the EU ETS covers only the largest industrial firms in activity. As a result, this is also what our sample covers.

One important element to note is that we have chosen to only keep firms in our sample whose main activity is regulated in the EU ETS. This means for example that we keep steelmakers, but exclude pasta producers that are regulated under the EU ETS because they own energy-generating installations. The reason for this is that the financial data declared in ORBIS is related to a firm's total activities, while the EUTL only covers a firm's activities that are regulated under the EU ETS. By only keeping firms whose main activity is regulated - as defined by the NACE code they declare in ORBIS - we ensure better consistency between the financial and climate data from both of these data sources. Appendix 3.D provides details on this procedure.

We also merge our data with Eurostat's PRODCOM database,[12]using the NACE codes provided in PRODCOM. While PRODCOM provides a nomenclature that is more disaggregated, we compute an aggregate value at the NACE 2 or NACE 4 level to remain consistent with the EUTL-ORBIS database. We use this data to compute competition variables. These are added to our regressions to control for the competitive environment firms operate in, as discussed below in section 3.3.4).

3.3.3 Measuring emission intensity

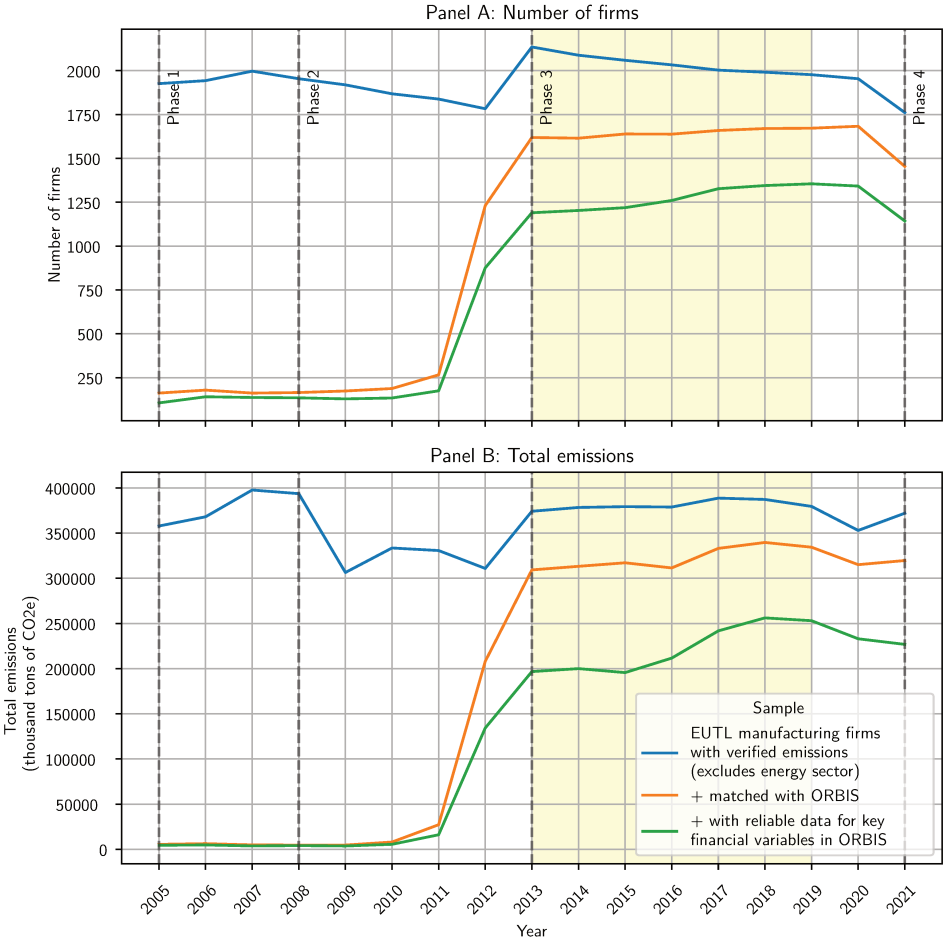
So far, most papers have measured emission intensity as total emissions over turnover (Dechezleprêtre et al., 2023), since this is easiest measure to compute with available data. However, turnover can come from activities other than industrial production, like

[10]This may seem counter-intuitive since other studies have been able to study these phases, however certain elements differ from ours: first, these studies generally look at the entirety of firms regulated by the EU ETS, rather than just industry, which expands their sample; second, other data sources, like the E-PRTR, are used which can provide better matches for earlier years, but restricts the sample to only certain countries; third, the overall sample size of these studies is much smaller than ours, and therefore not comparable (see for example Dechezleprêtre et al. (2023) who have 240 pairs of firms in their sample, or Colmer et al. (2023) who have around 300 pairs).

[11]These figures are computed using values from Eurostat's 'env_ac_ainah_r2' series for emissions and 'sbs_na_ind_r2' series for the number and size of firms. Further details on the representativeness of our sample by sector are provided in Appendix 3.C.

[12]The data series code is 'ds-056120'.

Figure 3.3: Data coverage over the EU ETS phases



Source: Authors based on EUTL and ORBIS.
Note: All samples include only EU 27 countries. The yellow-highlighted area is the time period covered by this study.

marketing or service provision. This can bias results to incorrectly measure the emission intensity of industrial production.

We propose a measure of emission intensity as emissions over production volumes to better capture only industrial production. Since data on firm production volumes is scarce, especially across different countries and sectors, we rely on estimates based on the methodology detailed in Appendix3.E. To summarize this methodology, we compute production volumes in year $t-1$ based on the volume of free allowances that installations receive in the EU ETS in year t:

$$V_{inst,t-1} = \frac{FA_{inst,t}}{B_{act} \times CSCF_t \times TCF_{sec,t}} \tag{3.1}$$

Where $FA_{inst,t}$ is the amount of free allowances an installation receives in year t, B_{act} is the activity emission intensity benchmark, $CSCF_t$ is the cross-sectoral correction

factor and $TCF_{sec,t}$ is the transitional correction factor.[13]To mitigate uncertainty around the application of the activity benchmark, we use a Monte Carlo simulation to estimate production volumes. The uncertainty linked to this benchmark derives from the fact that benchmarks are defined at the product level, but the EUTL defines installation-level activities. We therefore use the mean and standard deviation of the benchmarks associated with all the products that can be associated with one type of activity in the Monte Carlo simulation, with the mean and standard deviation of all the product benchmarks that can be associated with a given activity.

3.3.4 Constructing measures of exposure to international competition

One of the important elements that could impact how firms react to carbon pricing is their exposure to international competition. Indeed, the competition setting in which they operate determines whether they are able to pass through their costs or not. As such, we compute two indicators of exposure to competition to assess how this factor impacts the measure of firms' economic performance. The first is a measure of import intensity. The second is a measure of intra-branch trade intensity developed in Gruebel and Lloyd (1975). Both of these indicators are computed at the product level, both in volumes and values.

The first indicator measures the level of import intensity within a market, and is computed as:

$$\text{Import Intensity}_{pct} = \frac{\text{Imports}_{pct}}{\text{Domestic production}_{pct} + \text{Imports}_{pct}} \tag{3.2}$$

Where the numerator Imports_{pct} is the volume or value of imports of products p to country c in year t. The denominator represents the size of country c's domestic market, i.e., the sum of its imports and domestic production.

The second indicator measures intra-branch trade intensity, which is a proxy for differentiation within the production of a good. Indeed, if there is substantial intra-branch trading for one product, this means that the product is substantially differentiated depending on who produces it. Producers have more market power in a market where products are specialized depending on their origin/production than in a market where all manufacturers produce a homogeneous good, and where buyers are indifferent between buying from one producer or the other. The indicator varies between 0 and 1,

[13]Parameter $FA_{inst,t}$ is taken from the EU Transaction Log and parameters B_{act}, $CSCF_t$, and $TCF_{sec,t}$ are taken from EU legislation. Specific source documents for all of this information can be found in Appendix3.E.

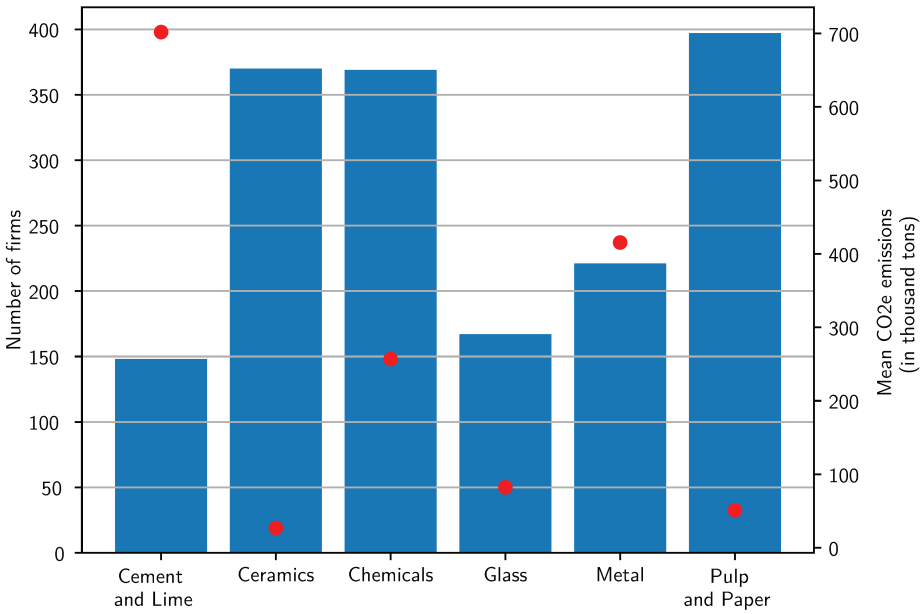
where 0 means that all trade within an industry is inter-branch, and that there is little differentiation, and 1 means all trade within an industry is intra-branch and there is a lot of differentiation. This measure was developed by Gruebel and Lloyd (1975) and is computed as:

$$\text{Intra-branch Trade}_{pct} = \frac{(\text{Exports}_{pct} + \text{Imports}_{pct}) - |\text{Exports}_{pct} - \text{Imports}_{pct}|}{\text{Exports}_{pct} + \text{Imports}_{pct}} \tag{3.3}$$

3.3.5 Trends of key variables and sectoral heterogeneity

The number of firms and mean emissions for each of these validated sectors is given in figure 3.4. While certain sectors only make up a small share of total firms in our dataset, their high level of emissions makes them have a large overall impact on total emissions (cement and lime for instance). On the other hand, installations in sectors like pulp and paper, or ceramics, are quite numerous but have low average emissions.

Figure 3.4: Number of firms (lhs, bars) and average emissions (rhs, dots) by sector (2019)



Source: Authors based on EUTL and ORBIS.
Note: Sample only includes EU-27 countries.

The evolution of the emission variables by sector (figure 3.5) reveals that there is no significant overall change in either emission volumes or intensity for any industrial sector over the course of phase 3. Another interesting element when digging deeper into this data is that the mean emission intensity by sector hides some level of heterogeneity among firms in a single sector. The bottom panel of figure 3.5 illustrates this by showing the

Table 3.2: Average values by sector for key variables

	Cement and Lime	Ceramics	Chemicals	Glass	Metal	Pulp and Paper
Return on assets	0.59	0.59	1.1	0.81	1.24	1.15
(€ turnover per € assets)	[0.44]	[0.44]	[0.75]	[0.47]	[1.56]	[0.66]
Turnover over costs	2.37	3.56	4.08	2.28	1.84	2.35
(€ turnover per € costs)	[1.86]	[6.52]	[15.17]	[1.14]	[6.81]	[7.13]
EBITDA margin (%)	14.59	7.15	10.44	12.59	4.54	9.38
	[12.9]	[17.53]	[11.43]	[10.69]	[12.83]	[10.86]
Profit margin (%)	5.95	-1.35	5.41	5.03	0.01	4.43
	[14.57]	[19.19]	[12.29]	[12.49]	[13.45]	[11.43]
Labor productivity (th.	271.92	159.66	1099.09	214.24	1179.84	735.55
euros per person)	[258.17]	[209.84]	[4979.69]	[159.31]	[13183.1]	[5902.21]
Emission intensity (tCO2	1.02	0.08	1.08	0.48	0.97	0.31
per ton product)	[0.38]	[0.06]	[2.98]	[0.13]	[0.48]	[0.55]
Emission intensity (tCO2	7.34	1.71	0.74	0.78	0.39	0.45
per th. euros)	[2.86]	[2.07]	[1.08]	[0.54]	[0.5]	[0.52]
Import intensity (volumes)	0.12	0.24	0.45	0.38	0.37	0.32
	[0.13]	[0.21]	[0.17]	[0.29]	[0.15]	[0.15]
Import intensity (value)	0.14	0.31	0.47	0.35	0.37	0.34
	[0.13]	[0.2]	[0.15]	[0.23]	[0.15]	[0.15]
Intra-branch trade intensity	0.38	0.32	0.43	0.5	0.41	0.46
(volumes)	[0.19]	[0.2]	[0.18]	[0.25]	[0.15]	[0.18]
Intra-branch trade intensity	0.42	0.47	0.48	0.59	0.43	0.48
(value)	[0.18]	[0.27]	[0.19]	[0.24]	[0.16]	[0.17]

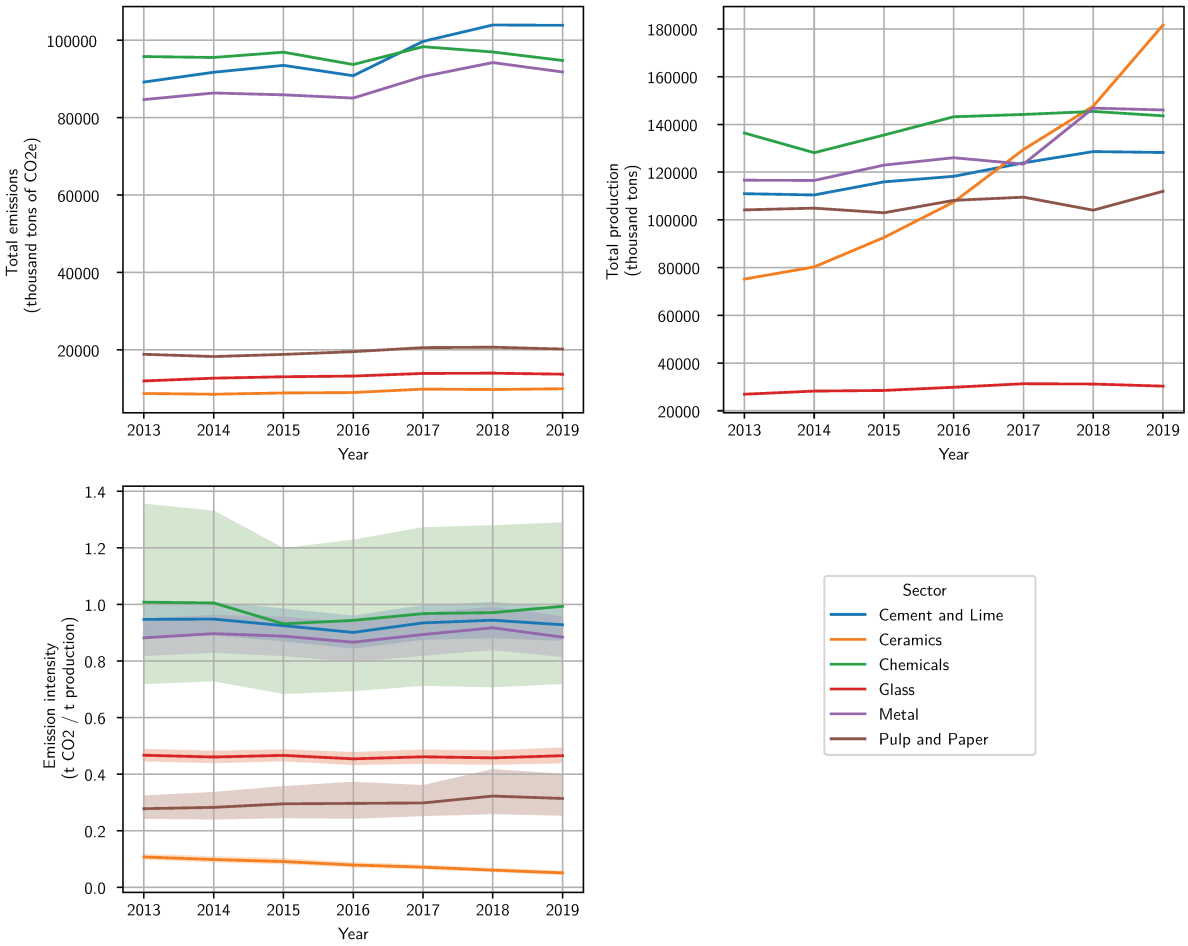
Note: Standard deviation is reported in square brackets.

interval of the 25th and 75th percentiles around the average value of carbon intensity by sector (depicted as the shaded area). There is a wide dispersion of values in the chemicals sector, while the ceramics sector has more homogeneous values. This dispersion illustrates the different technologies and production processes that can be used within one sector, and their associated carbon intensities. Appendix 3.F provides further information on the distribution of emission intensities within each sector.

Turning now to the economic variables, table 3.2 presents descriptive statistics, highlighting substantial variations in the characteristics of the sectors we study. For example, the cement and lime sector exhibits notably higher levels of profit and emission intensity (in volumes) than sectors like ceramics or metal.[14] However, there is a high variability between firms, as shown by the standard deviation. Moreover, the mean evolution of these variables by sector highlights the existence of sector-level dynamics. No sector is consistently performing better or worse than others across all measures (figure 3.6).

[14]Note that ORBIS uses the accounting definition of the margin rate – i.e., the ratio of profit before tax over operating revenue – rather than the margin rate as defined in microeconomics.

Figure 3.5: Volume of emissions, production and mean emission intensity by sector

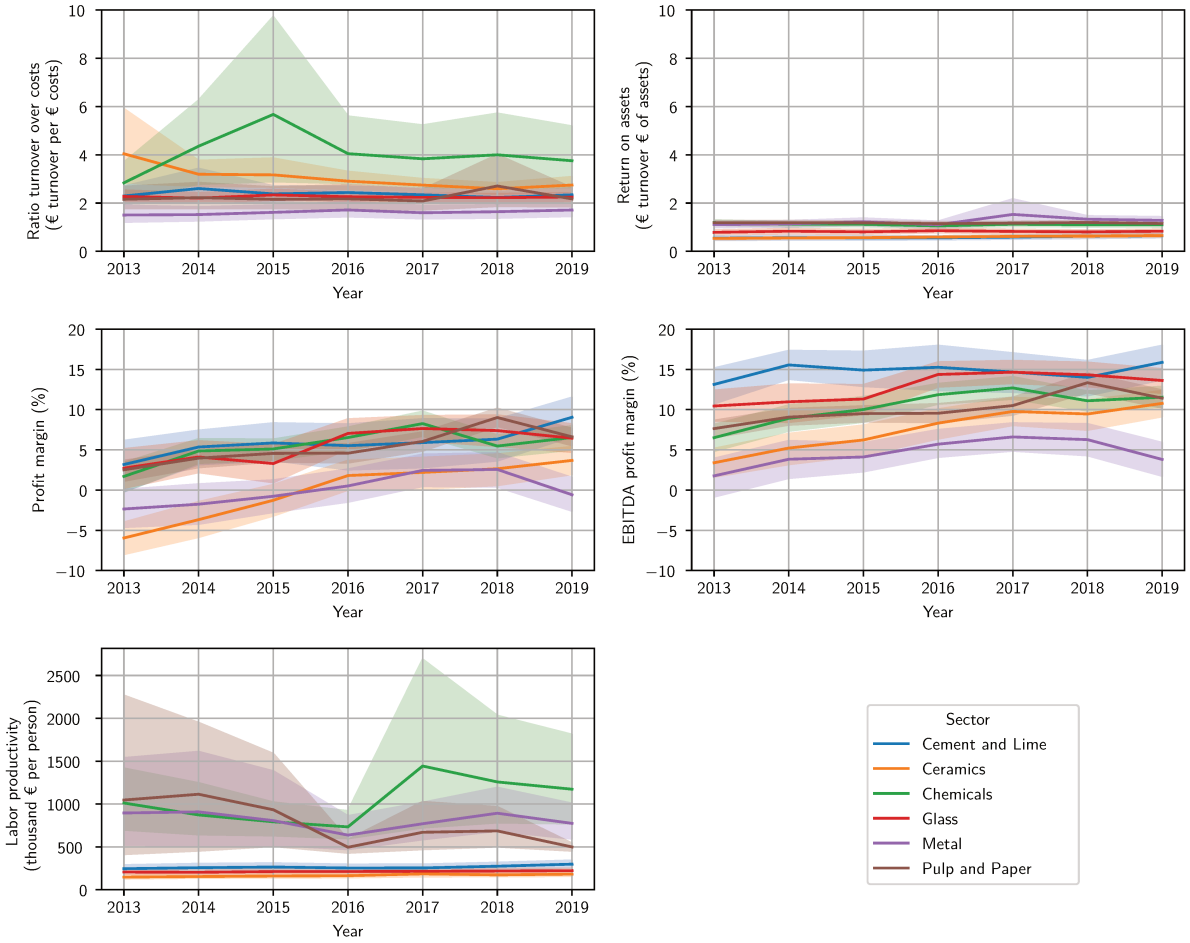


Source: Authors' own calculations based on EUTL and ORBIS.
Note: The shaded area in the bottom panel represents the interval between the 25th and 75th percentile of the sample.

As for the competition indicators, the dispersion in these measures illustrates that these sectors operate in different market conditions, which may affect their ability to absorb input price increases through a reduction of their profit margins. For example, we could expect that some sectors tend to operate in more restricted or regionalized markets because their products are not easily transportable. This is the case for cement and lime for instance, which has a very low average import intensity. Less globalized markets can mean that less competitors can access the same markets, making firms more able to pass their costs though to downstream consumers. On the other hand, the cement and lime sector also has a relatively low intra-branch trade intensity, meaning that consumers likely do not differentiate much between products coming from one producer rather than another. This implies that firms compete more on price than quality or specialization.

Looking at the evolution over time, an apparent trend is visible in most sectors, but depends on the measure that is used (figure 3.7). The level of intra-branch trade

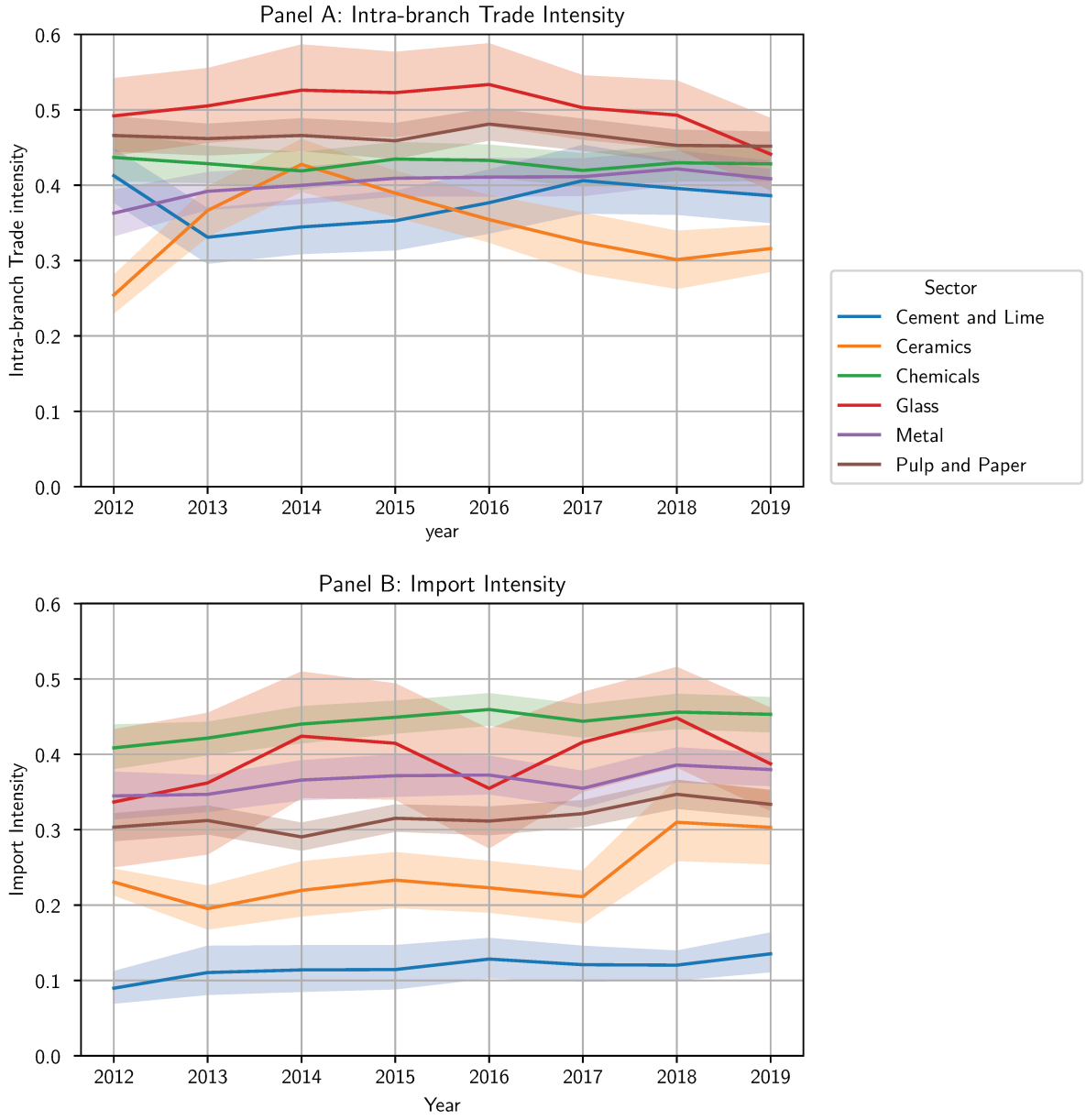
Figure 3.6: Evolution of variables of interest by sector



Source: Authors' own calculations based on EUTL and ORBIS.

intensity has increased for sectors such as cement and lime and metal, although with a slight decrease in recent years; it has remained stable for chemicals and pulp and paper, and decreased slightly for glass and substantially for ceramics (compared to 2014). Trends are not as clear for the second indicator, import intensity, except for ceramics and glass which exhibit an increase. It is clear that these different sectors do not face the same level of import intensity, and that this should be taken into account in our analysis.

Figure 3.7: Evolution of competition indicators by sector



Source: Authors' own calculations based on EUTL and ORBIS.

3.4 Methodology

3.4.1 Empirical specification

To assess the short-term impact of carbon intensity on corporate performance, we adopt a within-firm identification strategy. Partly following Trinks et al. (2020), we employ the following empirical specification as our baseline model:

$$\log \text{CorpPerf}_{f,t} = \beta_0 + \beta_1 \log \text{EmissPerf}_{f,t-1} + \boldsymbol{z\mu_f} + \Lambda + \varepsilon_{f,t} \tag{3.4}$$

The outcome variable, CorpPerf, is the economic or financial performance of a firm f in year t. We use several different variables in turn to capture different aspects of firm profitability and viability. The variables which measure financial performance are return on assets, profit margins and EBITDA margins; those that measure economic performance are labor productivity and turnover over costs.[15] Our explanatory variable of interest, EmissPerf, is a firm's emission performance, measured as emission intensity in value or in volumes. Section 3.3.3 describes how we compute our novel indicator of emission intensity in volumes, and what advantages it has compared to the more standard value-based measure of emission intensity. To address the issue of multiple hypothesis testing - since we use several different outcome variables which may be related to each other - we report the Holm-Bonferroni-corrected p-value of the coefficient for EmissPerf in all of our regression results (Holm, 1979).

We control for the following vector of firm-specific variables $\boldsymbol{\mu}$:

- The number of new installations that a firm opened in a year to capture composition effects that may drive changes in emission intensity at the firm level;[16]
- A measure of firm-level stringency of the EU ETS, measured as the ratio between a firm's verified emissions and the amount of free allocations it receives for a given year as proposed by Borghesi et al. (2015).
- A firm's size, measured as turnover.
- A firm's current ratio, measured as its assets over its liabilities. This is to control for a firm's level of debt compared to its assets, as a proxy for its long-term financial health.

[15] Table 3.1 in section 3.3.1 describes how each of these is defined.

[16] The number of installations that were closed is not included in the model because no firm in the sample closed an installation in the period that is studied.

- The net value of transactions a firm makes on the EU ETS, measured as the difference between the total value of its purchased allowances and of its sold allowances in a year. This is to remove any effects that would be driven purely by firms making profits from buying and selling allowances on the market from the results. This indicator is formally computed as:

$$\begin{aligned}&\text{Net transaction value}_t = \\ &\sum_{i=1}^{52} \text{Mean weekly price} \times \text{Total allowances purchased in a week} \\ &- \sum_{i=1}^{52} \text{Mean weekly price} \times \text{Total allowances sold in a week}\end{aligned} \tag{3.5}$$

We check for multicollinearity issues that may arise from including these control variables together in Appendix 3.G. Correlations between these variables are below |0.1| for most pairs of variables, with the exception of turnover and emission intensity, transaction values and emission intensity, and transaction values and turnover. For these three pairs, the correlation is still below |0.5|. Additionally, we run a simple IV regression without fixed effects and compute the variance inflation factor for each variable and find values close to 1 for all variables. This indicates multicollinearity is not an issue for these variables.

Finally, we also include a set of fixed effects Λ. In the OLS estimations, we include firm and sector-year fixed effects to control for unobserved characteristics and other confounding factors that may affect firms' emission and economic performances, such as the price for fossil fuel energy (Trinks & Hille, 2023).

All of the variables are log-transformed to facilitate interpretation of coefficients and to smooth the impact of outliers. We introduce a lag for the explanatory variables to address potential reverse causality bias, in line with the literature (Fontagné et al., 2023; Trinks et al., 2020). We also employ an instrumental variable strategy to address issues of endogeneity, as described in section 3.4.3.

In a second model, we explicitly control for the competition setting that firms operate in. This is done by including an interaction term between EmissPerf and the variable Comp, which captures this competition setting. Two alternative measures of Comp are used (import intensity and product specialization), as described in section 3.3.4. These are measured at the level of a product p and a country c.

The following specification is employed:

$$\begin{aligned}&\log \text{CorpPerf}_{f,t} = \beta_0 + \beta_1 \log \text{EmissPerf}_{f,t-1} + \beta_2 \log \text{Comp}_{pc,t-1} \\ &+ \beta_3 \log \text{EmissPerf}_{f,t-1} \times \log \text{Comp}_{pc,t-1} + \boldsymbol{z\mu_f} + \Lambda + \varepsilon_{f,t}\end{aligned} \tag{3.6}$$

3.4.2 Expectation of results

Based on existing literature, two opposite effects can drive the effect of emission performance on firms' economic and financial performance. The first effect derives from the fact that firms must incur abatement costs in order to reduce the emission intensity of their production. These abatement costs are defined in textbook environmental economics as the loss in profit induced by a reduction of emissions compared to baseline emissions (Tietenberg & Lewis, 2024). Incurring these abatement costs can reduce a firm's financial profitability, as well as its economic performance in the short run (Jaffe et al., 1995). We could therefore expect a positive relationship between emission intensity and economic and financial performance. In other words, if a firm abates its emissions and reduces its emission intensity, it must also suffer a drop in its financial results and economic viability.

The second effect points in the opposite direction, and stems from two different mechanisms (Busch & Lewandowski, 2018). The first of these effects is that reductions in emission intensity can lead to overall increases in productivity and profitability. This idea underpins the Porter hypothesis (Porter, 1991; Porter & van der Linde, 1995). One compelling example of this would be a firm which decides to invest in new production processes to improve its energy efficiency. These investments would reduce not just the emission intensity of its production, but also its total energy bill. If these "co-benefits" of decarbonization are strong enough, we would therefore expect a negative relationship between emission intensity and the outcome variables (Trinks & Hille, 2023). The second mechanism which explains this effect is that a firm covered by the EU ETS which reduces its carbon intensity or is over-allocated allowances can buy less or even sell allowances it no longer needs for compliance. This entails increases in profit and would further strengthen the negative relationship between emission intensity and financial or economic performance (Laing et al., 2014). We explicitly control for the second effect through the firm-level measure of the net value of transactions on the EU ETS. However, we do not have data on firm-level innovation patterns, and therefore cannot explicitly test for the first mechanism, though it would be a plausible explanation based on existing literature (Borghesi et al., 2015; Calel, 2020; Teixidó et al., 2019).

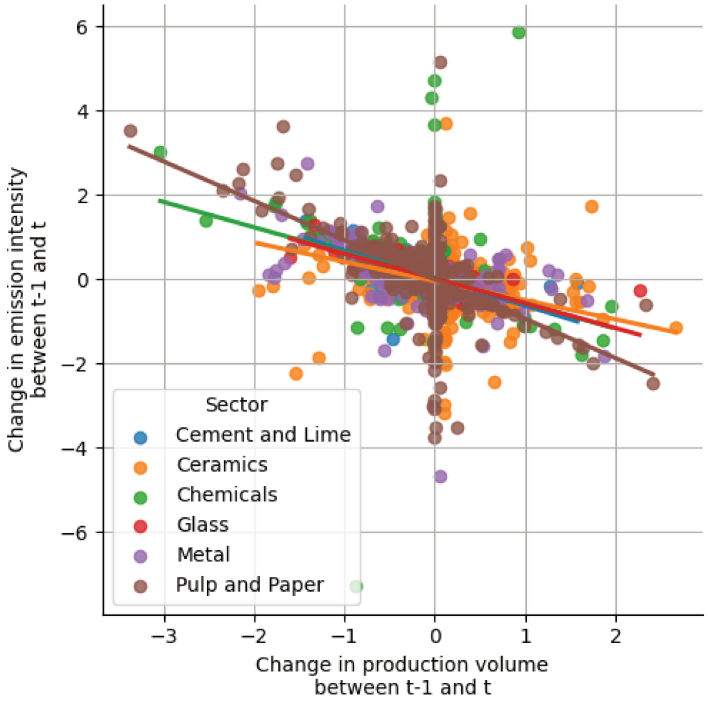
For the variables measuring financial performance, the empirical literature seems to point to the second effect being stronger than the first (Busch & Lewandowski, 2018). For the variables measuring economic performance, an additional consideration should be highlighted. The relationship between emission intensity and our economic variables could partly depend on whether there are economies or diseconomies of scale in emissions[17]

[17]Economies of scale in emissions are taken to mean that the marginal emission intensity of an additional unit of production is decreasing in the volume of production. The existence of these economies or diseconomies of scale in emissions has not yet been fully established in the literature (Agnolucci & Arvanitopoulos, 2019).

and economies or diseconomies of scale in production. To illustrate this, let us posit a case in which firms have diseconomies of scale in emissions, meaning that as they increase their production volumes, the marginal emission intensity of an additional unit increases proportionally more. In this case, these firms would have an incentive to reduce their production volumes instead of investing in the decarbonization of their production processes. Assuming there are economies of scale associated with their production, these reductions in volumes would result in a negative relationship between emission intensity (which increases) and firm productivity (which decreases).

We would also expect that these firms have large fixed costs due to their size and the nature of the production, and that they therefore have economies of scale in production. A reduction in volumes would negatively impact these firm's productivity. Figure 3.8 shows that in our data, it appears that changes in production volume are negatively correlated with changes in emission intensity. This might be a marker of economies of scale, which can mitigate the risk that the effects are purely driven by these scale effects. These aspects will be further analyzed by including an interaction term between firms that increase their volumes and those that decrease their volumes.

Figure 3.8: Change in emission intensity compared to change in production volumes



Source: Authors based on the EUTL and ORBIS.
Note: The year-on-year change is computed as the ratio of the value in year t and the value in year t-1. Lines represent linear regression by sector.

The model controlling for the competition setting that firms operate in (defined in equation 3.6) analyzes the way in which this setting impacts the relationship between

emission intensity and economic or financial performance. The variables we use to measure this are import intensity and intra-branch trade to measure product specialization. Some existing literature indicates that firms exposed to less competitive environments tend to have more power to pass through their costs to downstream sectors and consumers (Cludius et al., 2020). As a result, we would expect the coefficient associated with import intensity to be negative and the coefficient associated with intra-branch trade to be positive - since the latter represents the degree to which products are differentiated within a sector, which is related to the capacity that firms have to pass on their costs. However, there could also be a pro-competitive effect, as highlighted by some trade literature (Peltonen et al., 2008).

The interaction term which includes import intensity is expected to be negative. Indeed, we can hypothesize that companies faced with higher levels of competition have more pressure to decarbonize in ways that are also cost-cutting (or at least not cost-increasing) than firms faced with lower levels of competition that have slightly more capacity to absorb higher costs from decarbonization. On the other hand, the interaction term with intra-branch trade is expected to be positive for the opposite reasons.

Concerning the control variables, Table 3.3 summarizes our expectations for the sign of the associated coefficients.

Table 3.3: Expectations for control variables

Variable name	**Expected sign of coefficient**	**Rationale**
# opened inst	Positive	New installations are likely less emission intensive than older installations given their use of newer technology.
Stringency idx	Positive (H1) or negative (H2)	H1: Porter hypothesis; H2: Carbon pricing is an additional cost which diminishes corporate performance.
log Turnover	Neutral	Existing literature does not find a link between the size of a firm and its emission intensity (Agnolucci & Arvanitopoulos, 2019).
log Current ratio	Positive	Less leveraged firms are expected to exhibit better corporate performance (Trinks et al., 2020)
Net transactions (val)	Negative	Firms that buy more allowances than they sell would have a positive value for net transactions and would likely be negatively affected on measures of economic and financial performance.

3.4.3 Addressing endogeneity : Instrumental Variable (IV) approach

When measuring the effect of firms' emission performance on their economic performance, reverse causality and simultaneity bias can be of concern. Firm's emission performance and economic profitability mutually influence each other simultaneously. This mutual influence can complicate efforts to determine the true causal impact of emission performance on economic profitability, or vice versa. Simultaneity bias can also imply reverse causality. Firms that perform well in terms of economic results are likely to also perform relatively well from an environmental point of view due to factors like good management, efficient use of inputs, for instance. Moreover, a wealthy company has the financial capacity to invest towards technologies aiming at enhancing emission performance.

In recent energy pricing literature, there has been a growing emphasis on addressing endogeneity sources through the adoption of a Bartik (shift-share) instrument. We apply the same Bartik instrument as outlined in Fontagné et al. (2023) on our emission intensity variable.

The instrument is constructed as:

$$\text{EmissInt}^{IV}_{f,s,t} = \left[\frac{\text{EmissInt}_{f,s,t_0}}{\overline{\text{EmissInt}}_{s,t_0}}\right] \times \overline{\text{EmissInt}}_{s,t} \tag{3.7}$$

Where t_0 is the first time a firm is observed in the sample, and $\text{EmissInt}_{s,t}$ is the sectoral level of emission intensity at time t, excluding the observed firm f's emission intensity to mitigate endogeneity through a leave-one-out approach:

$$\overline{\text{EmissInt}}_{s,t} = \frac{1}{N-1}\sum_{i \neq f}^{N} \overline{\text{EmissInt}}_{i,s,t} \tag{3.8}$$

In line with Fontagné et al. (2023), our instrument's economic justification lies in the fact that firms' contemporaneous gap between their emission status and the overall sector's emission intensity is influenced by their enduring competitive position within their sector. Sector-specific shifts in emission intensity consequently affect individual firms' emission profiles through a stable, firm-specific factor that reflects their emission intensity status. Differences in the energy intensity of a firm and its sector average are assumed to have a persistent element.

We always report the first-stage coefficient and its significance to test the relevance of the IV, the Kleibergen-Paap Wald F-statistic to test for its weakness, and the p-value

of the Anderson-Rubin Wald test to check for the possibility of making inference even if there is a weak IV bias. In the IV2SLS estimations, we include firm and year fixed effects, excluding sector-year fixed effects.

3.5 Empirical results

This section presents the results of our econometric analysis to capture the impact of changes in a firm's emission intensity on its economic or financial performance. As outlined in section 3.4, we apply a log-transformation to our variables of interest hence the estimated coefficient can be interpreted as percentage changes. Overall, we find either no effect or a small but significant negative impact of emission intensity on the economic and financial outcome variables. This means that firms that reduced their emissions intensity either were not impacted by this reduction or slightly improved their corporate performance as a result of it. When we explicitly control for sector-specific competitive settings, this result remains robust, and becomes slightly stronger in magnitude.

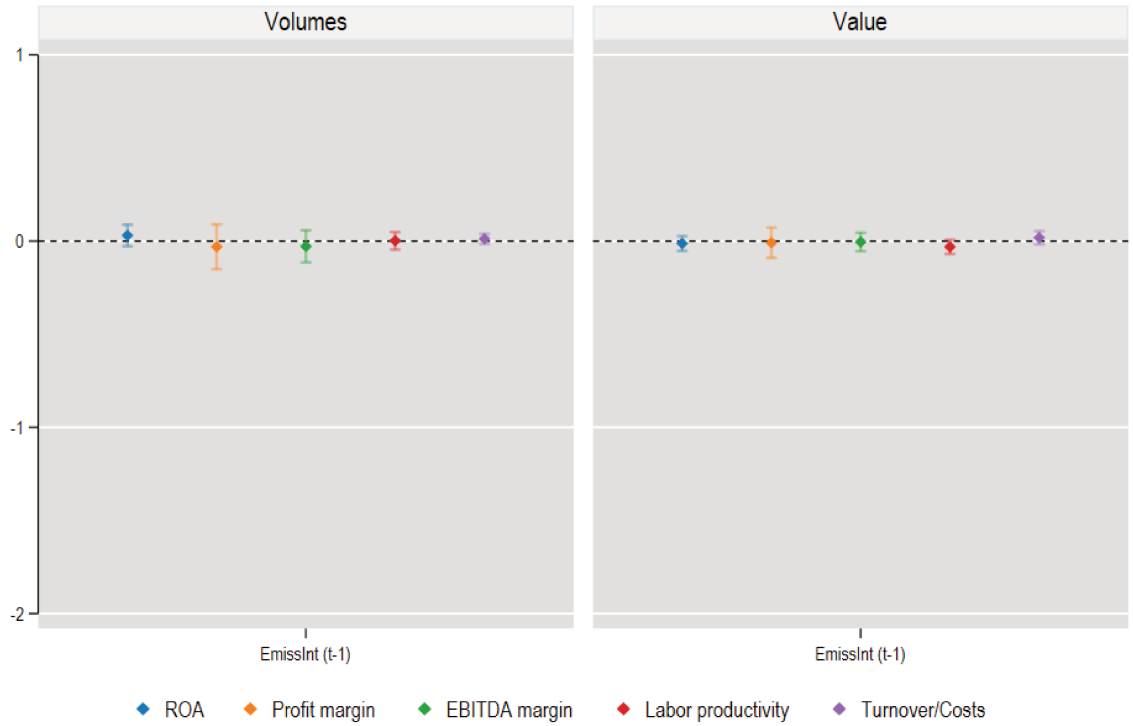
3.5.1 Impact of emission intensity on economic performance

We begin by reporting the results for equation 3.4. Figure 3.9 summarizes the results of the estimation of the model without using an IV. This illustrates that neither the volume-base nor the value-based measure of emission intensity significantly affect the variables of economic outcome.

We now turn to the results using our IV strategy. Full results are reported in Appendix3.H in tables 3.12 and 3.13 for the volume-based measure of emission intensity, and in tables 3.14 and 3.15 for the value-based measures. To check for the relevance of the IV, we report the first-stage coefficient for emission intensity, the first-stage Kleibergen-Paap (K-P) Wald F-statistic, and the p-value of the Anderson-Rubin (A-R) test on weak-instrument-robust-inference. The first-stage coefficients are positive and significant at the 1% level for all regressions, and the K-P Wald F-statistic is high enough to confirm the absence of a weak-IV bias for the volume-based estimations. This is not the case for the value-based estimates. For the regressions where the variable of interest has a significant result, the A-R p-value confirms that we can make inference based on this result.

The IV results shown in figure 3.10 indicate that emission intensity had a small but significant negative impact on return on assets when emission intensity is measured in volumes and in value. It also had a small significant negative effect on labor productivity when emission intensity is measured in value. However, only the coefficient return on assets in the volume-based estimation remains significant at the 10% level when we apply

Figure 3.9: Regression results - Non-IV Emission Intensity

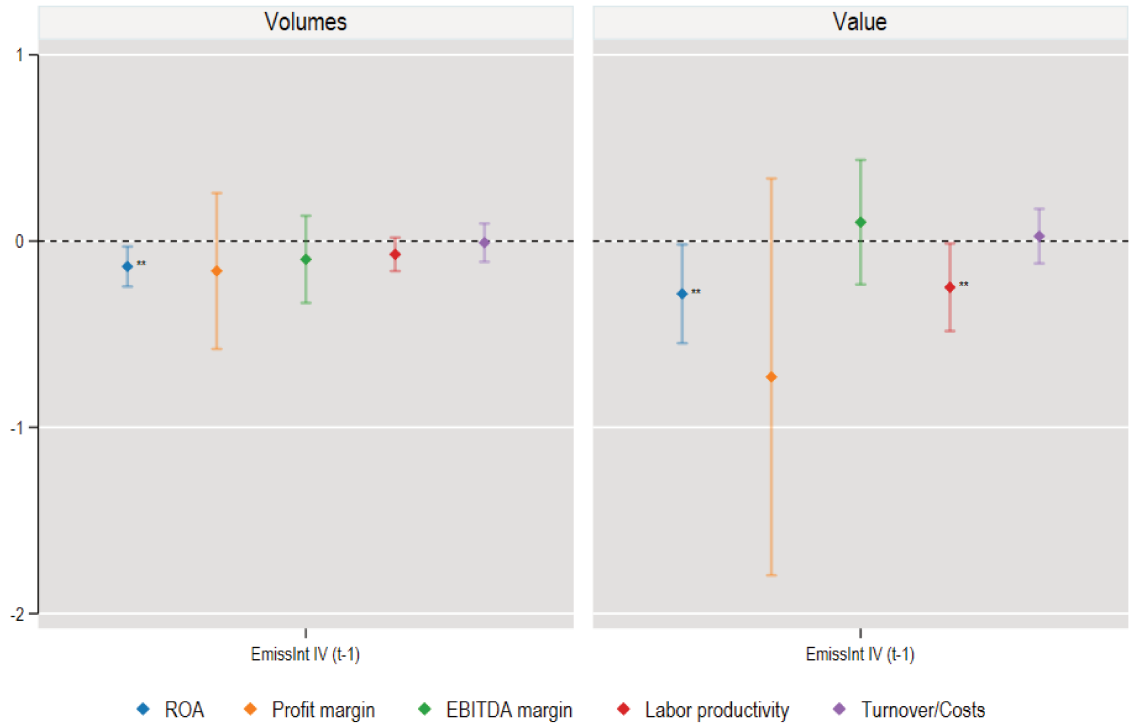


Note: Full regression results can be found in tables 3.24 to 3.27 of Appendix3.H. * p<0.10, ** p<0.05, *** p<0.01. Bars represent 5% confidence interval. Standard errors are clustered at the firm level. Firm-level control variables included. Firm and sector-time fixed effects included. Variables are in log form.

the more conservative Holm-Bonferroni correction to the p-values. In terms of values, the regressions indicate that a 1% change in emission intensity (in volumes) in a given year induces a 0.16% change in the opposite direction in return on assets in the following year. For the other variables, there is no significant effect of emission intensity.

Looking to the control variables, a few elements are worth highlighting. First, the stringency index has a significantly positive but very small effect on profit margins and EBITDA margins in the volume-based estimation. This could be a hint to the Porter hypothesis, meaning that firms that are faced with a higher stringency make their production processes slightly more efficient, and therefore also improve their margins. However, it has the opposite sign for labor productivity - and is also significant. This can mean that less carbon-intensive production processes are more labor-intensive than those which are more carbon-intensive. This hypothesis is plausible given existing evidence on this topic (Fragkos & Paroussos, 2018). Second, opening a new installation has a small but significant (at the 10 % level) on profit margins, in both the value- and volume-based estimations. This could indicate that new installations perform slightly better than older ones, but that this effect does not drive our results.

Figure 3.10: Regression results - IV Emission Intensity



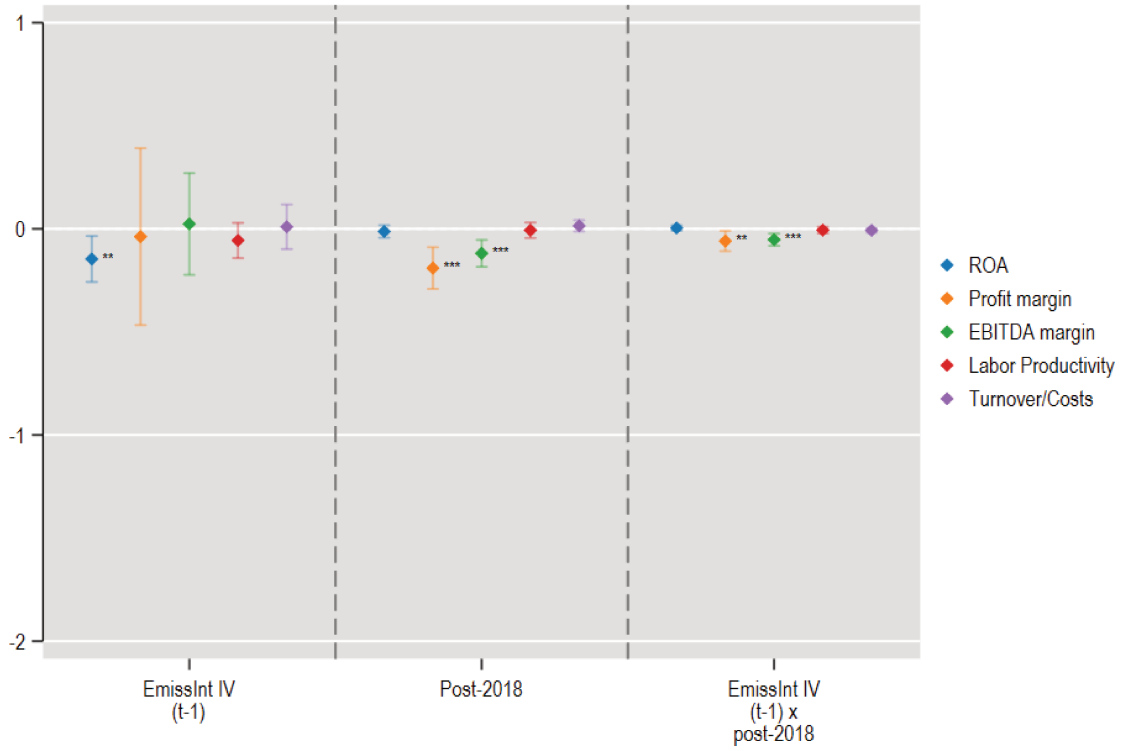
Note: Full regression results can be found in tables 3.12 to 3.15 of Appendix3.H. * p<0.10, ** p<0.05, *** p<0.01. Bars represent 5% confidence interval. Standard errors are clustered at the firm level. Firm-level control variables included. Firm and time fixed effects included. Variables are in log form.

Another issue we look into is whether the effect is stronger towards the end of the EU ETS' phase 3, when regulatory constraints got stronger and the price began to rise substantially. We therefore include a dummy for years from 2018 onward to capture this effect and summarize results in figure 3.11. The coefficient for emission intensity remains the same as in the previous regressions, but the interaction term as well as the post-2018 term are negative and significant in the regressions for profit margins and EBITDA margins. This indicates that on average starting in 2018, firms had worse profit and EBITDA margins and that changes in emission intensity had a stronger inverse effect on these margins. In other words, starting in 2018, reductions in emission intensity led to higher increases in profit and EBTIDA margins than they did before 2018.

3.5.2 Effect of competition setting

As discussed in section 3.3.4, we include a specification in which we interact the variable of interest, emission intensity, with indicators of the competition setting that firms operate in. This is to capture the difference in effects which may be driven by firms' capacity to pass through their costs to downstream sectors and consumers.

Figure 3.11: Regression results - IV Emission Intensity x post-2018 dummy



Note: Full regression results can be found in tables 3.16 to 3.17 of Appendix3.H. * p<0.10, ** p<0.05, *** p<0.01. Bars represent 5% confidence interval. Standard errors are clustered at the firm level. Firm-level control variables included. Firm and time fixed effects included. Variables are in log form.

Figure 3.12 summarizes the results for the volume-based estimations including an interaction term for import intensity and intra-branch trade. For both of these specifications, the first-stage coefficient for the variable of interest is always positive and significant at the 1% level and the K-P F-statistic is always above the threshold of 10, indicating the absence of a weak-IV bias.

Once the competition interaction term is included in our regressions, the effect of emission intensity on return on assets is doubled. In the regressions using both measures of competition setting, it remains highly significant (1% level), even when the H-B correction is applied to the p-values (drops to 5% level of significance). Additionally, the effect on labor productivity becomes significant and negative, even when taking the H-B correction into account (drops to 10% level of significance). The coefficient for profit margins is significant at the 10% level in the regression interacting intra-branch trade intensity, but does not remain significant with the H-B correction. These stronger effects of emission intensity on corporate performance variables seem to indicate that the competition setting matters in our specification, and that once cleaned of this effect, there is a stronger link between emission and corporate performance.

Figure 3.12: Regression results - IV Emission Intensity x competition variables



Note: Full regression results can be found in tables 3.20 to 3.23 of Appendix3.H. * p<0.10, ** p<0.05, *** p<0.01. Bars represent 5% confidence interval. Standard errors are clustered at the firm level. Firm-level control variables included. Firm and time fixed effects included. Variables are in log form.

While including this competition parameter changes the significance and values of some of the coefficients of interest, the interaction term and the competition term themselves are not always significant across specifications. Looking first at the effect of import intensity on the corporate performance variables, the coefficient is insignificant in all our regressions except when the outcome variable is EBITDA margins. In this case, the coefficient is positive and significant at the 1% level, which could indicate a pro-competitive effect (Peltonen et al., 2008). Turning to the coefficient measuring the effect of intra-branch trade intensity on corporate performance, we find that it is positive and significant in the regressions for profit margins and return on assets. This seems to indicate that for these two measures of financial performance, firms that operate in sectors where products become more differentiated are able to translate this into a better overall performance. However, this is not a strong effect as the H-B corrected p-values removes the significance of the coefficient for profit margins.

The interaction term for import intensity is positive and significant for EBITDA margins. This result could be explained by the fact that investments in decarbonization are not profitable when amortization is not taken into account. In the regressions which use intra-branch trade, the coefficient for the interaction term is positive and significant

for profit margins and EBITDA margins. The fact that the coefficient is positive for both of these measures is interesting. It could indicate that sectors where more product differentiation exists, investments in decarbonization can be profitable, even without accounting for amortization. An explanation for this could be that in sectors where product differentiation already exists, firms are more able to sell "greener" products at a premium by differentiating their offer based on this characteristic.

For the other outcome variables we have not discussed above, the competition setting does not appear to significantly affect the relationship between firms' emission intensity and their corporate outcomes.

For the value-based estimations, results are reported in tables 3.28 to 3.31 in Appendix3.H. These results present a weak-IV bias (K-P F-statistics are lower than 10) and the coefficients of interest are barely significant - and not significant when the H-B correction is applied.

3.5.3 Discussion of results

The first element to be highlighted from our results is that the coefficient associated with emission intensity is significantly negative across all of the specifications where the outcome variable is return on assets. This is in line with Trinks et al. (2020) who find that carbon efficiency is associated to higher returns on assets in their sample as well.

When looking at regulatory changes during the EU ETS' third phase, results suggest that there is a pre-2018 period and a post-2018 period. The latter coincides with higher carbon prices, as well as the implementation of the MSR and the establishment of the European Green Deal. Our results indicate that changes in emission intensity led to opposite changes in profit margins and EBITDA margins, but only starting in 2018. This could signal the importance of the increased regulatory stringency, which creates long-term expectations for firms and consumers.

Accounting for the competitive setting that firms operate in seems to reinforce the relationship between emission behavior and economic viability of firms. Indeed, the capacity for product differentiation tends to improve the relationship between emission intensity and firms' profit margins and EBITDA margins. In markets where products are already more differentiated, it may be easier to further differentiate products based on their carbon footprint, and to potentially increase sale prices and consequently, profit margins. Import intensity appears to have only a small pro-competitive impact on EBITDA margins.

3.5.4 Limitations and ways forward

While this work develops a solid methodology to account for a number of endogeneity concerns, it still presents several limitations. First, as mentioned before, due to the lack of emission data for countries or industries not covered by the EU ETS, isolating the pure effect of this treatment is not possible. It would be interesting to collect this type of data to investigate the effectiveness and full impact of this carbon market.

Moreover, we only study short-term effects (1 year) of firms' decarbonization dynamics on their performance. However, the impacts of decarbonization can span much longer periods. It would therefore be essential to continue monitoring these elements taking longer time-periods and lagged effects into account. A long term perspective would also need to test the Porter hypothesis. In this paper, we have discussed it as a potential explanation for the positive effect that is found between emission intensity and corporate performance. However, the data that is available to us does not allow for an explicit check of this channel. It would be particularly interesting to merge the dataset we have developed with other datasets on patents, like PATSTAT, or on firm-level research and development efforts. This would allow for a further exploration of the channels which underlie the effects we have highlighted in this study.

In our economic analysis, we have incorporated information regarding sectors' international exposure and product specialization to account for the fact that certain sectors may face more significant challenges in transitioning to low-carbon production processes than others. In this context, complementary measures could be explored to refine the assessment on the importance of specific product attributes. For instance, further research could delve into factors like the responsiveness of demand by estimating trade elasticities at the product level, as studied by Fontagné et al. (2019). Similarly, insights into product transportability, homogeneity, and complexity could also be valuable considerations in refining our understanding of sector-specific challenges and opportunities in the context of decarbonization efforts.

While we have focused on the context of carbon pricing in this paper, many other types of policies and contextual elements can also impact the profitability of firms in their transition. Some topics which would be particularly interesting to study include the effect of targeted support aimed at industrial decarbonization, and of energy price shocks.

Finally, there is an inherent limitation to our estimation of a volume-based emission intensity which is discussed in Appendix3.E detailing our methodology. Our estimation of production volumes is based on the EUTL, which reports the volume of free allocations provided to installations covered under the EU ETS. However, these free allocations are

actually determined at the sub-installation level. This means that there may be some inaccuracies in our estimation because we are not correctly associating benchmarks to installation-level reported activities. While we have attempted to mitigate this risk by including a Monte-Carlo simulation, it remains a limitation. It could be a particularly important limitation in the case where an installation reduces its emissions by switching from making its own inputs to importing them, but this is not declared because it happens at a sub-installation level. In our estimation, this would inaccurately be interpreted as a reduction of emission intensity, when it would actually be a case of carbon leakage. This worry is somewhat mitigated by the fact that production volumes do not significantly decrease at the aggregate level in our sample, so this likely does not represent a significant share of installations.

3.6 Conclusions and policy implications

This paper analyses the relationship between firms' emission intensity and their corporate performance based on a constructed dataset providing detailed micro-level information of industrial firms covered by the EU ETS. Unlike prior studies, our work covers the entire EU, all industrial sectors and provides results for the entirety of the EU ETS' third phase, except for 2020 which is excluded due to the COVID crisis. Additionally, we depart from the conventionally employed value-based metric for emission intensity and introduce a novel estimated volume-based measure of emission intensity.

Overall, we find a small but significant impact of changes in firms' emission intensity on their return on assets. This effect is stronger when we control for the competitive environment that firms operate in. It is also stronger in the years 2018-2019 when regulatory stringency was higher. For other metrics of firm performance, we find that decarbonization had no impact.

Our results have several implications from a policymaking perspective. Even in the EU ETS' third, most stringent phase, industrial firms who decarbonized their production were not negatively affected by this decision. On the contrary, their economic and financial performance improved along certain dimensions, especially in the last years of this phase. These findings present a promising indication that firms can strengthen their economic and financial resilience through the adoption of cleaner production methodologies. Firms should further exploit these joint benefits of decarbonization to reduce their total emissions.

One of the reasons that our results are small in magnitude could be that the ways in which firms are decarbonizing are only small, marginal changes for now - and therefore only have a minor impact on their overall functioning and profitability. However, heavy

industry sectors require large investments to develop entirely new production processes to fully, or substantially, decarbonize. These types of changes have not yet materialized because they represent large investments. The realization of these benefits depends on the ability of regulated sectors to effectively adapt and innovate while safeguarding their external competitiveness. This imperative is particularly pronounced in the face of climate targets requiring additional efforts for their fulfillment, combined with an increasingly complex environment shocked by an energy crisis, whose effects are still present, and an intensified competition in clean technology from foreign counterparts. In parallel to carbon pricing policies, policymakers should provide the right incentives to invest in the green transition, including fostering the re-industrialization of clean technology sectors and facilitating the decarbonization of EU industry. Recent EU initiatives outlined in the Green Deal Industrial Plan go in this direction, such as the Net-Zero Industry Act.

Moving forward, there are diverse opportunities for improving and extending this research. Firstly, further sector-level analyses of these effects could be beneficial, given the highly different nature and environments of the industrial sectors we study. Secondly, we could refine the emission intensity indicator further to address potential measurement errors arising from the lack of information at sub-installation level. Lastly, the question of the channels of effect is particularly relevant - incorporating data that proxies innovation and investments to better estimate and identify the potential long-term effects of climate regulations could be highly interesting. In this respect, further research is needed to investigate the underlying mechanisms of this relationship, with particular attention to the role of innovation in fostering the adoption of green or advanced technologies.

Appendix

3.A Cleaning and merging procedure

The firm-level dataset on verified CO_2 emissions and a range of financial indicators was constructed and cleaned following four steps.

3.A.1 Step 1: Cleaning of data from the European Union Transaction Log

The European Union Transaction Log (EUTL) records data on compliance and transactions for all entities participating in the EU ETS. Compliance data comes with a two-year lag and encompasses various variables including verified CO_2 emissions by installation, number of allowances freely allocated, bought, and surrendered, and usage of CER credits, among others. Transaction data comes with a three-year lag and records the volume of allowances transferred between any two accounts in the system. Both transaction and compliance data are published on a yearly basis. The EUTL has been active since the implementation of the EU ETS, i.e., since 2005.

Only regulated firms (e.g., a power plant that is required by regulation to buy and surrender CO_2 allowances) are required to provide data for the compliance part of the EUTL, but unregulated firms that participate in the EU ETS (e.g., a bank that acts as a financial intermediary between a power plant and the ETS compliance office) are recorded in the EUTL. In our sample we include only regulated firms.

We used data files provided by Abrell (2023).[18] To perform our analysis, we cleaned and merged these files, through the following steps. First, we removed all empty observations after 2021 or those missing company registration numbers. Second, we excluded all observations reported in the Swiss ETS (CH ETS). Third, we dropped observations failing to report Operator Holding Accounts, as well as observations whose installation activity was 'Aircraft operator activities'. Lastly, we excluded account holders that could not be matched with any account.

After this cleaning procedure, all observations were uniquely identifiable in the dataset by company registration number *(reg_id)*, installation identifier *(inst_id)*, and year *(year)*.

[18]The author scraped the data from the EUTL and compiled it into a relational database made up of various CSV files. These files, along with documentation on Abrell's work and output, are available for download on Abrell's website: https://www.euets.info/download/

3.A.2 Step 2: Cleaning of data from ORBIS

Firms regulated by the EU ETS were extracted from the flat file of the ORBIS database. This sample was cleaned in order to be consistent with the EUTL, so both datasets could be merged together. The following cleaning was applied to the extracted ORBIS data, following recommendations from Gal (2013), Gopinath et al. (2017), and Kalemli-Ozcan et al. (2015):

- Construction of a year value: observations do not have a year value but instead a closing date value, which refers to the date at which a company filed its yearly account information. For observations with only the year in the closing date, this year was kept. For observations with a year, month and/or day, the current year was kept if the date was after 1 June, and the prior year was instead used if the date was before 1 June;
- Dropped all observations with no value for the closing date (these had empty financial records anyways);
- Dropped all observations for which the number of months taken into account in the reporting was different from 12;
- Duplicates for a single company and year were cleaned according to the following rules (in order of priority):
  1. For companies reporting more than once in the same year, the latest date was kept;
  2. For companies with both an annual filing and a local registry filing, the annual filing was kept (this is the most consistent and comparable across firms and countries);
  3. Only unconsolidated accounts were kept;
- Dropped all firms whose NACE code was not an activity regulated under the EU ETS (as described in appendix 3.D).
- Dropped all observations with insufficient quality of data, based on the following criteria:
  - Missing any of the following variables: total assets, turnover, sales or cost of employees
  - If any of the following variables were negative: total assets, number of employees, sales, tangible fixed assets

- If any of the following variables were missing, negative, or equal to zero: material costs, total assets, tangible fixed assets, number of employees and operating revenue

After this cleaning, all observations were uniquely identifiable in this dataset by ORBIS company identifier and year.

3.A.3 Step 3: Finding matches between EUTL and ORBIS identifiers

ORBIS and the EUTL do not have any common firm identifiers. An initial matching was provided was provided by Letout (2021). However, this matching is now several years old and therefore does not take into account any new firms or changes in firm names since 2019. As a result, a new matching was developed for this chapter. This matching applies methods from Natural Language Processing. The full details on this matching and quality controls that were run is provided in Appendix XX. Here, we simply summarize the matching procedure as the four following steps:

1. Minimal cleaning of the primary variables used for matching;

2. NLP matching to find a set of possible matches for each firm in the EUTL (term-frequency/inverse-document-frequency analysis based on 3-character ngrams, then implementation of a nearest-neighbor algorithm);

3. Classic fuzzy matching on a secondary matching variable (similarity score on post-codes);

4. A filtering of possible matches to find the best option for each EUTL firm.

3.A.4 Step 4: Merging of the EUTL and ORBIS

In the final step, we merge the EUTL and ORBIS. It is important to note that some ORBIS identifiers are associated with more than one EUTL identifier. This is caused by a single firm (identified by the ORBIS identifier) opening several accounts within the EU ETS (each of which is identified by a single EUTL identifier). Sometimes the accounts are used for different plants, other times one account is opened for a certain period, and another opened for another period.

The matching process proceeded as follows:

1. Observations from the EUTL are matched many-to-one to the file contain all EUTL-ORBIS matches based on the EUTL company registration identifier *(reg_id)*. After this, observations are uniquely identified by EUTL company registration identifier *(reg_id)*, installation identifier *(inst_id)*, ORBIS identifier *(orbis_bvd_id)*, and year *(year)*.

2. Observations from ORBIS are matched many-to-many to the file contain all EUTL-ORBIS matches based on ORBIS company identifier *(orbis_bvd_id)*. After this, observations are uniquely identified by ORBIS company identifier *(orbis_bvd_id)*, EUTL company registration identifier *(reg_id)*, and year *(year)*.

3. Observations from the EUTL are matched many-to-one to ORBIS based on EUTL company registration identifier *(reg_id)*, ORBIS company identifier *(orbis_bvd_id)*, and year *(year)*.

All observations that do not have a match at any of these three steps were dropped. After this merging process, all observations were uniquely identifiable by EUTL company registration identifier *(reg_id)*, installation id *(inst_id)*, ORBIS company identifier *(orbis_bvd_id)*, and year *(year)*.

3.B Matching the EU Transaction Log and ORBIS: A Natural Language Processing approach

Foreword

Please note that this Appendix was published as a Technical Document by the European Commission and is available at the following address: https://single-market-economy.ec.europa.eu/single-market/services/economic-analysis/matching-eu-transaction-log-orbis-database_en?prefLang=cs. It was co-authored with Victor Ho. Please cite as:

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3.B.1 Introduction

This document describes the methodology used to provide a new matching of the European Union's Transaction Log (EUTL) and Bureau van Dijk's ORBIS database. The goal of this matching is to provide firm-level data on both climate metrics (i.e., yearly

emissions, allocation of free allowances on the EU's carbon market, etc...) and financial metrics (i.e., turnover, employment, capital expenditure, etc...).

This matching has been done in the past by several other researchers, namely including Simon Letout at the Joint Research Center. We invite the interested reader to refer to Letout (2021) for a detailed description of the structure of the EUTL and of ORBIS. The matching provided by Letout was done with EUTL data from 2020, but has not been updated since. While the process used by Letout can be replicated, it is quite time consuming and requires a substantial amount of manual processing.

The goal of the proposed methodology is to fully automate this process, so that it can be updated on a yearly basis when the EUTL is updated. This will allow for better data quality, since new firms will be matched and any name or structural changes will be captured.

3.B.2 Matching methodology

There are four steps applied in this matching procedure, each of which is detailed in a subsection below:

1. Minimal cleaning of the primary variables used for matching;
2. NLP matching to find a set of possible matches for each firm in the EUTL;
3. Classic fuzzy matching on secondary matching variables;
4. A filtering of possible matches to find the best option for each EUTL firm.

Primary matching variables are a firm's name and national identifier. These are the variables that are used to identify potential matches between the two databases. Secondary matching variables currently only include a firm's postcode, but could be extended to also include its address. These variables are used to verify and filter the potential matches that are found as described above.

Step 1: Cleaning of primary variables

A set of standard cleaning procedures is applied to the primary variables used for matching. These include:

- Harmonizing capitalization;
- Removing non-ASCII characters;

- Removing punctuation and brackets;
- Removing multiple spaces;
- Standardizing certain abbreviations (for example, '&' and 'and').

Additionally, letters specific to the German alphabet and all letters in the Cyrillic alphabet are transliterated into a standard Latin alphabet.

Step 2: Natural Language Processing (NLP) matching

Step 2a: Term frequency - inverse document frequency This step is adapted from the methodology by Taylor (2020). First taking the EUTL primary variables (firm name and national identifier), each unique value is turned into a vector of 3-character ngrams. For example, the firm name "Lafarge Ciments" would be turned into the following list of ngrams: "Laf", "afa", "far", "arg", "rge", "ge ", "e C", " Ci", "Cim", "ime", "men", "ent", "nts".

These lists are turned into a matrix which characterizes each firm name based on these ngrams. Table 3.4 illustrates what this would look like if we take two firms, "Lafarge Ciments" and "Ciments Calcia".

Instead of using a simple count however, the measure that is used to characterize each firm name is what is known as term frequency - inverse document frequency (TF-IDF). This measure essentially weights the frequency of an ngram within a word with the frequency of this ngram within the entire corpus. This allows for ngrams that are very frequent to be given less importance in characterizing a word than ngrams that are infrequent. The formula for TF-IDF is taken from the documentation for Pedregosa et al. (2011) and adapted to our case:

$$\text{tf-idf(ngram,word)} = \text{tf(ngram,word)} \times \text{idf(ngram)}$$

Where tf(ngram,word) is the relative frequency of an ngram within a word - meaning its frequency, weighted by the total number of ngrams in the word - and idf(ngram) is:

$$\text{idf(word)} = \log \frac{1 + \text{n}}{1 + \text{wf(ngram)}} + 1$$

Here, n is the total number of words in the word set (in our example, the total number of firm names) and wf(ngram) is the number of words in the word set that contain the given ngram. The measure of TF-IDF is normalized to have a mean of 0 and a variance of 1, which brings all features into a common scale.

Table 3.4: Ngram frequency for two terms

	Lafarge Ciments	Ciments Calcia
Ca	0	1
Ci	1	1
La	1	0
Cal	0	1
Cim	1	1
Laf	1	0
afa	1	0
alc	0	1
arg	1	0
cia	0	1
e C	1	0
ent	1	1
far	1	0
ge	1	0
ia	0	1
ime	1	1
lci	0	1
men	1	1
nts	1	1
rge	1	0
s C	0	1
ts	1	1

In our previous example, this would transform our table as follows:

This methodology allows us to turn a list of firm names (or any other variable) into a vector of numerical features measuring the relative importance of each ngram within a word. We implement this methodology using Pedregosa et al. (2011).

Step 2b: Nearest neighbor Once two matrices have been constituted (one for each database) for a primary variable, a nearest neighbor algorithm is used to identify the 5 closest potential matches between the two databases. For instance, for a unique firm name from the EUTL, the algorithm will identify the 5 firm names within the ORBIS matrix that most closely resemble it, based on the TF-IDF measure. We once again use Pedregosa et al. (2011) to implement this. Their algorithm minimizes a Euclidian distance to find these potential matches. Each match is given a score between 0 and 1, with 0 being the best outcome (exact match) and 1 being the worst outcome.

Given that we have two different primary variables, a firm's name and its national identifier, we run the algorithm twice and find a maximum of 10 potential matches for

Table 3.5: Term frequency - inverse document frequency for two terms

	Lafarge Ciments	Ciments Calcia
Ca	0.000000	0.307966
Ci	0.209415	0.219121
La	0.294325	0.000000
Cal	0.000000	0.307966
Cim	0.209415	0.219121
Laf	0.294325	0.000000
afa	0.294325	0.000000
alc	0.000000	0.307966
arg	0.294325	0.000000
cia	0.000000	0.307966
e C	0.294325	0.000000
ent	0.209415	0.219121
far	0.294325	0.000000
ge	0.294325	0.000000
ia	0.000000	0.307966
ime	0.209415	0.219121
lci	0.000000	0.307966
men	0.209415	0.219121
nts	0.209415	0.219121
rge	0.294325	0.000000
s C	0.000000	0.307966
ts	0.209415	0.219121

each EUTL firm. Once again taking the example of "Lafarge Ciments", the results would look as shown in Table 3.6.

Table 3.6: Example of potential matches found through nearest neighbor algorithm

EUTL name	ORBIS name	Name score	EUTL nat. ID	ORBIS nat. ID	Nat. ID score
Lafarge Ciments	Lafarge Ciments	0.00	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments	0.00	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments	0.00	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments	0.00	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments	0.00	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments Ciments Lafarge	0.18	302135561	302135561	0.00
Lafarge Ciments	Lafarge Ciments Distribution	0.62	302135561	451120331	-
Lafarge Ciments	Lafarge Ciments Distribution	0.62	302135561	451120331	-
Lafarge Ciments	Lafarge	0.69	302135561	542105572	-
Lafarge Ciments	Lafarge	0.69	302135561	334706413	-
Lafarge Ciments	Lafarge Sa Lafarge	0.73	302135561	342597424	-
Lafarge Ciments	Pythagore	-	302135561	430213561	0.80
Lafarge Ciments	Bredin Haute Coiffure	-	302135561	302135579	0.84
Lafarge Ciments	Rigolet Charles Et Fils	-	302135561	302135553	0.84
Lafarge Ciments	Pressing 86 Exelmans	-	302135561	534135561	0.88

Step 3: Similarity measure on postcodes

Once this set of possible matches has been found for all EUTL firms, we compute a measure of similarity between the postcode reported in the EUTL and the one reported in potential ORBIS matches. This is computed using the Levenshtein Distance. In broad terms, this distance measures the minimum number of characters that need to be changed to change one word into another - in our case, to change the EUTL postcode into the ORBIS postcode. The measure is normalized and goes from 0 to 100, with 0 being the worst score and 100 being the best (exact match).

In our example, the outcome of this measure is given in table 4.

Table 3.7: Similarity measure on potential matches

EUTL name	ORBIS name	EUTL postcode	ORBIS postcode	Similarity measure
Lafarge Ciments	Lafarge Ciments	92140	92130	80.00
Lafarge Ciments	Lafarge Ciments	92140	91320	60.00
Lafarge Ciments	Lafarge Ciments	92140	94380	60.00
Lafarge Ciments	Lafarge Ciments	92140	16400	60.00
Lafarge Ciments	Lafarge Ciments	92140	31100	40.00
Lafarge Ciments	Lafarge Ciments Ciments Lafarge	92140	13320	40.00
Lafarge Ciments	Lafarge Ciments Distribution	92140	92130	80.00
Lafarge Ciments	Lafarge Ciments Distribution	92140	31100	40.00
Lafarge Ciments	Lafarge	92140	92130	80.00
Lafarge Ciments	Lafarge	92140	26450	60.00
Lafarge Ciments	Lafarge Sa Lafarge	92140	47550	40.00
Lafarge Ciments	Pythagore	92140	55100	40.00
Lafarge Ciments	Bredin Haute Coiffure	92140	39000	40.00
Lafarge Ciments	Rigolet Charles Et Fils	92140	39270	60.00
Lafarge Ciments	Pressing 86 Exelmans	92140	75016	20.00

Step 4: Filtering potential matches

Step 4a: First general filtering To determine which match to keep among the different options that are available, we then apply a series of filters aimed at assessing the quality of each match. We determine an initial set of four conditions for each of the potential matches:

- Condition 1: true if the match is included in the results of the top 5 nearest neighbors for both the firm name and national ID.
- Condition 2: true if within a group of potential matches for a single EUTL firm, the match has the lowest score for both the firm name *and* national ID scores *and* the highest score for the postcode similarity score;
- Condition 3: true if the match has the lowest overall score, computed as:

$$\text{overall score} = \frac{[(0.5 \times \text{name score}) + (0.3 \times \text{nat ID score}) + (0.2 \times \text{postcode score})]}{3}$$

with the postcode score normalized to match the two other scores (best is 0 and worst is 1).

- Condition 4: true if none of the above conditions are true, but one of the primary variable matching scores is an exact match (= 0) and the postcode similarity score is also an exact match (= 100).

Based on these conditions, we rank the potential matches within each group of matches for a unique EUTL firm. The ranking is defined as follows:

1. Conditions 1 - 3 are all true;
2. Conditions 1 and 3 are true, but 2 is false;
3. Condition 1 is true, but 2 and 3 are false;
4. Conditions 1 - 3 are all false, but 4 is true;
5. All conditions are false.

We keep only the best ranking within each group of potential matches for an EUTL firm. For a vast majority of firms (≈80%), this returns only a single match, which is the one that is considered to be the best match available. For the firms that still have several potential matches that have equal ranks, further filtering is needed.

Step 4b: Second country-level filtering For the firms that still have several potential matches a set of conditions were established to keep the best match. These conditions were determined based on the patterns identified in the data, and structural characteristics of the data construction.

For example, in France, a mother firm will have an identifier with a length of 11 characters, while its subsidiaries will have the same identifier, with additional characters added to the end of it. In our case, we want to keep the mother company and would therefore only keep the firm which has a length of 11 characters.

For each of the countries that have firms with several potential matches remaining, we use the following criteria to determine which match to keep as the best match:

- For France: keep the match for which the ORBIS ID's length is equal to 11;

- For Italy: keep the match for which the ORBIS ID does not end with 'B';
- For Estonia, Denmark, Hungary, and Great Britain: keep the match for which the ORBIS ID ends with the national ID;
- For Germany: keep the match for which the national ID has the firm's region in parentheses;
- For the Netherlands: keep the match for which the ORBIS ID does not start with "NL0000" and does not end with "T".

Step 4c: Final filtering A final set of criteria can be applied to filter the potential matches of the final few firms that still have several available. The criteria are as follows:

- Keep the match that has an ORBIS identifier equal to the country code concatenated with the national ID;
- Keep the match that has an ORBIS identifier starting with the country code;
- For French firms, if I have only a set of subsidiaries as potential matches, get the mother company ORBIS ID;

After all these steps, there are about 700 firms for which it is not possible to find a single dominant match option. Further information would be needed to achieve this, for instance by looking at the postal address of the firms in question.

Quality control

To test for the quality of this methodology, as compared to the one proposed by Letout (2021), we compare our matching with the one provided by Letout (JRC).

First, there are around 400 firms that are in Letout's matching, but not in ours and about 1000 firms that are in our matching but not in Letout's. The 400 former firms are no longer in the EUTL so this is why they are not included in our matching. The 1000 latter firms can either be new firms, or firms for which no match was found by Letout.

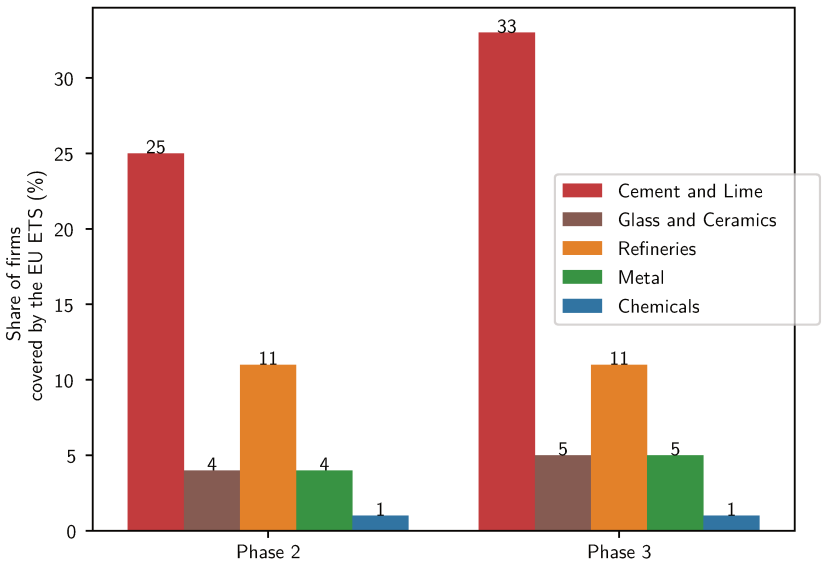
Second, of the firms that are in both matching, and that have only a single match left in our matching at the end of the filtering process, 7417 are matched to the same ORBIS ID as what is found by Letout. On the other hand, 229 firms are not matched to the same ORBIS ID. However, of these 229 firms, only 77 are considered "validated" in Letout's matching. This means that only 77 of the 229 matches are considered reliable enough according to Letout's methodology. As such, these are the only ones for

which it is somewhat worrying that we do not have the same match. It is worth noting that this represents only a small portion of all firms in our matching. Additionally, after checking these 77 matches manually, it seems that this is only a question of subsidiarity, meaning that either in our match, or in Letout's match, one of the ORBIS IDs is a subsidiary of the other. There is no consistent way to fix this issue without taking the address of the firm into account.

3.C Data representativeness

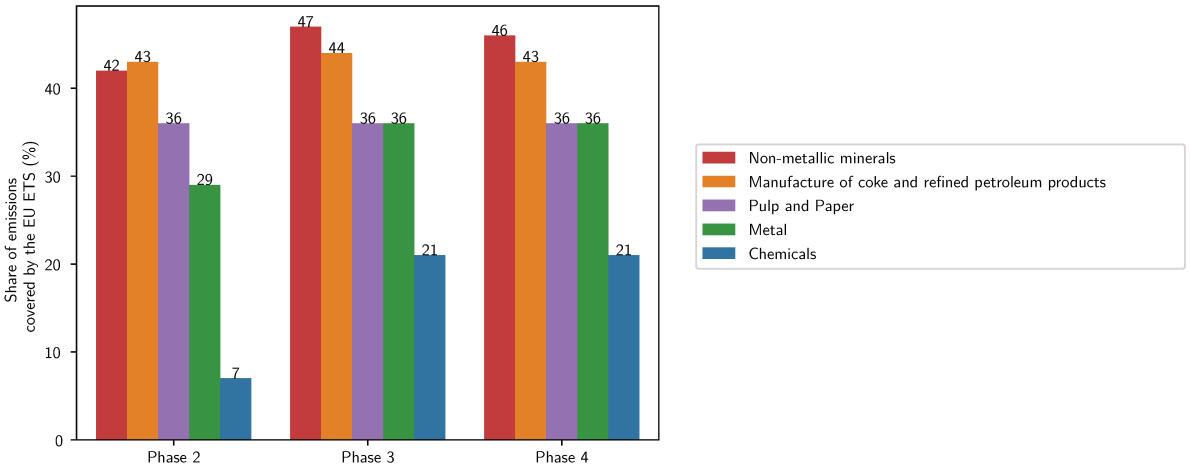
The dataset presented in this paper does not represent the entire universe of firms in the EU in the sectors that are studied. Indeed, only a small share of this universe is regulated by the EU ETS, as illustrated in figure 3.13. As a result, this database should not be taken as being representative of EU industry in a broad sense, but instead of the part of EU industry that is regulated by the EU ETS. However, since the criteria that is used to determine whether firms are regulated are based on firms' size and emission levels, this dataset does tend to capture the largest and most emission-intensive firms in the concerned sectors. This is illustrated by figure 3.14: while the EU ETS only regulates a small share of firms, a much larger share of total emissions in industrial sectors are covered. For example, the EU ETS only covers 5% of firms in the metal sector, but these firms generate more than a third of the sectors' GHG emissions. Additionally, figure 3.15 illustrates how our sample is biased towards larger firms, which are not the majority of firms in the sectors that we study. However, they are the firms that climate policies focus on as they are responsible for the most emissions.

Figure 3.13: Share of firms covered by the EU ETS by sector



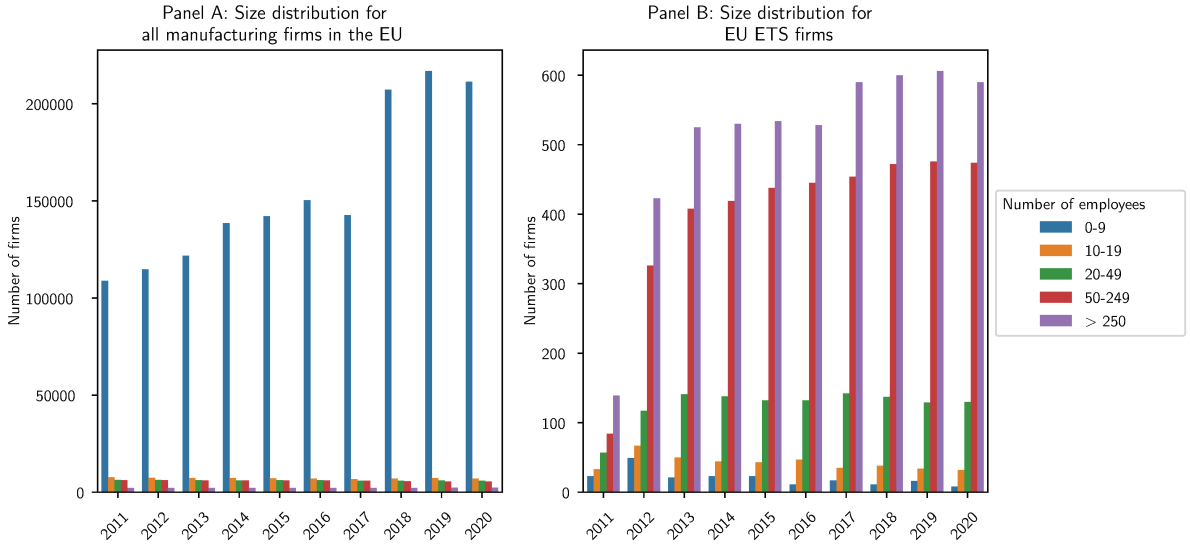
Source: EU Transaction Log and Eurostat (sbs_na_ind_r2).

Figure 3.14: Share of emissions covered by the EU ETS by sector



Source: EU Transaction Log and Eurostat (env_ac_ainah_r2).

Figure 3.15: Distribution by firm size (number of employees)



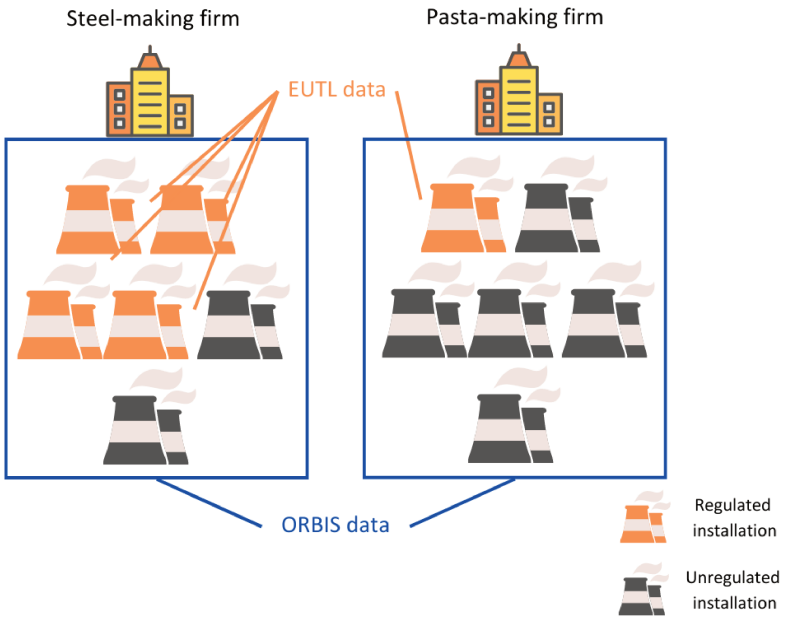
Source: EU Transaction Log, ORBIS and Eurostat (SBS_SC_IND_R2).

3.D NACE filtering procedure

When regulated firms report to their Union Registry for EU ETS compliance, they must provide information on their regulated installations' activity and annual emissions. When matching the EUTL's emissions data with financial data from ORBIS, the installation activity can no longer be used since an installation's activity does not always correspond to the overall activity or sector of its parent firm. ORBIS provides company-level NACE codes which can complement the EUTL's data on installation activity. Almost all sectors of the economy are represented in the matched database. However, not all available sectors should be kept for a rigorous analysis using both

financial and emissions data. Indeed, for firms in many of the sectors available, the regulated installations represent only a small fraction of their parent company's overall activity. Since ORBIS' financial data covers the entirety of a company's activities it cannot be compared to the EUTL emissions data that only covers regulated installations for these firms (see figure 3.16 for an illustration).

Figure 3.16: Compatibility between ORBIS and the EUTL



To give a concrete example of this issue, Barilla reports in its 2021 Sustainability Report that its Scope 1 emissions amounted to 263,282t CO_2 in 2021. Some of the company's co-generation plants are regulated under the EU ETS. Looking in the EU Transaction Log, only 96,321t CO_2 emissions were reported by Barilla for these plants in 2021, making up slightly more than a third of their total Scope 1 emissions. It is clear that for this company, most emissions come from unregulated parts of its production process (i.e., pasta making), which are not regulated under the EUTL. As a result, financial data from ORBIS cannot be compared to emissions data from the EUTL for this firm. On the other hand, emissions reported in the EUTL by ArcelorMittal make up more than 60% of the Scope 1 emissions they report for Europe . This means that most Scope 1 emissions for ArcelorMittal are covered by the EUTL, and that we can more reliably compare this data to financial data from ORBIS. The preferred sample to use ORBIS and EUTL data jointly is therefore the one which is restricted to firms whose main activity is regulated under the EU ETS. The sectors selected based on this criterion are detailed table 3.8, along with their associated NACE codes and number of observations available. This note only considers sectors that were validated using this logic.

Source: Authors

Table 3.8: Sectors selected for NACE-filtered sample

Sector category	NACE description	Associated NACE codes
Pulp and paper	Manufacture of paper and paper products	1700 (+ all subcategories)
Chemicals	Manufacture of chemicals and chemical products	2000 (+ all subcategories)
Glass	Manufacture of glass and glass products	2310 (+ all subcategories)
Ceramics	Manufacture of ceramic tiles and flags	2331
	Manufacture of other porcelain and ceramic products	2340 (+ all subcategories)
Cement and lime	Manufacture of cement, lime and plaster	2350 (+ all subcategories)
Metal	Manufacture of basic iron and steel and of ferro-alloys	2410
	Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	2420
	Manufacture of other products of first processing of steel	2430 (+ all subcategories)
	Aluminum production	2442
	Lead, zinc and tin production	2443
	Copper production	2444
	Other non-ferrous metal production	2445

3.E Estimation of production volumes

3.E.1 Methodology

In the EU ETS, the amount of free allowances given to each regulated installation is determined on a yearly basis depending on their past production volumes. Since the number of free allowances per installation is available in our dataset, it is possible to reverse the calculation and fall back on an estimate of production volumes for each installation. With some level of simplification,[19]free allocations are calculated as follows:

[19]In reality, allocation of free allowances is determined on the basis of product benchmarks, heat benchmarks, fuel benchmarks and process emission benchmarks. However, the most important benchmark for the sectors we study (which do not include electricity, refineries and steam and air conditioning) is the product benchmark. Additionally, no data is available regarding the other benchmarks, so these are excluded from our computation.

$$FA_{sub,t} = V_{sub,t-1} \times B_{prod} \times CSCF_t \times TCF_{sec,t}$$

Where:

- $FA_{sub,t}$ are free allocations for sub-installation sub in year t (free allocations are initially determined at the sub-installation level, although they are aggregated and reported at the installation level in the EUTL);
- $V_{sub,t-1}$ is the volume of production in tonnes for sub-installation sub in year $t-1$;
- B_{prod} is the production benchmark, given in free allowances per tonne of production and calculated based on the emission intensity of the 10% most efficient producers of this product;
- $CSCF_t$ is the yearly cross-sector correction factor, a correction factor applied to all installations in order to ensure the total amount of free allocations given out in a year is below the total yearly cap of allowances in the EU ETS;
- $TCF_{sec,t}$ is what we call the transitional correction factor, applied to gradually decrease the share of free allowances that installations receive in sectors not on the carbon leakage list (i.e., ensure a transition away from the free allocation). It therefore depends on the installation's sector of activity sec.

As such, it is possible to derive volumes from the following equation:

$$V_{sub,t-1} = \frac{FA_{sub,t}}{B_{prod} \times CSCF_t \times TCF_{sec,t}}$$

3.E.2 Data sources

Data is taken from the following sources for each of the variables in the equation above:

- FA: EUTL;
- B_{prod}: Annex I of the Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2011) 2772) (2011/278/EU);
- $CSCF_t$: Cross-sectoral correction factors between 2013 and 2016 are taken from Annex II of the Commission Decision of 5 September 2013 concerning national

implementation measures for the transitional free allocation of GHG emission allowances in accordance with Article 11(3) of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2013) 5666) (2013/448/EU). Between 2017 and 2020, they are taken from Annex II Commission Decision (EU) 2017/126 of 24 January 2017 amending Decision 2013/448/EU as regards the establishment of a uniform cross-sectoral correction factor in accordance with Article 10a of Directive 2003/87/EC of the European Parliament and of the Council. The initial decision from 2013 establishing these factors was invalidated in 2016 by the Court of Justice of the European Union and subsequently amended in 2017. See Cross-Sectoral Correction Factor (CSCF) - Emissions-EUETS.com for details on this topic;

- $TCF_{sec,t}$: The transitional correction factor for the years 2013 to 2020 is taken from Annex VI of the Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonized free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council (notified under document C(2011) 2772) (2011/278/EU). Note that the TCF for sectors on the carbon leakage list for phase 3 is always equal to 1.

3.E.3 Implementation

Given data availability, the equation used to calculate production volumes must be slightly modified. Indeed, free allowance volumes are available in the EUTL at the installation level, not the sub-installation level. Therefore, the equation is modified as follows:

$$V_{inst,t-1} = \frac{FA_{inst,t}}{B_{act} \times CSCF_t \times TCF_{sec,t}}$$

Since product benchmarks cannot be matched directly to sub-installation activity, we need to match them to installation activities. While some products can be matched one-to-one to installation activities, there are many cases where products can be matched to several activities, or vice-versa, where several products can be matched to a single activity. This means there may be several product benchmarks for a single installation. To take this into account, we generate production volumes using a Monte Carlo process with 1000 iterations that computes the above formula based on the mean and standard deviation of the benchmarks that are applied to each installation. We take the mean value of all the production values that are generated from this process as production volume for each installation.

3.E.4 Limitations

While this methodology can give an estimate of production volumes at the installation level, it is limited by the level of aggregation of the EUTL. Indeed, the installation activity reported in this dataset is the main activity of each installation. However, this could mask some heterogeneity in the activities of sub-installations and consequently, of free allocation benchmarks. While we try to highlight this heterogeneity by adding confidence intervals based on the standard deviation of the aggregated benchmarks, this remains a limitation. Until benchmarks are perfectly matched based on the product of a sub-installation, the volume estimated will remain an approximation of reality. In the meantime, this estimation is likely not too far off given that for most installations, the main activity is the one for which there is a majority of production.

3.F Distribution of emission intensity by sector

Figure 3.17: Distribution of emission intensity (volumes)

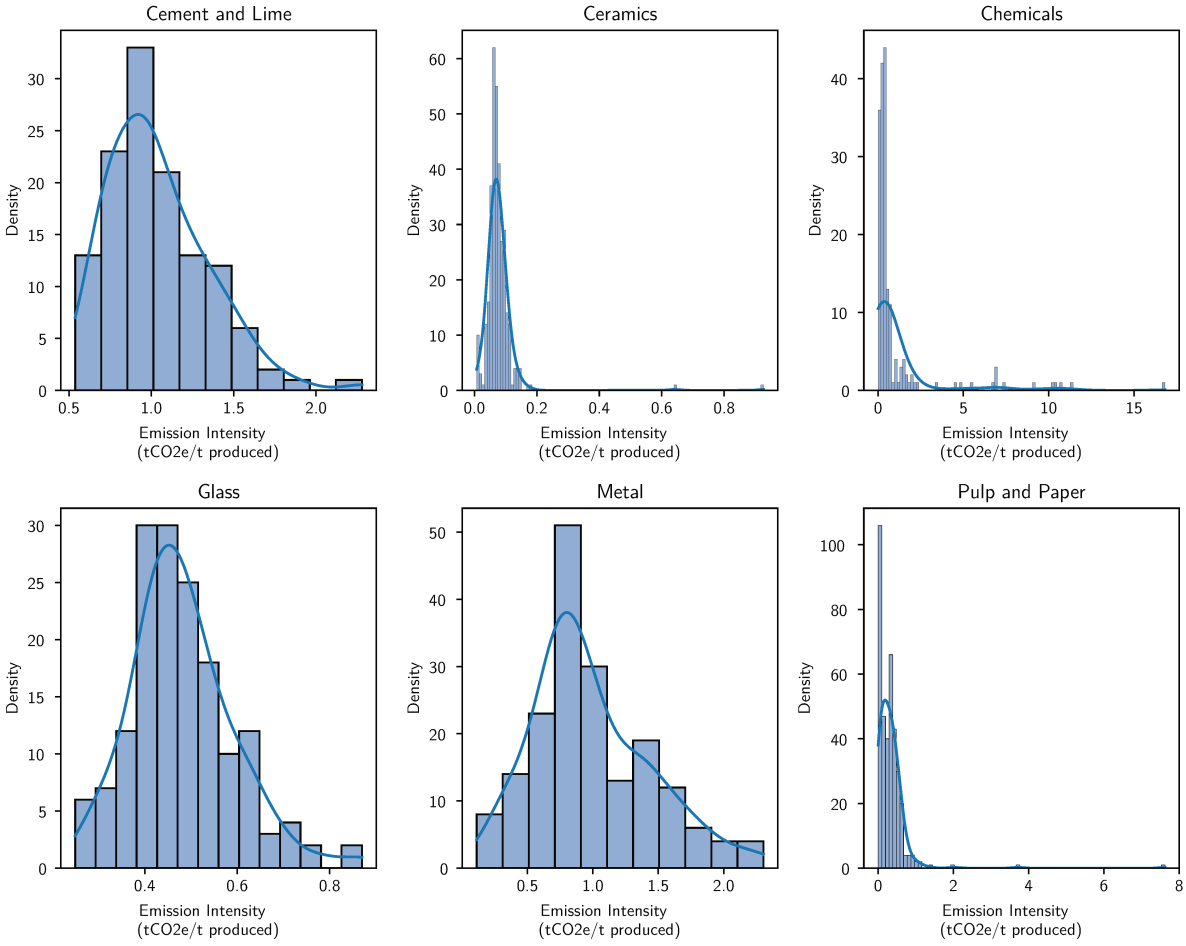
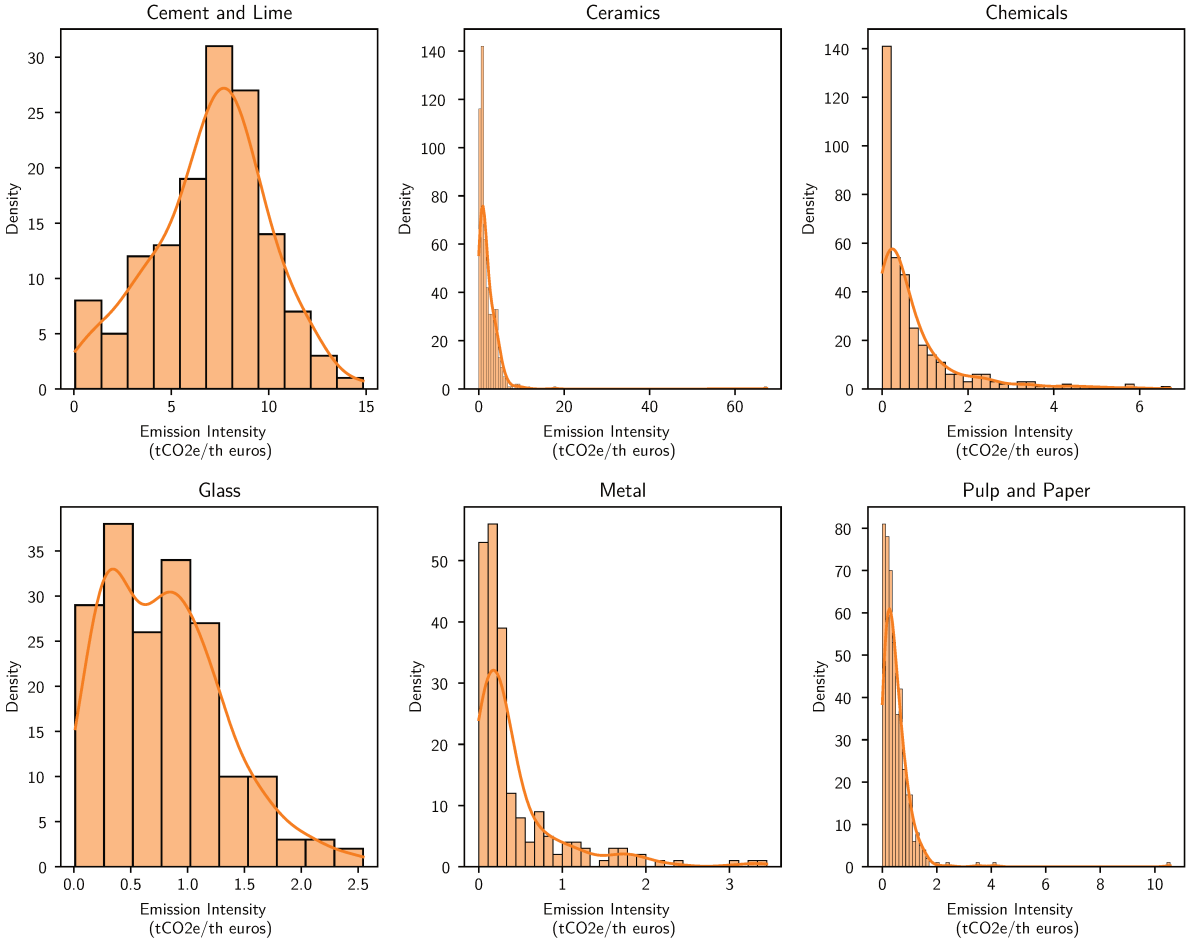


Figure 3.18: Distribution of emission intensity (values)



3.G Multicollinearity checks

Table 3.9: Correlation matrix of key variables

	log EmissIntVol	Opened inst.	Stringency	log Turnover	log Current ratio	log Transaction value
log EmissIntVol	1	.0240528	-.0730757	.3429667	-.0566665	.2079164
Opened inst.	.0240528	1	.007939	.0674004	-.0007898	.061425
Stringency	-.0730757	.007939	1	.0670358	-.0128045	.0681989
log Turnover	.3429667	.0674004	.0670358	1	-.0733747	.4671629
log Current ratio	-.0566665	-.0007898	-.0128045	-.0733747	1	.0112899
log Transaction value	.2079164	.061425	.0681989	.4671629	.0112899	1

Table 3.10: Simple IV regression for VIF computation

	log ROA	log Profit Margin	log EBITDA Margin	log Turnover over costs	log Labor productivity
	(1) 2SLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS
log EmissInt$_{t-1}$ (vol)	0.0522***	0.0191	0.0239**	0.0457***	0.0935***
	(0.00959)	(0.0154)	(0.0100)	(0.00738)	(0.0106)
# opened inst$_{t-1}$	−0.203***	−0.0275	−0.0300	−0.130***	−0.206***
	(0.0202)	(0.0308)	(0.0211)	(0.0156)	(0.0223)
Stringency idx$_{t-1}$	−0.00000309***	0.00000143	0.00000208**	−0.00000228***	−0.000000419
	(0.000000891)	(0.00000126)	(0.000000879)	(0.000000686)	(0.000000983)
log Turnover$_{t-1}$	0.0133*	0.0869***	−0.0293***	−0.215***	0.203***
	(0.00686)	(0.0115)	(0.00744)	(0.00528)	(0.00757)
log Current ratio$_{t-1}$	−0.0783***	0.259***	0.123***	0.0670***	0.00437
	(0.0149)	(0.0252)	(0.0161)	(0.0115)	(0.0164)
logNet transactions (val)$_{t-1}$	−0.00297**	0.00177	0.00312**	−0.000686	−0.00366***
	(0.00120)	(0.00194)	(0.00125)	(0.000926)	(0.00133)
Observations	6021	4577	5380	6021	6021
Firm Controls	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Firm FE	*No*	*No*	*No*	*No*	*No*
Time FE	*No*	*No*	*No*	*No*	*No*
Sector-Time FE	*No*	*No*	*No*	*No*	*No*

Table 3.11: VIF values

	log ROA	log Profit margin	log EBITDA margin	log Turnover over costs	log Labor productivity
log Turnover $_{t-1}$	1.191728	1.140188	1.156539	1.191728	1.191728
log EmissIntVol $_{t-1}$	1.173391	1.121242	1.139218	1.173391	1.173391
Stringency $_{t-1}$	1.019598	1.023702	1.020757	1.019598	1.019598
log Transac. value $_{t-1}$	1.011593	1.01197	1.012304	1.011593	1.011593
Opened inst. $_{t-1}$	1.011431	1.010631	1.012084	1.011431	1.011431
log Current ratio $_{t-1}$	1.010969	1.009439	1.010531	1.010969	1.010969

3.H Supplementary regression results

See next page.

Table 3.12: Regression of financial performance indicators on emission intensity

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EB
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	
log EmissInt_{t-1} (vol)	-0.164^{***}	-0.136^{**}	-0.188	-0.160	
	(0.0572)	(0.0547)	(0.220)	(0.214)	
# opened inst_{t-1}		0.00372		0.0255^{*}	
		(0.00452)		(0.0154)	
Stringency idx_{t-1}		-0.000000819		0.00000528^{***}	
		(0.00000122)		(0.000000846)	
log Turnover_{t-1}		0.229^{***}		0.189	
		(0.0627)		(0.132)	
log $\text{Current ratio}_{t-1}$		-0.0520^{***}		0.0418	
		(0.0151)		(0.0444)	
log$\text{Net transactions (vol)}_{t-1}$		-0.000422		0.000221	
		(0.000432)		(0.00156)	
Observations	5943	5943	4465	4465	5
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
Sector-Time FE	*No*	*No*	*No*	*No*	
First-stage coefficient	0.366^{***}	0.370^{***}	0.316^{***}	0.321^{***}	
K-P rk Wald F-stat	119.831	122.672	71.920	72.920	
A-R Wald test (p-val)	0.004	0.013	0.394	0.455	
HB-corrected p-value	0.021	0.064	0.787	0.906	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.13: Regression of economic performance indicators on emission intensity

	log Labor productivity	log Labor productivity	log Turnover over co
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt$_{t-1}$ (vol)	-0.0946^{*}	-0.0711	0.00566
	(0.0499)	(0.0459)	(0.0524)
# opened inst$_{t-1}$		0.00105	
		(0.00408)	
Stringency idx$_{t-1}$		-0.00000177^{**}	
		(0.000000846)	
log Turnover$_{t-1}$		0.195^{***}	
		(0.0563)	
log Current ratio$_{t-1}$		-0.0419^{***}	
		(0.0144)	
logNet transactions (vol)$_{t-1}$		-0.000464	
		(0.000382)	
Observations	5943	5943	5943
Firm Controls	No	Yes	No
Firm FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Sector-Time FE	No	No	No
First-stage coefficient	0.366^{***}	0.370^{***}	0.366^{***}
K-P rk Wald F-stat	119.831	122.672	119.831
A-R Wald test (p-val)	0.058	0.123	0.914
HB-corrected p-value	0.232	0.485	0.914

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.14: Regression of financial performance indicators on emission intensity

	log ROA	log ROA	log Profit Margin	log Profit Margin	log E
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	
log EmissInt_{t-1} (val)	−0.313**	−0.283**	−0.640	−0.729	
	(0.131)	(0.135)	(0.427)	(0.543)	
# opened inst_{t-1}		0.00332		0.0335*	
		(0.00470)		(0.0174)	
Stringency idx_{t-1}		−0.00000128		0.000000299	
		(0.000000889)		(0.00000169)	
log Turnover_{t-1}		0.0647		−0.357	
		(0.0659)		(0.351)	
log Current ratio_{t-1}		−0.0359**		0.103**	
		(0.0160)		(0.0459)	
logNet transactions $(\text{vol})_{t-1}$		−0.000933**		0.000249	
		(0.000453)		(0.00166)	
Observations	7738	7738	5741	5741	
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	
Sector-Time FE	*No*	*No*	*No*	*No*	
First-stage coefficient	0.172***	0.155***	0.189***	0.158***	
K-P rk Wald F-stat	17.511	12.993	13.984	8.797	
A-R Wald test (p-val)	0.001	0.005	0.064	0.077	
HB-corrected p-value	0.086	0.181	0.400	0.539	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.15: Regression of economic performance indicators on emission intensit

	log Labor productivity	log Labor productivity	log Turnover over co
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt$_{t-1}$ (val)	-0.262^{**}	-0.248^{**}	0.0580
	(0.113)	(0.120)	(0.0730)
# opened inst$_{t-1}$		0.00150	
		(0.00542)	
Stringency idx$_{t-1}$		0.000000856	
		(0.000000654)	
log Turnover$_{t-1}$		0.0439	
		(0.0635)	
log Current ratio$_{t-1}$		-0.0222	
		(0.0148)	
logNet transactions (vol)$_{t-1}$		-0.00103^{**}	
		(0.000415)	
Observations	7738	7738	7738
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.172^{***}	0.155^{***}	0.172^{***}
K-P rk Wald F-stat	17.511	12.993	17.511
A-R Wald test (p-val)	0.003	0.008	0.422
HB-corrected p-value	0.083	0.156	0.853

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.16: Regression of financial performance indicators on emission intensity IV (volum

	log ROA	log ROA	log Profit Margin	log Profit Margin	log E
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	
log EmissInt_{t-1} (vol)	-0.163^{***}	-0.146^{**}	-0.0522	-0.0378	
	(0.0584)	(0.0568)	(0.223)	(0.219)	
log EmissInt_{t-1}(vol) × Post-2018	-0.000383	0.00411	-0.0636^{**}	-0.0593^{**}	
	(0.00710)	(0.00661)	(0.0254)	(0.0249)	
Post-2018	0.0143	-0.0127	-0.171^{***}	-0.190^{***}	
	(0.0138)	(0.0155)	(0.0480)	(0.0514)	
# opened inst_{t-1}		0.00378		0.0244	
		(0.00453)		(0.0155)	
Stringency idx_{t-1}		-0.000000843		0.00000541^{***}	
		(0.00000122)		(0.000000932)	
log Turnover_{t-1}		0.230^{***}		0.167	
		(0.0628)		(0.132)	
log $\text{Current ratio}_{t-1}$		-0.0520^{***}		0.0393	
		(0.0151)		(0.0439)	
log$\text{Net transactions (vol)}_{t-1}$		-0.000426		0.000109	
		(0.000433)		(0.00156)	
Observations	5943	5943	4465	4465	
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	
Sector-Time FE	*No*	*No*	*No*	*No*	
First-stage coefficient	0.461^{***}	0.460^{***}	0.417^{***}	0.418^{***}	
K-P rk Wald F-stat	48.016	49.156	30.431	31.062	
A-R Wald test (p-val)	0.014	0.033	0.032	0.044	
HB-corrected p-value	0.026	0.050	1.000	0.863	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.17: Regression of economic performance indicators on emission intensity IV (volun

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt_{t-1} (vol)	−0.0704	−0.0562	0.0186
	(0.0471)	(0.0436)	(0.0545)
log EmissInt_{t-1}(vol) × Post-2018	−0.00979	−0.00609	−0.00522
	(0.00840)	(0.00801)	(0.00529)
Post-2018	0.0154	−0.00673	0.00250
	(0.0177)	(0.0192)	(0.0114)
# opened inst_{t-1}		0.000956	
		(0.00408)	
Stringency idx_{t-1}		−0.00000174**	
		(0.000000839)	
log Turnover_{t-1}		0.192***	
		(0.0562)	
log Current ratio_{t-1}		−0.0420***	
		(0.0145)	
logNet transactions $(\text{vol})_{t-1}$		−0.000458	
		(0.000382)	
Observations	5943	5943	5943
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.461***	0.460***	0.461***
K-P rk Wald F-stat	48.016	49.156	48.016
A-R Wald test (p-val)	0.137	0.289	0.615
HB-corrected p-value	0.540	0.791	1.000

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.18: Regression of financial performance indicators on emission intensity IV (volumes) x

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBITDA M
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	(5) IV2SLS
log EmissInt_{t-1} (vol)	-0.164^{***}	-0.136^{**}	-0.192	-0.163	-0.107
	(0.0567)	(0.0543)	(0.223)	(0.216)	(0.122)
log EmissInt_{t-1}(vol) × Prod Decrease	0.0195^{***}	0.0159^{**}	0.00214	-0.000982	0.0047
	(0.00635)	(0.00645)	(0.0247)	(0.0251)	(0.0150
Prod Decrease	0.00305	-0.000709	0.0200	0.0183	0.0071
	(0.0101)	(0.0101)	(0.0364)	(0.0370)	(0.0225
# opened inst_{t-1}		0.00337		0.0257^{*}	
		(0.00451)		(0.0154)	
Stringency idx_{t-1}		-0.000000867		0.00000535^{***}	
		(0.00000126)		(0.000000869)	
log Turnover_{t-1}		0.227^{***}		0.190	
		(0.0625)		(0.132)	
log $\text{Current ratio}_{t-1}$		-0.0512^{***}		0.0414	
		(0.0150)		(0.0445)	
log$\text{Net transactions (vol)}_{t-1}$		-0.000427		0.000216	
		(0.000431)		(0.00156)	
Observations	5943	5943	4465	4465	5286
Firm Controls	*No*	*Yes*	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*	*No*	*No*
First-stage coefficient	0.467^{***}	0.469^{***}	0.414^{***}	0.417^{***}	0.430*
K-P rk Wald F-stat	60.278	61.662	35.950	36.377	48.616
A-R Wald test (p-val)	0.001	0.007	0.678	0.727	0.685
HB-corrected p-value	0.019	0.062	0.776	0.898	1.000

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.19: Regression of economic performance indicators on emission intensity IV (volumes) ×

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt_{t-1} (vol)	−0.0946*	−0.0705	0.00610
	(0.0491)	(0.0451)	(0.0522)
log EmissInt_{t-1}(vol) × Prod Decrease	0.00746	0.00433	−0.00354
	(0.00797)	(0.00802)	(0.00583)
Prod Decrease	0.000624	−0.00281	−0.00273
	(0.0130)	(0.0128)	(0.00845)
# opened inst_{t-1}		0.000936	
		(0.00409)	
Stringency idx_{t-1}		−0.00000180**	
		(0.000000833)	
log Turnover_{t-1}		0.194***	
		(0.0563)	
log Current ratio_{t-1}		−0.0415***	
		(0.0144)	
logNet transactions $(\text{vol})_{t-1}$		−0.000464	
		(0.000384)	
Observations	5943	5943	5943
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.467***	0.469***	0.467***
K-P rk Wald F-stat	60.278	61.662	60.278
A-R Wald test (p-val)	0.077	0.218	0.824
HB-corrected p-value	0.217	0.473	0.907

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.20: Regression of financial performance indicators on emission intensity IV x imp

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBITDA M
	(1)	(2)	(3)	(4)	(5)
	IV2SLS	IV2SLS	IV2SLS	IV2SLS	IV2SLS
log EmissInt_{t-1} (vol)	-0.364^{***}	-0.332^{***}	-0.419	-0.397	-0.0400
	(0.106)	(0.0997)	(0.387)	(0.381)	(0.216)
log $\text{EmissInt}_{t-1}\times$ log ImpInt_{t-1} (vol)	-0.0168	-0.0159	0.0375	0.0380	0.0579
	(0.0104)	(0.0102)	(0.0269)	(0.0268)	(0.0179
log ImpInt_{t-1} (vol)	-0.00163	-0.00570	0.0518	0.0512	0.0741
	(0.0331)	(0.0330)	(0.0421)	(0.0420)	(0.0377
# opened inst_{t-1}		-0.00177		0.0318^{**}	
		(0.00629)		(0.0141)	
Stringency idx_{t-1}		-0.000000979		0.00000456^{***}	
		(0.00000116)		(0.00000106)	
log Turnover_{t-1}		0.281^{***}		0.0923	
		(0.0925)		(0.155)	
log Current ratio_{t-1}		-0.0533^{***}		0.00425	
		(0.0157)		(0.0459)	
logNet transactions $(\text{vol})_{t-1}$		-0.000144		-0.00235	
		(0.000536)		(0.00182)	
Observations	4367	4367	3258	3258	3869
Firm Controls	*No*	*Yes*	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*	*No*	*No*
First-stage coefficient	0.515^{***}	0.515^{***}	0.484^{***}	0.485^{***}	0.488^{**}
K-P rk Wald F-stat	24.958	25.468	11.098	11.080	19.580
A-R Wald test (p-val)	0.001	0.002	0.020	0.022	0.000
HB-corrected p-value	0.003	0.004	0.837	0.891	0.853

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.21: Regression of economic performance indicators on emission intensity IV x imp

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1)	(2)	(3)
	IV2SLS	IV2SLS	IV2SLS
log EmissInt_{t-1} (vol)	-0.248^{***}	-0.216^{**}	0.0311
	(0.0933)	(0.0868)	(0.107)
log $\text{EmissInt}_{t-1}\times$ log ImpInt_{t-1} (vol)	−0.0102	−0.00928	−0.00247
	(0.00977)	(0.00965)	(0.0110)
log ImpInt_{t-1} (vol)	−0.0202	−0.0241	−0.0179
	(0.0242)	(0.0243)	(0.0313)
# opened inst_{t-1}		−0.000441	
		(0.00446)	
Stringency idx_{t-1}		-0.00000179^{*}	
		(0.000000946)	
log Turnover_{t-1}		0.278^{***}	
		(0.0712)	
log Current ratio_{t-1}		-0.0502^{***}	
		(0.0165)	
logNet transactions $(\text{vol})_{t-1}$		−0.000198	
		(0.000475)	
Observations	4367	4367	4367
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.515^{***}	0.515^{***}	0.515^{***}
K-P rk Wald F-stat	24.958	25.468	24.958
A-R Wald test (p-val)	0.009	0.016	0.833
HB-corrected p-value	0.032	0.051	1.000

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.22: Regression of financial performance indicators on emission intensity IV x intra-bra

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBITDA M
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	(5) IV2SLS
log EmissInt_{t-1} (vol)	-0.310^{***}	-0.267^{***}	-0.651^{*}	-0.628^{*}	-0.248
	(0.0913)	(0.0861)	(0.357)	(0.348)	(0.201)
log $\text{EmissInt}_{t-1}\times$ log IbInt_{t-1} (vol)	0.0125	0.0114	0.0685^{**}	0.0664^{**}	0.0427
	(0.00894)	(0.00891)	(0.0333)	(0.0322)	(0.0189
log IbInt_{t-1} (vol)	0.0609^{***}	0.0536^{**}	0.192^{**}	0.184^{**}	0.0874
	(0.0215)	(0.0213)	(0.0920)	(0.0895)	(0.0580
# opened inst_{t-1}		-0.000966		0.0363^{**}	
		(0.00602)		(0.0155)	
Stringency idx_{t-1}		-0.000000988		0.00000448^{***}	
		(0.00000117)		(0.00000119)	
log Turnover_{t-1}		0.257^{***}		0.156	
		(0.0795)		(0.143)	
log $\text{Current ratio}_{t-1}$		-0.0519^{***}		0.0602	
		(0.0162)		(0.0507)	
log$\text{Net transactions (vol)}_{t-1}$		-0.000345		-0.00118	
		(0.000509)		(0.00175)	
Observations	4864	4864	3643	3643	4313
Firm Controls	*No*	*Yes*	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*	*No*	*No*
First-stage coefficient	0.396^{***}	0.399^{***}	0.366^{***}	0.367^{***}	0.373**
K-P rk Wald F-stat	34.858	35.717	16.137	16.178	27.085
A-R Wald test (p-val)	0.000	0.000	0.011	0.011	0.018
HB-corrected p-value	0.003	0.010	0.204	0.213	0.432

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.23: Regression of economic performance indicators on emission intensity IV x intra-bra

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt_{t-1} (vol)	−0.275***	−0.235***	−0.0432
	(0.0838)	(0.0782)	(0.0846)
log EmissInt_{t-1}× log IbInt_{t-1} (vol)	−0.00708	−0.00835	0.00199
	(0.0130)	(0.0130)	(0.00750)
log IbInt_{t-1} (vol)	0.00188	−0.00564	0.0113
	(0.0327)	(0.0324)	(0.0180)
# opened inst_{t-1}		−0.000131	
		(0.00444)	
Stringency idx_{t-1}		−0.00000189*	
		(0.000000985)	
log Turnover_{t-1}		0.249***	
		(0.0641)	
log Current ratio_{t-1}		−0.0430***	
		(0.0156)	
logNet transactions $(\text{vol})_{t-1}$		−0.000236	
		(0.000447)	
Observations	4864	4864	4864
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.396***	0.399***	0.396***
K-P rk Wald F-stat	34.858	35.717	34.858
A-R Wald test (p-val)	0.000	0.001	0.712
HB-corrected p-value	0.004	0.011	0.610

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.24: Regression of financial performance indicators on emission intensit

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBI
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	
log EmissInt_{t-1} (vol)	0.0553	0.0306	−0.0166	−0.0302	
	(0.0338)	(0.0295)	(0.0631)	(0.0612)	
# opened inst_{t-1}		0.00448		0.0377**	
		(0.00396)		(0.0162)	
Stringency idx_{t-1}		−0.00000120		0.00000455***	
		(0.00000126)		(0.000000903)	
log Turnover_{t-1}		0.207***		0.161	
		(0.0628)		(0.134)	
log $\text{Current ratio}_{t-1}$		−0.0464***		0.0384	
		(0.0152)		(0.0442)	
log$\text{Net transactions (vol)}_{t-1}$		−0.000518		−0.000735	
		(0.000431)		(0.00160)	
Observations	6021	6021	4577	4577	53
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
Time FE	*No*	*No*	*No*	*No*	
Sector-Time FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
HB-corrected p-value	0.507	1	1	1	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.25: Regression of economic performance indicators on emission intensit

	log Labor productivity	log Labor productivity	log Turnover ove
	(1) OLS	(2) OLS	(3) OLS
log EmissInt_{t-1} (vol)	0.0241	0.00177	−0.0026
	(0.0249)	(0.0239)	(0.0176
# opened inst_{t-1}		−0.000951	
		(0.00387)	
Stringency idx_{t-1}		−0.00000232**	
		(0.000000958)	
log Turnover_{t-1}		0.185***	
		(0.0589)	
log Current ratio_{t-1}		−0.0378***	
		(0.0144)	
log$\text{Net transactions (vol)}_{t-1}$		−0.000455	
		(0.000379)	
Observations	6021	6021	6021
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*No*	*No*	*No*
Sector-Time FE	*Yes*	*Yes*	*Yes*
HB-corrected p-value	1	0.941	0.883

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.26: Regression of financial performance indicators on emission intensi

	log ROA	log ROA	log Profit Margin	log Profit Margin	log E
	(1)	(2)	(3)	(4)	
	OLS	OLS	OLS	OLS	
log EmissInt_{t-1} (val)	−0.0412*	−0.0127	−0.0232	−0.00855	
	(0.0240)	(0.0203)	(0.0397)	(0.0415)	
# opened inst_{t-1}		0.00624		0.0409**	
		(0.00451)		(0.0166)	
Stringency idx_{t-1}		−0.00000139**		−0.000000523	
		(0.000000657)		(0.00000129)	
log Turnover_{t-1}		0.175***		0.0859	
		(0.0469)		(0.117)	
log Current ratio_{t-1}		−0.0385***		0.0854**	
		(0.0140)		(0.0415)	
logNet transactions $(\text{vol})_{t-1}$		−0.00109***		−0.00184	
		(0.000402)		(0.00145)	
Observations	7861	7861	5893	5893	
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	
Time FE	*No*	*No*	*No*	*No*	
Sector-Time FE	*Yes*	*Yes*	*Yes*	*Yes*	
HB-corrected p-value	0.346	1	1	1	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values
for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.27: Regression of economic performance indicators on emission intens

	log Labor productivity	log Labor productivity	log Turnover ove
	(1)	(2)	(3)
	OLS	OLS	OLS
log EmissInt_{t-1} (val)	-0.0516^{**}	-0.0307	0.0368
	(0.0244)	(0.0197)	(0.0225)
# opened inst_{t-1}		0.00181	
		(0.00533)	
Stringency idx_{t-1}		0.000000732	
		(0.000000624)	
log Turnover_{t-1}		0.131^{***}	
		(0.0457)	
log Current ratio_{t-1}		-0.0248^{*}	
		(0.0132)	
logNet transactions $(\text{vol})_{t-1}$		-0.00113^{***}	
		(0.000380)	
Observations	7861	7861	7861
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*No*	*No*	*No*
Sector-Time FE	*Yes*	*Yes*	*Yes*
HB-corrected p-value	0.172	0.591	0.305

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.28: Regression of financial performance indicators on emission intensity IV x im

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBI
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS	(4) IV2SLS	I
log EmissInt_{t-1} (val)	−0.301*	−0.278*	−0.513	−0.620	
	(0.159)	(0.160)	(0.466)	(0.575)	
log EmissInt_{t-1}× log ImpInt_{t-1} (val)	−0.0152	−0.0139	−0.0368	−0.0422	
	(0.00973)	(0.00976)	(0.0320)	(0.0366)	
log ImpInt_{t-1} (val)	−0.124*	−0.117*	−0.288	−0.321	
	(0.0690)	(0.0693)	(0.210)	(0.238)	
# opened inst_{t-1}		0.000519		0.0380**	
		(0.00510)		(0.0183)	
Stringency idx_{t-1}		−0.000000898		−0.000000973	
		(0.00000112)		(0.00000173)	
log Turnover_{t-1}		0.0637		−0.460	
		(0.0716)		(0.368)	
log Current ratio_{t-1}		−0.0306*		0.0610	
		(0.0185)		(0.0456)	
logNet transactions $(\text{vol})_{t-1}$		−0.000798		−0.00244	
		(0.000518)		(0.00182)	
Observations	5838	5838	4300	4300	5
Firm Controls	*No*	*Yes*	*No*	*Yes*	
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	Y
Sector-Time FE	*No*	*No*	*No*	*No*	
First-stage coefficient	0.491***	0.476***	0.501***	0.467***	
K-P rk Wald F-stat	6.143	5.023	5.725	3.727	
A-R Wald test (p-val)	0.065	0.097	0.466	0.456	
HB-corrected p-value	0.291	0.407	0.542	0.562	

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.29: Regression of economic performance indicators on emission intensity IV x im

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1)	(2)	(3)
	IV2SLS	IV2SLS	IV2SLS
log EmissInt_{t-1} (val)	−0.127	−0.110	0.159
	(0.121)	(0.122)	(0.107)
log EmissInt_{t-1}× log ImpInt_{t-1} (val)	0.000269	0.00114	0.00569
	(0.00933)	(0.00932)	(0.00910)
log ImpInt_{t-1} (val)	−0.0276	−0.0238	0.0207
	(0.0618)	(0.0619)	(0.0771)
# opened inst_{t-1}		0.00124	
		(0.00528)	
Stringency idx_{t-1}		0.000000477	
		(0.000000685)	
log Turnover_{t-1}		0.101	
		(0.0688)	
log Current ratio_{t-1}		−0.0249	
		(0.0173)	
logNet transactions $(\text{vol})_{t-1}$		−0.000865*	
		(0.000441)	
Observations	5838	5838	5838
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.491***	0.476***	0.491***
K-P rk Wald F-stat	6.143	5.023	6.143
A-R Wald test (p-val)	0.336	0.389	0.205
HB-corrected p-value	0.297	0.369	0.415

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.30: Regression of financial performance indicators on emission intensity IV x intra-bra

	log ROA	log ROA	log Profit Margin	log Profit Margin	log EBITDA
	(1)	(2)	(3)	(4)	(5)
	IV2SLS	IV2SLS	IV2SLS	IV2SLS	IV2SLS
log EmissInt_{t-1} (val)	-0.293^{**}	-0.265^{**}	-0.332	-0.385	0.31
	(0.124)	(0.126)	(0.374)	(0.453)	(0.16
log $\text{EmissInt}_{t-1}\times$ log IbInt_{t-1} (val)	-0.0106	-0.00964	0.0898^{*}	0.0900	0.06
	(0.0165)	(0.0155)	(0.0537)	(0.0556)	(0.03
log IbInt_{t-1} (val)	-0.0271	-0.0218	0.669	0.672	0.48
	(0.105)	(0.0987)	(0.415)	(0.431)	(0.26
# opened inst_{t-1}		0.00157		0.0383^{**}	
		(0.00485)		(0.0177)	
Stringency idx_{t-1}		-0.00000129		$-8.26e-09$	
		(0.000000854)		(0.00000160)	
log Turnover_{t-1}		0.0615		-0.299	
		(0.0642)		(0.310)	
log $\text{Current ratio}_{t-1}$		-0.0317^{*}		0.111^{**}	
		(0.0173)		(0.0489)	
log$\text{Net transactions (vol)}_{t-1}$		-0.000936^{*}		-0.00153	
		(0.000500)		(0.00171)	
Observations	6447	6447	4760	4760	5654
Firm Controls	*No*	*Yes*	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*	*No*	*No*
First-stage coefficient	0.439^{***}	0.425^{***}	0.464^{***}	0.434^{***}	0.44
K-P rk Wald F-stat	10.148	7.725	9.579	6.180	9.58
A-R Wald test (p-val)	0.013	0.031	0.125	0.131	0.06
HB-corrected p-value	0.092	0.175	0.374	0.790	0.15

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Table 3.31: Regression of economic performance indicators on emission intensity IV x intra-br

	log Labor productivity	log Labor productivity	log Turnover over costs
	(1) IV2SLS	(2) IV2SLS	(3) IV2SLS
log EmissInt_{t-1} (val)	−0.204*	−0.193*	0.0784
	(0.104)	(0.109)	(0.0676)
log EmissInt_{t-1}× log IbInt_{t-1} (val)	0.00971	0.00945	0.0143*
	(0.0132)	(0.0128)	(0.00787)
log IbInt_{t-1} (val)	0.0846	0.0817	0.0966*
	(0.0867)	(0.0838)	(0.0550)
# opened inst_{t-1}		0.00132	
		(0.00551)	
Stringency idx_{t-1}		0.000000826	
		(0.000000643)	
log Turnover_{t-1}		0.0560	
		(0.0627)	
log Current ratio_{t-1}		−0.0176	
		(0.0163)	
logNet transactions $(\text{vol})_{t-1}$		−0.000922**	
		(0.000450)	
Observations	6447	6447	6447
Firm Controls	*No*	*Yes*	*No*
Firm FE	*Yes*	*Yes*	*Yes*
Time FE	*Yes*	*Yes*	*Yes*
Sector-Time FE	*No*	*No*	*No*
First-stage coefficient	0.439***	0.425***	0.439***
K-P rk Wald F-stat	10.148	7.725	10.148
A-R Wald test (p-val)	0.001	0.003	0.158
HB-corrected p-value	0.205	0.227	0.493

Notes: Standard errors are in parenthesis, clustered at the firm level. Holm-Bonferroni-corrected p-values for the Emission Intensity coefficient.

* p<0.10, ** p<0.05, *** p<0.01

Chapter 4

Green on paper? The effect of green patents on EU ETS firms

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Abstract

On On 29 January 2025, the European Commission unveiled the Competitiveness Compass, a set of policy guidelines that highlights the need to align industrial decarbonization and long-term competitiveness. While existing literature recognizes the importance of innovation to develop or scale up low-carbon technologies, the link between firm-level green inventions and their real-world impacts on technological change, efficiency and emission levels has largely been overlooked. This paper investigates this relationship in the context of heavy industry firms regulated by the European Union Emissions Trading System from 2013 to 2020. In a first stage, efficiency and technological progress are assessed using a Technological Frontier Analysis, applied to emissions data from the EU Transaction Log and financial and operational data from ORBIS. In a second stage, a firm-level panel econometric model evaluates the effects of green patenting—measured using PATSTAT data—on firms' efficiency and technological progress. The results reveal a paradox: firms engaging in green patenting are, on average, less likely to contribute to technological change in their sector than non-green-patenting firms. This suggests that carbon-intensive technological lock-in may constrain the transformative impact of green innovation, allowing firms using conventional technologies to achieve greater performance gains from their innovative activities.

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This chapter was co-authored with Sylvain Belrose and Marc Baudry.

Chapter dissemination

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4.1 Introduction

On 29 January 2025, the European Commission unveiled the Competitiveness Compass, a set of policy guidelines aimed at "reigniting economic dynamism in Europe" (European Commission, 2025b). A central pillar of this initiative is the creation of a joint road map that aligns industrial decarbonization with long-term competitiveness. This vision was formalized in the Clean Industrial Deal, which identifies heavy industry as one of two priority sectors requiring policy intervention to support the EU's climate and competitiveness objectives (European Commission, 2025a). These recent policy developments underscore the challenge policymakers are facing to design decarbonization policies without harming the industrial sector's competitiveness in a globally fragmented climate policy context.

A major barrier preventing heavy industry from significantly decarbonizing without policy intervention is that most low-carbon technologies are either not yet market-ready or are more expensive than their business-as-usual counterparts (Diesing et al., 2025; International Energy Agency, 2024; IPCC, 2023). This highlights the need for investments in low-carbon innovation to develop or scale up the industrial technologies needed for the transition. The EU's carbon market—the EU Emissions Trading Scheme (EU ETS)—recognizes this and aims to spur low-carbon innovation through market-based incentives (European Parliament and Council, 2003).

Designing effective policies that promote green innovation and industrial decarbonization while maintaining competitiveness requires a nuanced understanding of how these objectives interact, and of the policy instruments capable of shaping their alignment. A deeper grasp of industrial production systems can allow policymakers to design interventions that are both well-targeted and efficient—ensuring that they support climate goals while remaining compatible with the physical science and security requirements inherent to many industrial processes and products (Dakpo et al., 2016; Diesing et al., 2025; Morfeldt & Silveira, 2014).

Building on this need for a better understanding of industrial production systems in view of decarbonization, this paper contributes to the research on directed technical change and the impact of the EU ETS in heavy industry by addressing a key gap in the literature: the missing link between green inventions and actual firm-level decarbonization and production outcomes. While prior studies have established that the EU ETS has spurred low-carbon patenting activity (Calel, 2020; Calel & Dechezleprêtre, 2014), and others have assessed general trends in technical change within EU ETS sectors (Dzemydaitė & Naruševičius, 2023; Morfeldt & Silveira, 2014), there remains limited evidence

on whether such patented inventions have translated into measurable emission reductions or efficiency gains.

This study complements and extends the existing literature by jointly analyzing technical and climate efficiency at the firm level among industrial firms regulated under the EU ETS' third phase (2013–2020). Applying a Technological Frontier approach, the analysis goes beyond identifying innovation signals to evaluate whether firms that engage in low-carbon patenting are also those that shift or approach the technological frontier. In doing so, the paper provides new insights into the effectiveness of patented inventions to transform heavy industry production systems. This can help policymakers to better target innovation policies towards firms that have not been able to innovate so far and investment policies towards firms that struggle to transform their inventions into tangible efficiency gains.

The choice of employing a Technological Frontier Analysis (TFA) stems from this methodology's capacity to model the joint production of industrial products (like cement or steel) and emissions. This reflects the fact that emissions are an inevitable and undesirable by-product of industrial processes (Färe et al., 2005). This paper uses data on firm-level emissions from the EU Transaction Log and on financial and operational data from ORBIS to run a TFA via a deterministic linear-quadratic minimization program. The TFA is applied to a sample of around 900 firms in 17 heavy industry sectors. This yields a measure of sector-level technological frontiers. These frontiers represent the best available performance within a sector. A firm's distance to the frontier is taken as a measure of its relative efficiency within its sector. In a second step, patent data is added and used to run a firm-level panel econometric analysis in which a firm's distance to the frontier is explained by firm characteristics and patenting behavior.

The TFA in this paper highlights two main insights into EU ETS sectors' efficiency and technological patterns. First, the level of dispersion in firm-level efficiency varies widely across sectors. Sectors like paper, chemicals, and non-metallic minerals display significant heterogeneity in their firms' efficiency levels, while firms in sectors such as cement and steel produced via electric arc furnaces (EAF) are more uniform. Second, technological frontier displacement—used here as a proxy for technological progress—is highly concentrated among a few firms, often the same ones year after year. These findings reveal the uneven pace of progress and point to the potential of targeted policies to boost lagging firms.

Our second-stage econometric analysis finds that firms that file green patents become less efficient than their competitors. The most plausible explanation for this is that brown innovation in heavy industry benefits from decades of research and technological lock-in, while green innovation has a large research gap to make up for. As a result, firms diverting

resources from brown innovation to green innovation lose out to firms that are pushing the technological frontier faster by continuing their investments in brown technologies. This is in line with the mechanisms of innovation path dependency as theorized by Acemoglu et al. (2012) and empirically studied by Aghion et al. (2016). We highlight further research avenues that could be pursued to strengthen this claim in our discussion.

The rest of this paper is organized as follows. Section 4.2 reviews the literature that relates to innovation, the EU ETS, and technical efficiency. Section 4.3 presents the theoretical framework of technological frontiers as it is applied in this paper. Section 4.4 and Section 4.5 respectively present the data and empirical approach that are used. Section 4.6 presents the results from our two-stage analysis, which Section 4.7 discusses. Finally, Section 4.8 concludes and presents avenues for future research.

4.2 Related literature

4.2.1 Directed technical change

One of the core objectives of the EU ETS is to "encourage the use of more energy-efficient technologies", as outlined in its founding directive (European Parliament and Council, 2003). Since the market's launch in 2005, policy reforms have further institutionalized this objective and leveraged the transition from free allocation of allowances to auctioning as the default allocation mode. These reforms include (1) the earmarking of some of the revenues from auctioning allowances to the Innovation Fund, which channels funds into large-scale low-carbon projects, and (2) requirements that Member States reinvest national ETS revenues into climate adaptation and mitigation, with a focus on research and innovation (European Commission, 2023a; European Parliament and Council, 2024).

This objective is in line with the idea known as directed technical change, which posits that the direction of innovation responds to economic incentives (Hicks, 1932). In the case of climate change mitigation, instruments like the EU ETS create incentives for firms to reduce their emissions by imposing a price on carbon (Porter & van der Linde, 1995). This type of directed technical change is a necessary (but insufficient) condition to meet climate objectives (Bataille et al., 2018; IPCC, 2023). However, decades of climate inaction have entrenched a brown technological lock-in—a situation where industrial systems, infrastructure, and knowledge bases are deeply embedded in fossil-fuel technologies. This lock-in creates structural inertia which makes it difficult for green innovation to compete without targeted support. Empirical studies have found evidence of carbon-intensive technology lock-in in the automobile (Aghion et al., 2016) and chemicals

industries (Janipour et al., 2020) for instance. To break this cycle, complementary policies like innovation subsidies are essential (Acemoglu et al., 2012).

4.2.2 Trends in EU ETS sectors' technical change

Some studies document technical change trends in EU ETS-regulated sectors without making a causal claim about the policy's impacts. The most comprehensive multi-sector analysis of this sort, Baudry and Faure (forthcoming), applies a linear-quadratic minimization framework to nine four-digit NACE sectors (iron and steel, cement, flat glass, hollow glass, ceramic tiles, ceramic bricks, pulp, paper, and chemicals) from 2012–2021. Calibrating sector-specific annual frontiers for 249 EU ETS firms, they categorize sectors as exhibiting non-directed technological change (iron and steel, flat and hollow glass, ceramic tiles, and chemicals), weakly directed technical change—meaning that firms reduced their carbon intensity but increased total emissions through output growth (cement, pulp, ceramic bricks)—or indeterminate technological change due to a high level of heterogeneity between firms (paper).

Sector-specific papers further study these trends. For iron and steel, Morfeldt and Silveira (2014) use a DEA-based Malmquist index to distinguish technical change (innovation-driven efficiency gains) from energy efficiency (firms' average distance to best practices) across 15 EU countries from 1992–2010. While technological progress occurred, energy efficiency gaps widened between frontier and lagging producers. In the Swedish pulp and paper sector, Bostian et al. (2018) find productivity declines between 2002 and 2008 when emissions are accounted for in the DEA frontier. For chemicals, Dzemydaitė and Naruševičius (2023) highlight robust technological progress (2000–2019) measured via Stochastic Frontier Ananlysis (SFA). Oggioni et al. (2011) attribute stable efficiency gains in EU cement (2005–2008) to advanced kilns and alternative fuels but do not disentangle EU ETS incentives from other drivers. Overall, there is little recent evidence on firm-level technical change across all heavy industry sectors covered by the EU ETS.

4.2.3 Has the EU ETS caused directed technical change?

A separate strand of literature evaluates whether the EU ETS *caused* directed technical change, with two main approaches. The first group assesses the EU ETS' impact on TFA-based measures of technological progress, while the second group does so on proxies of technological progress, namely patents and investments in research and development.

Within the first group, Löschel et al. (2019) perform a difference-in-differences analysis on 473 EU ETS-regulated firms and 35,122 non-EU ETS firms in Germany (2003–

2012). They apply an SFA to estimate sector-specific economic efficiency frontiers for the entire period. Efficiency improvements are measured as the reduction of a firm's distance to the frontier over time. While EU ETS firms initially lagged in efficiency, their median distance to the frontier decreased by 2012—notably in the paper sector—while non-ETS firms showed no improvement. The authors show that the EU ETS improved economic efficiency. However, their methodology only allows them to measure general technological progress, without commenting on its direction with regards to emission efficiency. Contrary to this result, Lundgren et al. (2015) assess 90 Swedish firms (1998–2008) and find that CO_2 taxes and the EU ETS had negligible or negative effects on productivity, but that fossil fuel prices spurred stronger incentives for efficiency gains through technological progress. They are able to decompose efficiency gains from technological change by computing a Luenberger Total Factor Productivity indicator. This indicator defines technological change as the displacement of the technological frontier from one year to the next and efficiency gains as the change in firms' distance to the frontier from one year to the next.

Within the second strand of literature, researchers have exploited the EU ETS' installation-level inclusion criteria to assess the market's causal impact on patents or investments in research and development—used as proxies for technological change. Calel (2020) adopt this approach on a panel of British firms and find that the EU ETS has encouraged low-carbon patenting and spending in research and development between 2005 and 2012. Applying a similar approach on a panel of around 3,500 firms, Calel and Dechezleprêtre (2014) find that the EU ETS increased low-carbon patenting in regulated firms by as much as 10% from 2005 to 2009. While this research points in the direction of directed technical change induced by the EU ETS, there is one significant limitation: low-carbon patents indicate that a firm has invented a new process or product, but not that it has implemented this invention in its production process (making it an innovation), nor that this implementation has effectively reduced emissions or emission intensity.

This paper aims to complement the existing literature highlighted in this section by providing an analysis of technical change in EU ETS firms and by studying whether low-carbon patenting by EU ETS firms has led improvements in emission and production efficiency. We now turn to the theoretical framework that allows us to measure firm-level efficiency accounting both for technical and emission parameters.

4.3 Theoretical framework

4.3.1 Technological frontiers

We apply the theoretical framework of technological frontiers, first formalized by Shephard (1970) and later generalized by Chambers et al. (1998). A technological frontier represents a firm's maximum attainable output with a given set of inputs if the firm is fully efficient. A firm's inefficiency is therefore measured as its distance to the technological frontier. Following Färe et al. (2005), we examine a setting where firms produce both a desirable and an undesirable output.

General setup. We consider $\sum_{s=1}^{S} N_s$ firms in S sectors over T time periods (years). Firm i ($i = 1, ..., N_s$) in sector s ($s = 1, ..., S$) produces $O = 2$ types of outputs Y_o at time t ($t = 1, ..., T$): one good output Y_g (production of an industrial good such as cement) and one bad output Y_b (CO_2 emissions). The bad output is an undesirable side effect of production. The output of firm i at time t is a O-dimensional vector given by: $Y_{it} = (Y_{itg}, Y_{itb})' \in \Re_+^O$.

Firm i uses $Q = 3$ inputs X_q for its production: capital X_k, labor X_l, and material inputs X_m (which include energy and raw materials). The inputs used by firm i at time t are a Q-dimensional vector given by: $X_{it} = (X_{itk}, X_{itl}, X_{itm})' \in \Re_+^Q$.

Firm i transforms the vector of inputs X_{it} into the vector of outputs Y_{it} by using a production technology P that is common to all firms within a sector s (Färe et al., 2005). All the equations that follow are given for a specific sector s. To simplify notations, we forego the s subscript in the rest of this section.

Production technology. The production technology P is defined as:

$$P(X_{it}) = \{Y_{it} : X_{it} \text{ can produce } Y_{it}\} \tag{4.1}$$

This specification follows a set of standard neoclassical micro-economic assumptions, augmented to account for joint production of desirable and undesirable outputs (Färe et al., 2005; Shephard & Färe, 1974; Shephard, 1970). For notational simplicity, we omit firm i and time t subscripts when presenting these assumptions below, though all properties hold for each firm-period observation.

- **Inputs are strongly and freely disposable**, meaning that a firm cannot decrease its output level if it does not also decrease its input level:

$$\text{If } X' \geq X \text{ then } P(X') \subseteq P(X) \tag{4.2}$$

- **Null-jointness of Y_g and Y_b**, meaning that a firm cannot produce any level of the good output without also producing some amount of the bad output:

$$\text{If } (Y_g, Y_b) \in P(X) \text{ and } Y_b = 0 \text{ then } Y_g = 0 \tag{4.3}$$

- **Good and bad outputs together are weakly disposable**, meaning that for a given level of X, cutting down proportionally on Y_b and Y_g is technologically feasible (the decrease in Y_g represents the cost of cutting down on Y_b):

$$\text{If } (Y_g, Y_b) \in P(X) \text{ and } 0 \leq \zeta \leq 1 \text{ then } (\zeta Y_g, \zeta Y_b) \in P(X) \tag{4.4}$$

- **Good outputs are strongly disposable**, meaning that the firm can dispose of the good output at no cost:

$$\text{If } (Y_g, Y_b) \in P(X) \text{ and } (Y'_g, Y_b) \leq (Y_g, Y_b) \text{ then } (Y'_g, Y_b) \in P(X) \tag{4.5}$$

To further explain the characteristics of the technological frontier framework, we turn to a graphical representation (Figure 4.1). The technological frontier is represented by the solid line.[1] Firms' inputs have been normalized to an equal amount and each dot represents the level of good and bad outputs that each firm produces given this normalized amount of inputs.

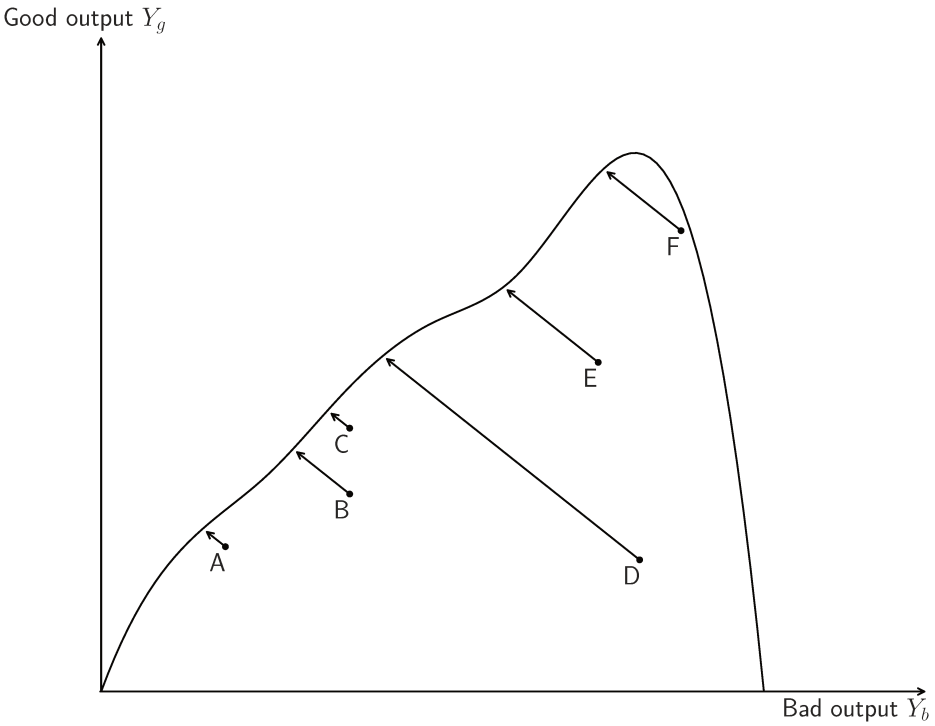
4.3.2 Efficiency

Broadly speaking, efficiency can be understood as firms' capacity to use the lowest amount of inputs (resources) to produce the largest amount of outputs. In practice, efficiency is measured either as an input-oriented measure or an output-oriented measure. Input-oriented efficiency measures the extent to which a firm could reduce its use of inputs and still be able to produce the same level of output. Output-oriented efficiency is the opposite, meaning the extent to which a firm could expand its level of output without using more inputs. Both measures are relative to the best-performing firms in a sector (Bogetoft & Otto, 2011).

In this paper, efficiency has to integrate both a good and a bad output. We therefore use an output-oriented measure of efficiency, defined as a firm's capacity to produce the largest amount of good outputs, while producing the smallest amount of bad outputs, with a fixed level of inputs.

[1]The technological frontier has an inverse-U shape for three reasons: (1) the assumption of null-jointness of Y_g and Y_b imposes that it passes through $(0, 0)$; (2) it must be above or equal to all firms' outputs; (3) the assumption that Y_g is strongly disposable means that it passes through $(\max(Y_b), 0)$.

Figure 4.1: Representation of an output-oriented technological frontier



Source: Authors.

To integrate both a good and a bad output, we use the concept of Shephard's distance applied to an output-oriented efficiency (Shephard, 1970). Shephard's distance measures how far each firm is from its sector's technological frontier. The further away a firm is from the frontier, the higher its inefficiency. The solid arrows going from the firm-level observations to the frontier in Figure 4.1 illustrate this measure of inefficiency. Formally, Shephard's distance is defined as a directional distance function

$$\overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; v_g, -v_b) = \max\{\phi : Y_{itg} + \phi v_g; Y_{itb} - \phi v_b) \in P(X_{it})\} \tag{4.6}$$

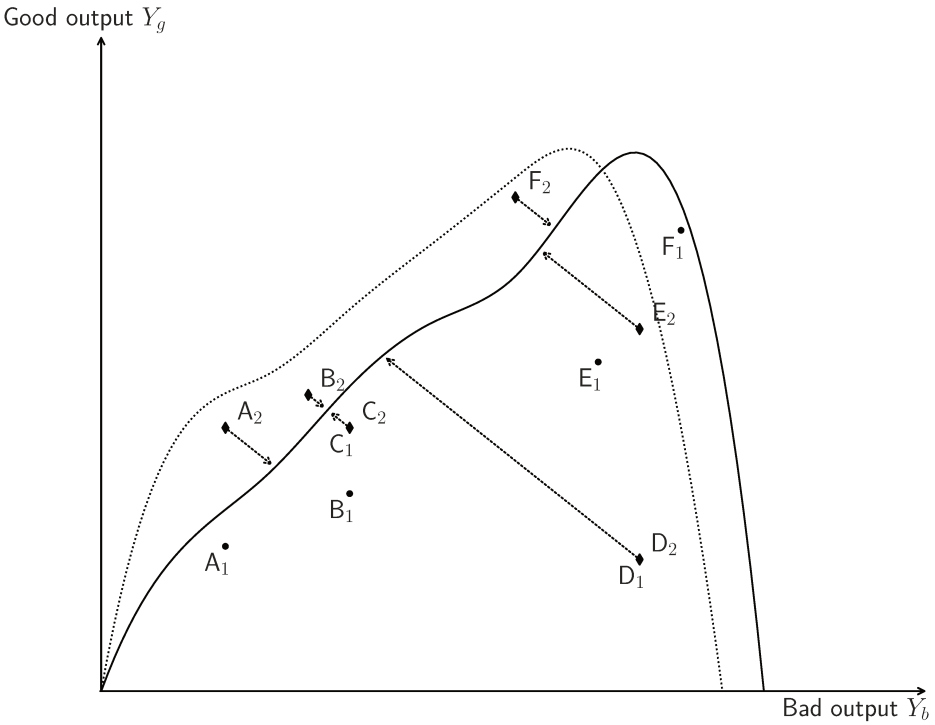
where ϕ represents the most the good output can grow (or the bad output can shrink) based on a plant's technology, moving in a specific direction defined by $v = (v_g, -v_b)$, where v represents the direction for good outputs (v_g) and bad outputs (v_b).

4.3.3 Technological progress

In this framework, technological progress occurs when the production frontier shifts upward from one period to the next (represented by the dashed frontier line in Figure 4.2). This shift reflects an expansion of production possibilities.

Our focus is on identifying the firm-level drivers of technological progress. Specifically, we aim to pinpoint which firms are responsible for pushing the frontier outward. To do this, we compute each firm's position relative to the $t-1$ frontier (represented as the diamonds in Figure 4.2) by evaluating its t-period inputs and outputs against the frontier's $t-1$ coefficients. This also allows us to compute a firm's distance to the $t-1$ frontier (represented as the dotted arrows in Figure 4.2). If a firm's production lies beyond the $t-1$ frontier, it has contributed to displacing the frontier outward in period t (for example, firms A, B and F in Figure 4.2) and has a negative value for its distance. If it lies below the frontier, it has not driven technological progress (for example, firms C, D and E in Figure 4.2) and has a positive value for its distance.

Figure 4.2: Representation of frontier displacement



Source: Authors.

4.4 Data

4.4.1 Data sources

Three main databases were merged to provide data on firm-level climate and economic variables: Moody's ORBIS database,[2] the EU Transaction Log (EUTL),[3] and the European Patent Office's (EPO) PATSTAT database.[4]

ORBIS is a proprietary dataset that includes around 550 million businesses throughout the world. It harmonizes financial information into a uniform global template, enabling comparisons between countries. The EUTL, managed by the European Commission, serves as the primary system for reporting and tracking all EU ETS compliance and transaction information. It provides public access to GHG emission compliance data for installations covered by the EU ETS. PATSTAT is a proprietary database compiled by the EPO. It provides patent data at the firm level from patent offices in major industrialized and developing countries and includes bibliographical and legal information.

4.4.2 Data preparation

Data cleaning

EUTL We use the data files provided by Abrell (2022).[5] We implement the following steps to clean these files for the purpose of our analysis. First, we remove all observations lacking company registration numbers and entries from the Swiss ETS (CH ETS). Second, we discard entries not reporting Operator Holding Accounts, as well as those with "Aircraft operator activities" as their installation activity. Finally, we exclude account holders without any corresponding installations.

ORBIS We follow recommendations from Gal (2013), Gopinath et al. (2017), and Kalemli-Ozcan et al. (2015) to ensure that we eliminate all observations without sufficient data quality from our sample. In particular, we drop all observations that meet the following criteria:

[2] https://www.moodys.com/web/en/us/capabilities/company-reference-data/orbis.html
[3] https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1
[4] https://www.epo.org/en/searching-for-patents/business/patstat
[5] Abrell (2022) scraped the data from the EUTL and compiled it into a relational database made up of various CSV files. These files, along with documentation on Abrell's work and output are available for download at the following website: https://www.euets.info/download/

- Missing any of the following variables: total assets, turnover, sales, cost of employees, tangible fixed assets, material costs

- Any of the following variables are negative: total assets, number of employees, sales, tangible fixed assets, material costs, operating revenue

- Any of the following variables are equal to zero: material costs, total assets, tangible fixed assets, number of employees or operating revenue

Additionally, we deflate all the data reported in euros in ORBIS. Following Curzi et al. (2021), we deflate turnover with Eurostat's output price index data series and tangible fixed assets with Eurostat's implicit deflator for fixed assets data series. Both of these data series come from national accounts data. Labor costs are deflated using Eurostat's labor cost index for wages and salaries data series. Material costs are deflated through a combined index, computed as the simple average of price indexes for natural gas and metals from the IMF, and electricity prices from Eurostat.[6]

Finally, following Cameron and Garrone (2024), we keep only firms whose main activity as stated by its ORBIS NACE code is an activity regulated by the EU ETS. This is to ensure better compatibility between ORBIS and EUTL data.

PATSTAT To assess the level of patented inventions among EU ETS firms, we exploit the EPO's PATSTAT database. Patents signal novel and significant advances over the current state of the art in technology and confer exclusive industrialization and commercial rights within the relevant jurisdiction.

To avoid double counting of the same invention filed in multiple jurisdictions, we rely on observations at the patent family level (defined as the INPADOC family classification).[7] Since our focus is on inventions within EU member states, we only consider patents filed with the EPO, or, in the absence of such, with a national office of an EU ETS country.

[6]Data codes are the following for Eurostat data series: "NAMA_10_A64" for the output price index series, "NAMA_10_AN6" for the implicit deflator for fixed assets deflator series, "LC_LCI_R2_A" for the labor cost index data series, and "TEN00117" for the electricity price data series. All of these data series are provided for industry only (NACE code D) and by country and year. The IMF data for natural gas and metal price indexes are taken from the Primary Commodity Price Systems database. The natural gas data is provided as an EU average and the metal data is provided as a world average. Both are for all sectors of the economy.

[7]An extended patent family is a collection of patent documents covering a technology. The technical content covered by the applications is similar, but not necessarily the same. See Martinez (2010) and the EPO's website for a complete discussion on the use of patent families: https://www.epo.org/en/searching-for-patents/helpful-resources/first-time-here/patent-families/inpadoc

We define the date of invention as the filing date, which better reflects the timing of inventive activity than the grant date. We do not restrict the dataset to granted patents, to capture early-stage inventions and avoid truncation biases in recent years.

We construct two different measures of patent counts. One is a stock value and the other is a flow value. The stock value begins in the first year of our sample (2013) and is a cumulative count of the patents filed since then. We do not include the stock before 2013 because it does not vary over time and is therefore accounted for in our firm-level fixed effects. The patent flow value is the simple count of patents filed in a single year.

Patent families are classified either as "Low-carbon" or "Not low-carbon" in our data. This is determined based on the Cooperative Patent Classification (CPC) system. The EPO and the United States Patent and Trademark Office developed a tagging system that identifies patents linked to climate change mitigation technologies. The tagged patents are given a CPC code that begins with "Y02" (Angelucci et al., 2018). Patent families can have several associated CPC codes if they are related to several technical fields. As a result, a single patent family may be associated both with CPC codes starting with "Y02" and others that are not.

To avoid double counting these patent families, we count those with both "Y02" and non-"Y02" CPC codes as 0.5 Low-carbon and 0.5 Not Low-carbon. We refer to the category of Low-carbon patent families as green inventions and Not low-carbon patent families as brown inventions. We include a robustness test that counts patent families with both types of CPC codes as 1 in each category of inventions. Results for this test are reported in Appendix 4.C.

Finally, we also compute a variant of our stock count of patent families that includes a rate of depreciation of inventions. This is to account for the progressive loss of value of inventions as they grow older. Following the literature, we compute this with an annual depreciation rate of 5% (de Rassenfosse & Jaffe, 2018; Huang & Diewert, 2011). Results that use the depreciated patent family stock variable are reported in Appendix 4.C.

Matching databases at the firm level

The matching between ORBIS and the EUTL was conducted in previous work by Cameron and Ho (2024). The full procedure, as well as the resulting matched dataset, has been published by the European Commission and is available online.[8]

[8]The matching procedure and data can be accessed at https://single-market-economy.ec.europa.eu/single-market/services/economic-analysis/matching-eu-transaction-log-orbis-database_en?prefLang=sv

Turning to the PATSTAT–EUTL matching, no common unique identifiers exist between the two datasets. We therefore implement a matching protocol based on firm names and geographic information.

First, we extract all patent filings from firms located in countries participating in the EU ETS, between 1992 and 2020. We then construct a name-matching algorithm following Cameron and Ho (2024) that applies an N-gram similarity algorithm to compare firm names across PATSTAT and the EUTL, incorporating data on zip codes to improve the precision of matches. The resulting candidate matches are evaluated using a combination of automated similarity scores and complementary manual validation to ensure correspondence between legal entities.

We subsequently merge the outputs of the two separate matched databases (i) PATSTAT–EUTL, and (ii) EUTL–ORBIS. Upon inspection, we observed that in some cases, firm names from ORBIS—distinct from their EUTL counterparts—matched closely with PATSTAT applicant names. To account for this, we re-applied the N-gram algorithm to the subsample of ORBIS firms already matched to the EUTL but not matched in the original PATSTAT-EUTL procedure. This procedure results in a balanced panel of 872 firms that were observed between 2013 and 2020.

Sectoral classification

One of the fundamental assumptions in TFA is that firms within a given sector employ the same production technology, meaning they share a common production/technology set. This assumption is crucial because firm efficiency is assessed through benchmarking against other firms in the same sector. If firms differ in their outputs, production technologies, or input types, efficiency measurements may be biased (Walheer, 2024).

This assumption poses two challenges for empirical implementation. First, sectoral nomenclatures typically classify firms based on their economic activity or outputs, rather than the production technologies they use. This may not be a problem for sectors where production technologies for one output or activity are relatively homogeneous (e.g., paper production), but it is one in sectors that have several distinct production pathways (e.g., steel production). The second challenge is that, although using the most disaggregated nomenclature maximizes technological homogeneity within sectors, it also creates sectors that are too narrow for empirical analysis—for instance, at the 4-digit level, 21 NACE sectors contain only a single firm in our sample. We must thus strike a balance between achieving sufficient disaggregation to reflect homogeneous technological processes while avoiding excessive fragmentation that results in sectors that contain very few firms.

To determine the sectoral classification that best ensures technological homogeneity within sectors while avoiding over-fragmentation, we evaluate available nomenclatures using a Multiple Analysis of Variance (MANOVA).[9] There are four nomenclatures available in our dataset: 2-digit NACE codes, 3-digit NACE codes, 4-digit NACE codes, and installation activity codes from the EUTL. The indicators employed in the MANOVA are firms' capital intensity, labor intensity, material input intensity, and emission intensity.[10]

We begin with the most disaggregated nomenclature available—the 4-digit NACE codes—which achieves the best MANOVA scores across all test (brown bars in Figure 4.3). Sectors with fewer than 20 firms are subsequently merged with their closest parent NACE sector (orange bars in Figure 4.3).[11] While the 3-digit NACE classification (purple bars in Figure 4.3) and the EUTL installation activity nomenclature (red bars in Figure 4.3) both yield better scores than the new aggregated nomenclature for some of the test statistics, they suffer from the same issue as the 4-digit classification, with some sectors containing too few firms. Therefore, the final proposed nomenclature represents the most disaggregated classification in which all sectors contain at least 20 firms.

We refine this classification and address the first challenge described above by incorporating information on steel production technologies. Neither the NACE nor the EUTL installation activity classifications distinguish between steel firms operating electric arc furnaces and those using basic oxygen furnaces, despite the significant differences between these technologies (Cameron, 2025). To address this gap, we merge our dataset at the installation level with the Global Steel Plant Tracker database, which provides information on steel mill production technologies (Global Energy Monitor, 2024).[12] This additional classification step slightly enhances the MANOVA scores of the final nomenclature (green bars in Figure 4.3).

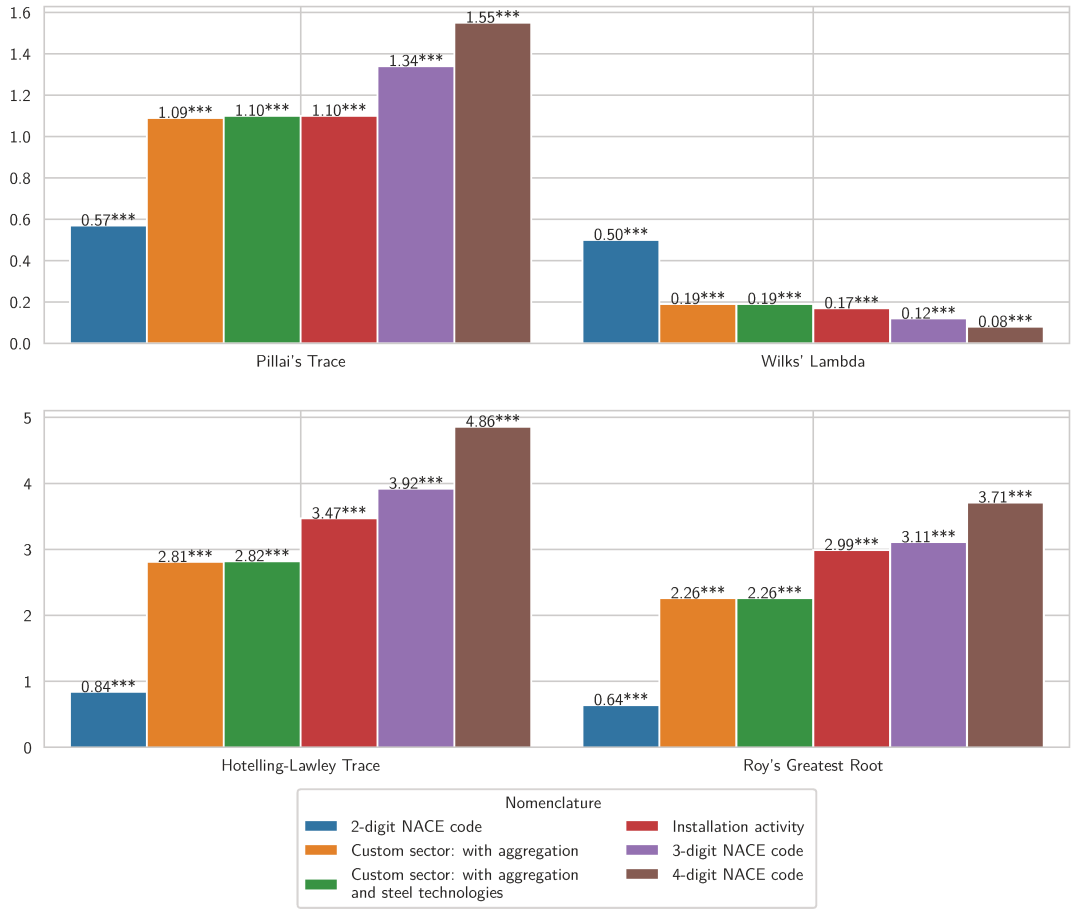
[9]We report results for the four most common MANOVA test statistics: Wilk's Lambda, Hotelling-Lawley's Trace, Roy's Greatest Root, and Pillai's Trace. While all assess group differences across dependent variables, they handle variability differently and rely on distinct data assumptions. Regardless of the test statistic used, the results of the nomenclature assessment remain broadly consistent.

[10]Capital intensity serves as a proxy for the machinery used in production (Bellocchi et al., 2023; Kaldor, 1957); labor intensity reflects skill and labor requirements (Acemoglu & Autor, 2011); material input intensity characterizes the type and quantity of inputs needed (Rigby & Essletzbichler, 1997); and emission intensity represents the emission profile associated with different production pathways (OECD, 2024).

[11]The complete list of these aggregations is provided in Appendix 4.A.

[12]These datasets are first matched based on geographic location, then manually verified using installation and company name similarities. Unmatched steel mills are categorized under "Unknown technology".

Figure 4.3: Results of MANOVA for sectoral classification



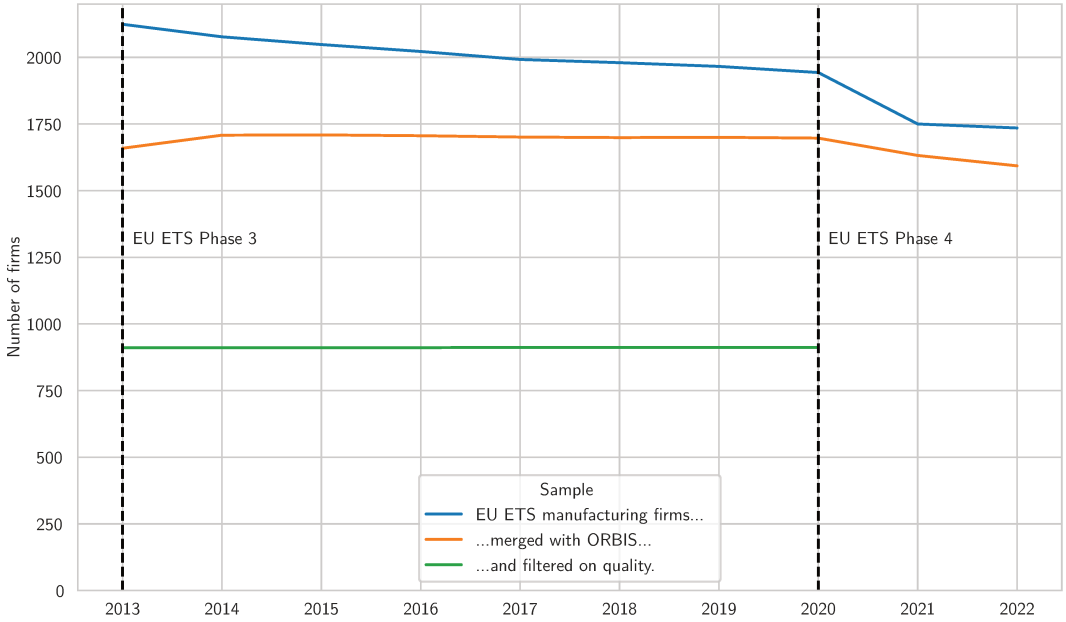
Note: Higher scores for Hotelling-Lawley's Trace, Roy's Greatest Root and Pillai's Trace indicate a higher level of differentiation between sectors, while the opposite is true for Wilk's Lambda (i.e. a lower score indicates a higher level of differentiation between sectors).
Source: Authors.

4.4.3 Data characteristics

Final sample

The sample in this study comprises heavy industry firms regulated under the EU ETS, which are not representative of all EU heavy industry firms. Due to the EU ETS inclusion criteria, the dataset disproportionately reflects the largest and most polluting firms in the sector (Cameron & Garrone, 2024). Data limitations further constrain the analysis: attrition occurs during the matching and cleaning processes (Figure 4.4). Observations prior to 2013 are excluded because data from ORBIS are unavailable for earlier years. The final sample we use in our analysis is a balanced panel of observations with sufficient data quality—meaning they are likely the largest firms, not a representative set.

Figure 4.4: Sample size at the different stages of data preparation



Source: Authors.

Descriptive statistics

The dataset spans 17 heavy industry sectors, which are heterogeneous in their sizes, and input and output structures. In our sample, Paper & paperboard have the most firms (160 firms), followed by Ceramic tiles (100 firms), while Iron & steel via the EAF route and Pulp have the least (20 firms each). Basic chemicals (173M€) and Pulp (168M€) have the highest mean levels of capital, though with high volatility (standard deviation of up to 263M€), while Other metals (653M€) and Basic chemicals (467M€) have the highest levels of material inputs. Mean labor costs are highest in Chemical products (85M€), but with high dispersion (standard deviation of 442M€), suggesting heterogeneous firm sizes. Finally, Other metals (761M€) and Chemical products (724M€) have the highest mean level of output and Cement by far has the largest mean level of emissions (1203ktCO_2).

Table 4.1: Mean firm-level values by sector

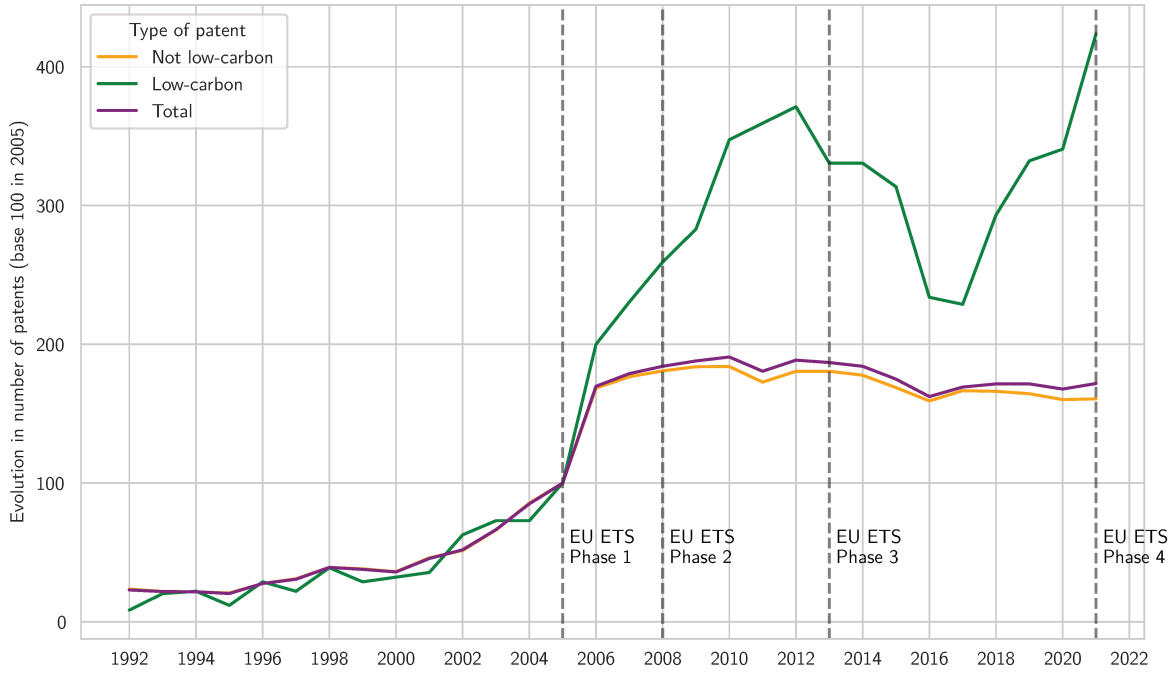
Sector	N firms	Capital (M€)	Labor (M€)	Material inputs (M€)	Output (M€)	Emissions ($ktCO_2$)
Baked clay products	70	17.32	7.05	13.69	33.02	36.02
		[26.6]	[14.54]	[26.64]	[59.73]	[56.64]
Basic chemicals	34	173.1	45.46	467.17	638.58	343.87
		[179.55]	[74.98]	[772.15]	[920.29]	[426.65]
Cement	43	109.85	24.36	66.0	159.04	1202.57
		[98.6]	[26.58]	[78.3]	[134.12]	[901.93]
Ceramic tiles	96	27.66	10.27	22.57	55.29	34.17
		[39.47]	[12.18]	[37.37]	[66.38]	[41.34]
Chemical products	59	157.07	85.39	460.3	723.96	194.03
		[469.57]	[441.79]	[1754.72]	[2856.32]	[566.65]
Hollow glass	45	50.47	22.04	62.84	123.97	91.74
		[46.77]	[29.69]	[105.91]	[151.95]	[119.56]
Iron & steel - EAF	22	114.16	31.27	317.7	436.7	105.61
		[147.2]	[27.85]	[264.32]	[341.31]	[83.05]
Iron & steel - Unknown	32	63.77	23.07	148.49	210.51	74.11
		[58.57]	[24.81]	[117.36]	[166.72]	[77.7]
Lime & plaster	59	26.1	6.27	18.88	43.53	227.26
		[40.71]	[9.44]	[23.05]	[52.48]	[322.99]
Metal processing	45	75.23	33.68	176.02	255.0	48.79
		[80.9]	[52.98]	[216.37]	[296.44]	[67.33]
Other glass	42	71.14	19.87	63.15	126.56	98.0
		[69.48]	[20.22]	[68.37]	[119.06]	[108.52]
Other metals	29	108.39	34.04	653.1	761.11	73.0
		[125.14]	[43.85]	[1325.3]	[1393.81]	[97.21]
Other non-metallic minerals	48	43.31	14.46	48.71	97.46	101.88
		[56.86]	[18.66]	[64.75]	[117.78]	[216.48]
Paper & paperboard	160	68.66	18.4	89.02	160.94	47.83
		[187.06]	[39.08]	[194.17]	[345.87]	[93.75]
Paper & paperboard products	42	51.1	18.25	79.37	136.92	62.86
		[111.97]	[26.01]	[144.42]	[229.37]	[130.49]
Pulp	21	167.69	18.68	140.2	243.5	35.84
		[263.4]	[21.83]	[225.14]	[357.27]	[44.3]
Sanitary goods	26	53.79	25.86	126.36	200.39	30.26
		[49.44]	[34.39]	[171.52]	[225.07]	[31.93]

Note: Standard deviation in square brackets.
Source: Authors based on EUTL and ORBIS.

The data presented above has been matched to patent data from PATSTAT to explore the relationship between patenting, green patenting and technical progress. As discussed in Section 4.2, the existing literature finds that the EU ETS induced green

patenting in regulated firms (Calel, 2020; Calel & Dechezleprêtre, 2014). As a purely descriptive check, we examine whether firms in our sample exhibit a similar trend. Figure 4.5 shows the evolution of patent families filed by these firms as an index with a base of 100 in 2005. It confirms that, following the introduction of the EU ETS, firms in our sample increased the number of low-carbon patent families they filed more than other types of patent families. This trend remained strong during the second and third phases of the EU ETS, with the exception of a noticeable dip in 2016–2017, followed by a sharp increase. This is only an indication of the evolution of patenting trends, not of the number of patent families that have been filed in each category. Many more non-low-carbon patent families have been filed, as illustrated by the fact that the total trend follows the non-low-carbon trend very closely.

Figure 4.5: Patenting trends in the sample



Source: Authors based on PATSTAT

4.5 Empirical approach

4.5.1 Choice of an approach for the Technological Frontier Analysis

Since the inception of TFA, many empirical methods have been developed to bring the theory to the data. In this subsection, we review the main TFA methods in economic literature and highlight their strengths and weaknesses. Finally, we argue for the choice

of using a Minimization Program (MP) approach in this paper. Figure 4.6 describes the nomenclature of methodologies that have been applied for TFA and summarizes their main advantages and drawbacks.

Flexibility. These methodologies can first be classified as either parametric or non-parametric. This characterizes whether they make assumptions about the data process underlying the observed data. Non-parametric approaches are more flexible than their parametric counterparts because they do not impose assumptions on the functional form of the production function or on the distribution of the unknown parameters (Assaf & Josiassen, 2016). This can be an advantage when little is known about the true distribution of the data. Some parametric approaches can relax the restrictiveness of their distribution assumption, namely the Generalized Method of Moments (GMM) and Bayesian Inference (BI). GMM are relatively flexible because they only require moment conditions rather than assumptions about full probability distributions (Atkinson & Tsionas, 2018). BI can relax distribution assumptions by starting with noninformative priors (Fernández et al., 2000).

Outliers. While non-parametric methods offer flexibility, this advantage comes with heightened sensitivity to outliers. Due to this flexibility, a single highly efficient firm can disproportionately influence the frontier's shape. In contrast, parametric methods mitigate the impact of outliers by leveraging distributional assumptions, which aid in identifying and accounting for these outliers.

Statistical inference. Non-parametric methods do not rely on statistical inference and therefore do not allow for hypothesis testing or sensitivity analyses. Parametric methods are the opposite.

Multi-output setting. Non-parametric approaches are more easily applied to multi-output settings than parametric models (Assaf & Josiassen, 2016). This is because they are applied through mathematical programs that can easily be generalized to include multiple outputs. Additionally, these methods are very close to the theoretical underpinning of TFA. Some parametric methods are also adapted to multi-output settings, namely a Minimization Program (MP), GMM, and BI. On the other hand the use of Maximum Likelihood Estimation (MLE) is ill-suited for multiple outputs because it is an econometric method that can only have a single dependent variable (output). Researchers have proposed two options to work around this, as detailed below. However, neither of these options are consistent with the theoretical and empirical setting in the present paper, meaning MLE is excluded.

- Outputs are aggregated into a single variable, either with a ratio or a sum. For example, Robaina-Alves et al. (2015) use a ratio of a good output over a bad output as their dependent variable. The issue with this approach is that it fully departs from the theoretical framework of TFA and no longer allows for efficiency to be defined according to a frontier.

- A system of equations is estimated, with one equation for each output type. The efficiency term can be linked between these different equations via a copula function (Skevas, 2025). This model makes the explicit assumption that the different outputs are produced by distinct sub-technologies. While this can make sense for models whose outputs are different products (e.g.: one production technology to produce hats and another to produce shoes, or multi-crop farms in agriculture), this assumption does not reflect the setting in this paper. The bad outputs of industrial production are intrinsically linked to the production technology of the good outputs (e.g.: emissions from cement production are produced by the cement kiln).

Error term. Non-parametric and parametric deterministic methods do not include an error term and therefore attribute all noise in the data to firm-level inefficiency. This can be problematic for two reasons:

1. There are random effects that affect firms' production that are unrelated to their efficiency (e.g.: changing weather patterns and extreme events, changes in local policies, etc... (Atkinson & Tsionas, 2018)).

2. There are likely reporting errors and biases in the data we use (e.g.: Liu (2020) reports on issues with data consistency, survival and selection biases and misclassifications in ORBIS; the European Securities and Markets Authority (2022) identified consistency errors in the EUTL due to the absence of common entity identifiers).

Data availability. Most of the methodologies presented here can be applied via a distance function derived from a production function. This means they only need data on production volumes or values, as well as input and emission volumes or values. There is one exception however, namely GMM. GMM requires input and output price data as it relies on the estimation of a cost function with prices as instrumental variables (Atkinson & Tsionas, 2018). This data is very difficult to find given its commercial sensitivity, which forces us to exclude GMM.

Computational needs. DEA, Free Disposal Hull (FDH, which is a specific form of DEA with no assumption on the convexity of the distance function), MLE and GMM

all have ready-to-use, optimized packages in statistical programming languages. These allow for computation of the distance function with fairly low computational needs. While MP is not available in the form of a ready-to-use package, it can be programmed in a mathematical computation program and requires low computational needs. The only exception is BI, which has extremely high computational needs given its reliance on high-iteration Monte Carlo simulations.

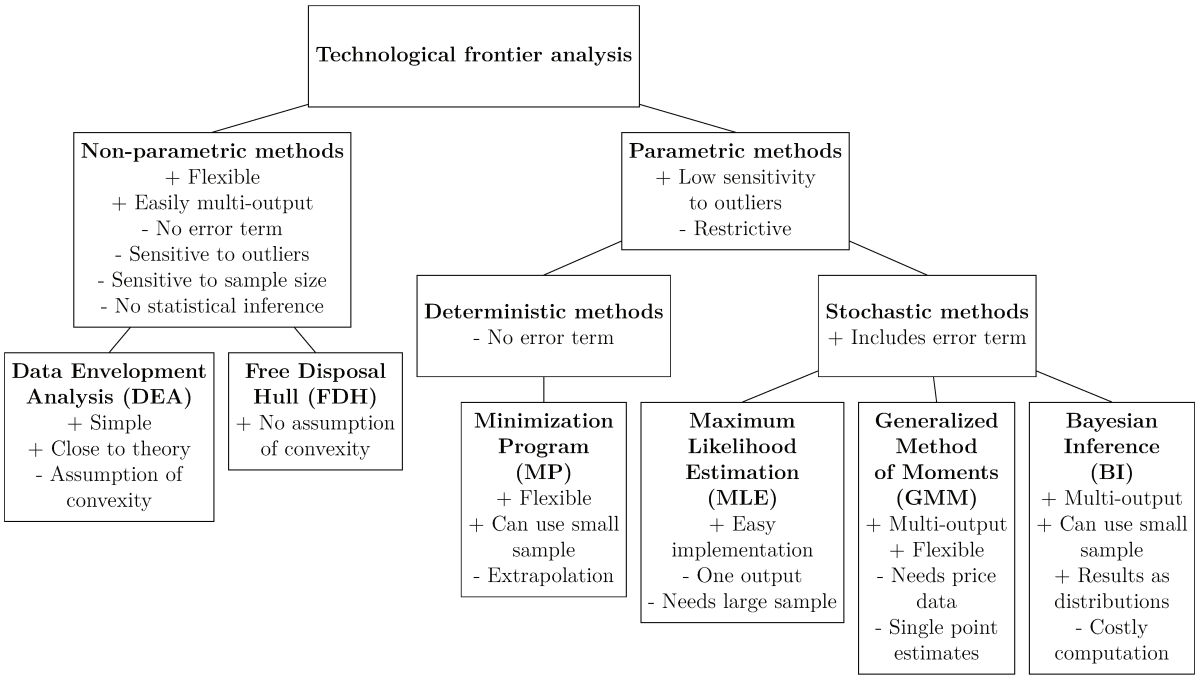
Final choice. Based on the above evaluation of available methodologies, this paper uses MP to perform TFA. This methodology fits well with the theoretical framework of one bad output and one good output and does not require many observations by sector, which corresponds well to our data. It is more flexible than a DEA and allows for a smoother representation of the frontier rather than a piece-by-piece linear approximation. It thus offers a mid-point between DEA and econometric approaches. To minimize the risk of outliers skewing our results, we ensure the quality of our data through the steps detailed in Section 4.4.2.

While it would be preferable to use a stochastic method to account for noise in the data, each of the possible methods are excluded for the following reasons:

- MLE is ill-suited to the multi-output framework, especially with one good output and one bad output.
- GMM requires data on the price of inputs and outputs, which is not available to us.
- BI has computational needs that go beyond the infrastructure available to us. This is nonetheless the most promising method for future research.

As a result, we opt for the MP methodology, which has the advantage of being highly flexible as it only makes assumptions about the functional form of the directional distance function. Additionally, it can be a first step towards a BI approach which requires values for priors to reduce computation needs.

Figure 4.6: Approaches to Technological Frontier Analysis



4.5.2 Step 1: TFA through linear-quadratic minimization programming

We apply a deterministic linear-quadratic minimization program for the TFA. Following Färe et al. (2005) and Baudry and Faure (forthcoming), we apply the following linear-quadratic program $\mathcal{P}$ to calibrate sector- and year-specific technological frontiers

$$\min \left[\sum_{i=1}^{N} \overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; v) \right] \text{ such that}$$

(a) $\overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; v) \geq 0 \, \forall \, i$

(b) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial Y_{itg}} \leq 0 \, \forall \, i$

(c) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial Y_{itb}} \geq 0 \, \forall \, i$

(d) $\dfrac{\partial \overrightarrow{D_{it}}}{\partial X_{itq}} \geq 0 \, \forall \, q \text{ and } \forall \, i$

(e) $\overrightarrow{D_{it}}(X_{it}, 0, 0; v) < 0 \, \forall \, i$

where $\overrightarrow{D_{it}}(X_{it}, Y_{itg}Y_{itb}; v)$ is specified as a quadratic function to fulfill the constraints of the production technology model described in Section 4.3:

$$\begin{aligned}\overrightarrow{D_{it}}(X_{it}, Y_{itg}, Y_{itb}; v_g, -v_b) =& \beta_{0t} + \sum_{q=1}^{3} \beta_{tq} X_{itq} + \sum_{o=1}^{2} \beta_{tp} Y_{ito} + \sum_{q=1}^{3}\sum_{q'=1}^{3} \beta_{tqq'} X_{itq} X_{itq'} \\ &+ \sum_{o=1}^{2}\sum_{o'=1}^{2} \beta_{to'} Y_{ito} Y_{ito'} + \sum_{q=1}^{3}\sum_{o=1}^{2} \beta_{tqp} X_{itq} Y_{ito}\end{aligned} \tag{4.7}$$

The direction parameters v do not appear explicitly in Equation 4.7 because they are integrated in the constraints imposed on the β parameters.

Implicitly, $\hat{D}_{it}(X_{it}, Y_{itb}, Y_{itg}; v) = 0$ defines the technological frontier, since it defines a situation where a firm has no inefficiency. The program's constraints ensure the technological frontier takes on the appropriate shape, namely:

- (a) implies that firms are either on or below the technological frontier;
- (b) implies that a marginal increase in the good output increases a firm's efficiency;
- (c) implies that a marginal increase in the bad output decreases a firm's efficiency;
- (d) implies that a marginal increase in input use decreases a firm's efficiency;
- (e) implies that any use of inputs must be associated with some production;
- all the constraints allow for $Y_{itb} > 0$ even with a null production $Y_{itg} = 0$, which means $\mathcal{P}$ respects the assumption of weak disposability of good and bad outputs jointly, defined in Equation 4.4.

4.5.3 Step 2: Exploring technological progress

The purpose of our empirical analysis is to assess the effect of low-carbon patenting—measured here through patent families belonging to the CPC class Y02—on firms' technological progress—as defined through our frontier approach. We therefore estimate the following equation:

$$\begin{aligned}\text{TechProg}_{i,t} = \gamma_1 \log \text{GreenInv}_{i,t-1} + \gamma_2 \log \text{Inv}_{i,t-1} \\ + \sum_k \delta_k x^k_{i,t} + \mu_i + \mu_{ct} + \epsilon\end{aligned} \tag{4.8}$$

where:

- $\text{TechProg}_{i,t}$ is the dependent variable representing technical progress. It is either the continuous variable representing a firm's distance to the previous year's techno-

logical frontier (which takes a negative value when the firm is beyond the frontier, i.e., it contributed to technological change, and a positive value if it is below the frontier, i.e., it did not contribute to technological change) or the binary variable indicating if a firm displaced the previous year's technological frontier or not;

- $\text{GreenInv}_{i,t-1}$ and $\text{Inv}_{i,t-1}$ are respectively the count of low-carbon or "green" patent families (measured either as a flow or a stock) and the count of non-low-carbon or "brown" patent families (measured either as a flow or a stock) of firm i in time $t-1$;
- x_{it}^{k} is the set of firm-level control variables;
- μ_i are firm fixed effects;
- μ_{ct} are country-year fixed effects;
- ϵ is the error term.

We run two different specifications of this equation. The first is an OLS regression in which the dependent variable is firm's distance to the previous year's technological frontier. In this specification, we use the stock patent family count variables because distance is a continuous variable and it is likely that a firm's accumulation of knowledge rather than its knowledge at a specific time explains its relative efficiency within its sector. The second specification is a logit regression in which the dependent variable is the binary variable indicating whether a firm has displaced the frontier in a specific year. In this specification, we instead use the flow patent family count variables because the dependent variable is meant to capture a "jump" in a firm's knowledge and therefore is more likely explained by its patenting behavior in the year preceding the jump.

To mitigate potential reverse causality whereby proximity to the frontier may itself affect invention decisions (firms that are more efficient are those that are more likely to innovate), we lag both invention variables by one period. This lag also reflects the delay in the realization of productivity benefits from inventions.

In our baseline specification, we include a set of control variables designed to isolate the impact of low-carbon patented inventions and non-low-carbon patented inventions on firms' distances to the previous year's technological frontier. These controls account for observable heterogeneity which may affect a firm's invention patterns and its relative technological position, thereby mitigating omitted variable bias.

First, we include two dummy variables indicating organizational changes, namely, whether a firm has opened or closed an installation during the period under consideration. It takes the value of 1 the year that an installation is opened or closed and 0 otherwise.

These indicators allow us to account for major internal restructuring events that may affect a firm's technological performance independently of its patenting activity. The opening of a new facility may reflect strategic expansion or investment in new capabilities, while a closure may signal downsizing or internal reallocation of resources, both of which can alter a firm's innovation dynamics and hence distance to the technological frontier (Cameron & Garrone, 2024).

We also account for firm-level environmental stringency, as measured by the proportion of its GHG emissions for which the firm must purchase allowances. This variable captures the extent of the regulatory pressure firms face under the emissions trading scheme (Borghesi et al., 2015) since heavy industry firms still received free allowances throughout all of Phase 3 of the EU ETS. Reverse causality may arise when examining the relationship between environmental regulatory stringency and firm-level efficiency (Rubashkina et al., 2015). Specifically, improvements in productivity or technological innovation may lead to reductions in emissions or lower abatement costs, thereby influencing the very measure intended to capture regulatory stringency. To address this concern, we lag the measure of environmental regulation to ensure that the policy variable is temporally prior to observed outcomes (Franco & Marin, 2017).

Another factor of endogeneity that could bias our results is measurement error. In our case, the dependent variable may be subject to this bias. If the measurement error is neither correlated with the error term nor the regressors, our estimates will remain unbiased, but the standard deviations will increase. This bias works against finding a significant effect.

To capture the possible correlation in errors arising from the fact that distances are computed relative to sector-year technological frontiers, errors are clustered at the sector-year level. If a frontier is biased for a specific sector-year, all the distances that are computed relative to it will inherit the same bias. This level of clustering thus allows us to avoid overemphasizing the importance of these types of errors.

A key concern in our framework arises from the dynamic nature of both innovation and technological distance, each of which reflects accumulated activity. The stock of low-carbon patented inventions and the firm's proximity to the technological frontier are inherently time dependent variables and potentially subject to hysteresis, shaped by intertemporal investment and learning dynamics. Consequently , current measures of technological distance may reflect prior innovation that is itself a function of past regulatory environments and firm specific factors. This time dependence introduces a risk of reverse causality. In our empirical strategy we account for this endogeneity threat by including firm fixed effects to control for time-invariant unobserved heterogeneity across firms—such as managerial quality, historical R&D capacity, or long-term strategic

orientation. Furthermore, we use a short panel (up to seven year for firm) which helps isolate within-firm variation over time of our main regressors without worrying about confounding factors. We also test whether some specific firm-level controls (firm size and a firm's initial stock of patent families) can explain firms' distance to the frontier in a specification that excludes firm fixed effects. Lastly, we include country-year fixed effects in our preferred specification to control for policy shifts at the country level, including macroeconomic trends or regulatory stringency variations, which might simultaneously affect innovation incentives and the evolution of the technological frontier.

4.6 Results

4.6.1 Trends in firm-level distance to the frontier

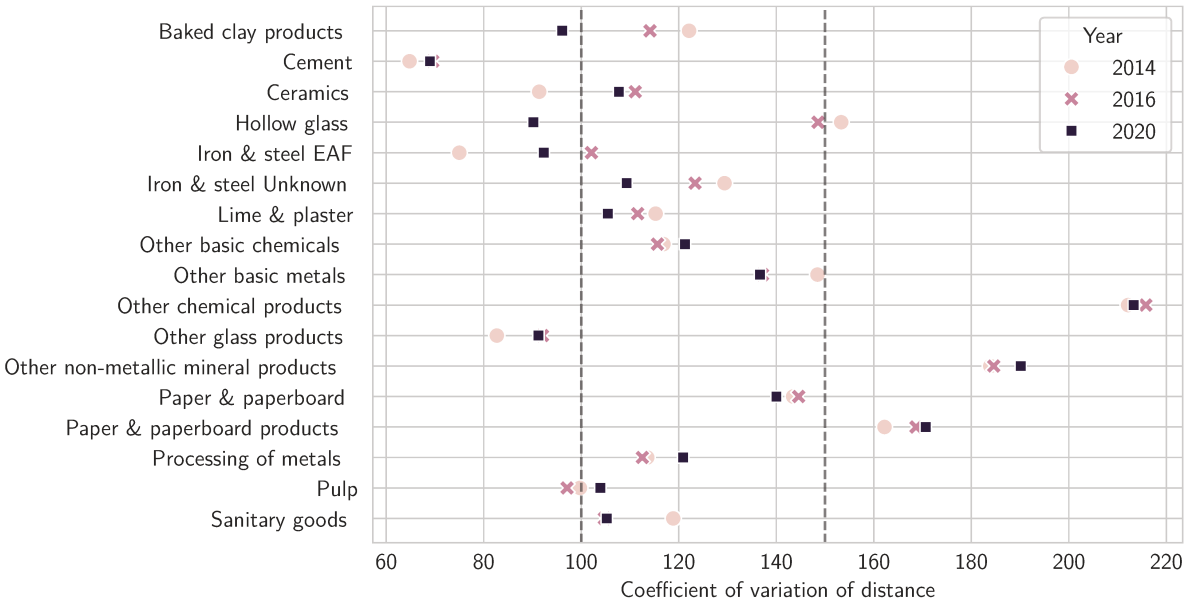
An interesting result from our analysis lies in the within-sector dispersion of firms' distances to the technological frontier. While the level values of distances are not comparable across sectors due to the within-sector calibration of the frontier, dispersion metrics (e.g., coefficient of variation) can reveal meaningful intra- and inter-sector dynamics. High dispersion signals significant heterogeneity in firm efficiency, whereas low dispersion reflects homogeneity—i.e., firms are clustered tightly around the sectoral mean efficiency. These patterns are not static; they evolve over time, offering insights into convergence or divergence of efficiency at the sector level (Figure 4.7).

The sectors in our analysis can be split into three groups based on the dispersion of their efficiency values. The first group comprises sectors with low levels of dispersion (coefficient of variation (CV) below 100%, meaning that the standard deviation is smaller than the mean). This group includes Cement and Other glass products for all years of the analysis, as well as Baked clay products, Hollow glass, and EAF Iron and steel in the most recent year of data (2020). The second group holds the most sectors. It is composed of sectors with middling dispersions, displaying a CV between 100 and 150%. This includes Iron and steel from an unknown technology, Lime and plaster, Other basic chemicals, Other basic metals, Paper and paperboard, Processing of metals, and Sanitary goods. Pulp and Ceramics are also in this category in 2020. Finally, the last group is composed of sectors that have high levels of dispersion (CV above 150%, meaning the standard deviation is more than 1.5 times the mean). In this category, Other chemical products has the highest CV, followed by Other non-metallic mineral products, then Paper and paperboard products.

The evolution of dispersion also varies across sectors. The Hollow glass sector stands out as having the largest absolute change in dispersion between 2014 and 2020 (-63 per-

centage points), indicating a shrinking heterogeneity among firms. Baked clay products and Iron and steel from an unknown technology also became more homogeneous over this period (-26 and - 20 percentage points, respectively). On the other hand, Ceramics and EAF Iron and steel display a widening heterogeneity, increasing their CV by 16 and 17 percentage points, respectively. Some sectors' dispersion remained relatively stable over the entire period, with a difference in CV of less than 5 percentage points in absolute terms. This includes Other basic chemicals, Pulp, Cement, Other chemical products, and Paper and paperboard.

Figure 4.7: Coefficient of variation of distance to frontier



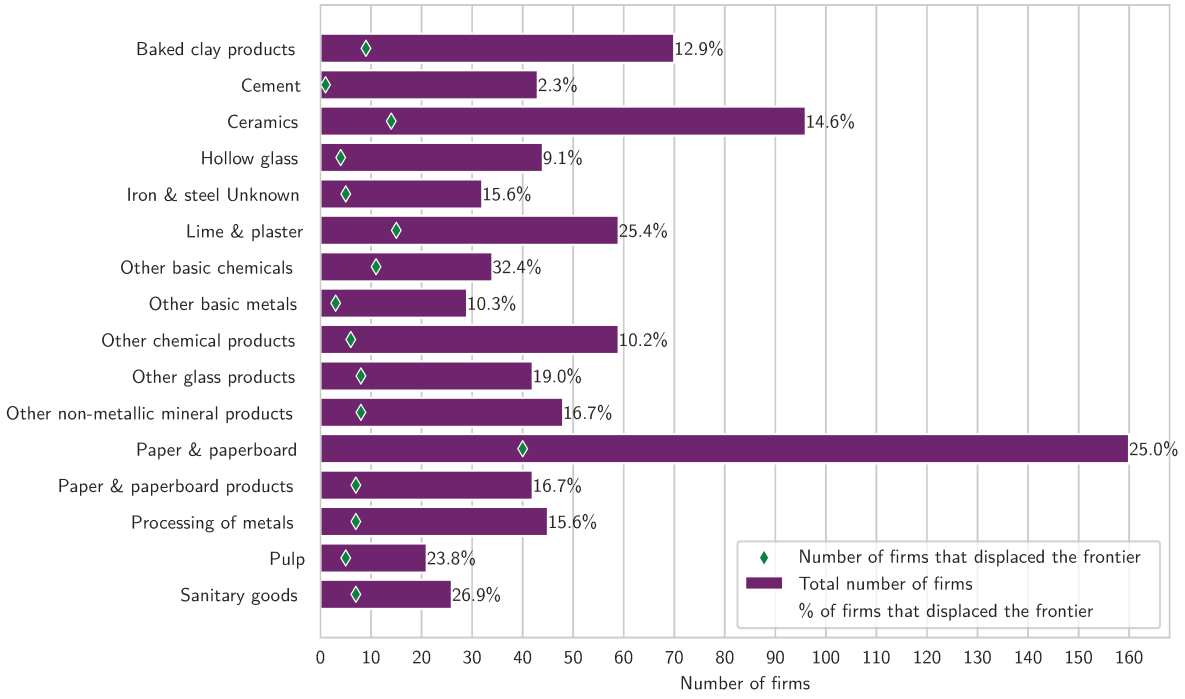
Source: Authors.
Note: The coefficient of variation is computed as the ratio of a sector's standard deviation and its mean, multiplied by 100.

Another key finding that is relevant to the second part of our empirical analysis concerns the trends in frontier displacement. Which firms are driving these shifts? Are the same firms consistently responsible for shifts in the frontier?

In all sectors except Pulp and paperboard, 15 or fewer firms displace the frontier at least once in our sample.[13] Some sectors exhibit particularly low numbers: Cement has only 1 firm (2% of the total), Other basic metals has 3 (10%), Hollow glass has 4 (9%), while Iron & steel (unknown technology) and Pulp have 5 each (15% and 24%, respectively). These results suggest that technological progress is concentrated in a small subset of firms within each sector (Figure 4.8).

[13]Pulp and paperboard is an exception, though this sector also contains significantly more firms than the others.

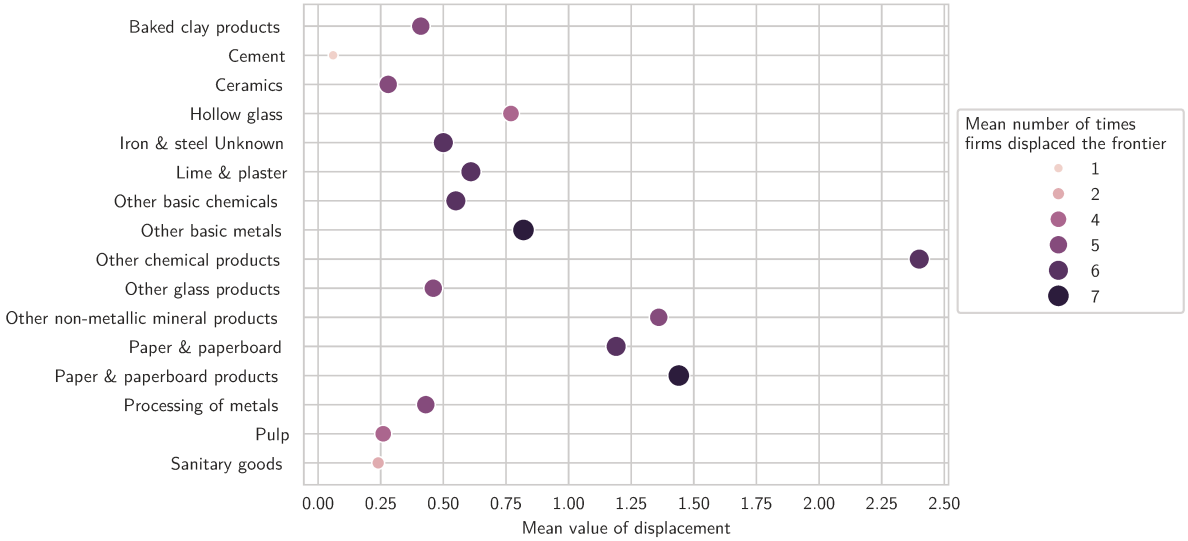
Figure 4.8: Number of firms that displace the frontier



Source: Authors.

There are also differences regarding the frequency with which firms displace the frontier in each sector—i.e., whether the same firms consistently displace the frontier every year or if the firms displacing the frontier change over time. In some sectors, frontier displacement is rare and sporadic. The Cement firm that displaced the frontier did so only once in our sample. Firms in the Sanitary goods sector displaced the frontier 2–3 times on average, and Pulp and Hollow glass firms did so 3–4 times on average. In contrast, sectors like Paper and paperboard products and Other basic metals exhibit consistent displacement, with the same firms driving progress every year (Figure 4.8).

Figure 4.9: Average frequency of frontier displacements



Source: Authors.

4.6.2 Do patents explain technological progress?

We now turn to the second stage of our analysis. Here, we present the results of the estimations that study the effect of patenting on firms' distances to the previous year's frontier, our proxy for technological progress.

Initial specification. Table 4.2 begins by showing the results from our simplest specification, a flexible version of Equation 4.8 where we replace country-year fixed effects by year fixed effects and use a within-firm estimator. These results show the impact of both the stock of low-carbon and of non-low-carbon patented inventions on a firm's distance to the previous year's technological frontier. Column 1 shows that the coefficient for the stock of low-carbon patented inventions is positive and significant at the 5% level. This indicates that, on average, an increase in low-carbon patented inventions between 2013 and 2020 increased a firm's distance to the previous year's technological frontier. In other words, it decreased its propensity to displace the technological frontier.

This is robust to the inclusion of the lagged variable for firm-level EU ETS stringency and both variables controlling for firms' internal restructuring (column 3).[14] Among the control variables, only the variable measuring whether a firm closed an installation in a specific year is significant. This coefficient is negative, indicating that firms that close an installation become relatively more efficient (i.e., decrease their distance to the

[14]Estimating the model without using a lag on the stringency variable produces the same results.

technological frontier). This is fairly intuitive as the installations that get closed are likely those that have the worst performance.

In column 5, the stock of brown patented inventions is added to ensure that the estimated effect in columns 1 and 3 is not a global effect of the stock of patented inventions due to correlation between the stock of green and brown inventions, but rather a specific effect of the stock of low-carbon patented inventions. The coefficient for the stock of low-carbon patented inventions remains constant in magnitude and significance. Perhaps surprisingly, the stock of non-low-carbon patented inventions has no significant effect by itself (column 2) or when combined with the other variables (column 4 and 5).

Table 4.2: Initial OLS specification results

	Dependent variable: Distance$_t$				
	(1)	(2)	(3)	(4)	(5)
	OLS	OLS	OLS	OLS	OLS
log StockGreenInnov$_{t-1}$	0.322**		0.323**		0.334**
	(0.128)		(0.128)		(0.132)
log StockInnov$_{t-1}$		0.0325		0.0332	-0.0113
		(0.0243)		(0.0243)	(0.0233)
Stringency $_{t-1}$			0.309	0.694	0.354
			(5.331)	(5.308)	(5.332)
Installation Closed $_t$			-0.121**	-0.121**	-0.121**
			(0.0570)	(0.0573)	(0.0571)
Installation Opened $_t$			-0.0225	-0.0188	-0.0219
			(0.0174)	(0.0175)	(0.0172)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Country-Year FE	No	No	No	No	No
Adjusted R^2	0.945	0.944	0.945	0.944	0.945
F-statistic	6.330	1.787	2.949	1.883	2.380
Observations	6104	6104	6104	6104	6104

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standard errors are reported in parentheses. Errors are corrected for clustering at the sector-year level. ***, ** and * indicate significance at the one, five and ten percent levels respectively.

Preferred specification. Next, Table 4.3 presents the results for our preferred specification. The difference with the previous specification is that year fixed effects are dropped and replaced with country-year fixed effects. Combined with the inclusion of

firm fixed effects as in the previous specification, this change significantly reduces the potential for bias. With these fixed effects, we control for time-invariant firm heterogeneity and country-specific temporal shocks, such as environmental policy changes or macroeconomic conditions.

A key finding emerging from the analysis is that the effect of low-carbon patented inventions on firms' distance to the previous year's technological frontier is positive and statistically significant. Across all specifications where it is included (columns 1, 3, and 5), the coefficient for this variable remains remarkably stable in magnitude—ranging from 0.337 to 0.340—and is consistently significant at the 1% level. This result is robust to the inclusion of additional controls, suggesting a stable relationship. In this log-level specification, the coefficient can be interpreted as a semi-elasticity. These results thus imply that a 1% increase in the stock of low-carbon patented inventions is associated with a 0.34 unit increase in a firm's distance to the previous year's technological frontier, on average and all else being equal.

Thus, the core result from Table 4.2 holds in both significance and magnitude, reinforcing the argument that the observed effect is not confounded by macro-level policy shifts. The only notable difference is observed in columns 2 and 4, where the coefficient on the stock of brown patented inventions becomes positive and significant at the 10% level. However, this effect turns negative and is no longer significant when we include all controls and both green and brown patented inventions stocks.

Exploring firm characteristics. We aim to investigate which firm-level characteristics might help explain the between variation in firms' distances to the previous year's frontier. To do this, we replace firm fixed effects with observable firm characteristics. If the coefficients on the patented invention variables remain stable and the included firm characteristics are found to be significant, this would suggest that the firm fixed effects were primarily capturing those characteristics. Conversely, if the results change, it would imply that the fixed effects are accounting for other, unobserved firm-level traits.

In our analysis, we focus on two specific firm-level characteristics: the initial stock of green and brown patented inventions at the beginning of our study period— measured on the basis of patent applications that were filed during the decade before our start date (2013). The initial stock variables are designed to capture a firm's innovative capacity prior to 2013, to test the hypothesis that inherently inventive firms are more likely to continue driving technological change. However, only the initial stock of green patented inventions is significant, and only in two model specifications without control variables, suggesting limited robustness.

Table 4.3: Preferred OLS specification results

	Dependent variable: Distance$_t$				
	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS
log StockGreenInnov$_{t-1}$	0.337***		0.338***		0.340***
	(0.122)		(0.122)		(0.127)
log StockInnov$_{t-1}$		0.0406*		0.0415*	-0.00222
		(0.0225)		(0.0226)	(0.0229)
Stringency $_{t-1}$			1.626	1.975	1.636
			(5.302)	(5.277)	(5.316)
Installation Closed $_t$			-0.119*	-0.119*	-0.118*
			(0.0604)	(0.0614)	(0.0605)
Installation Opened $_t$			-0.0272	-0.0237	-0.0271
			(0.0179)	(0.0177)	(0.0177)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Country-Year FE	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.945	0.945	0.945	0.945	0.945
F-statistic	7.661	3.253	2.863	1.963	2.310
Observations	6104	6104	6104	6104	6104

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standard errors are reported in parentheses. Errors are corrected for clustering at the sector-year level. ***, ** and * indicate significance at the one, five and ten percent levels respectively.

When we include the second firm-level characteristic we are interested in, firm size—as measured by total sales—its coefficient emerges as positive and statistically significant at the 1% level. This suggests that, all else equal, larger firms tend to be further from the previous year's frontier, implying they contribute less to technological progress. This result aligns with the idea that smaller firms may be more agile and better positioned to adopt and implement new technologies. Overall, our findings indicate that the firm fixed effects from earlier regressions likely capture more than just size and pre-existing inventiveness, as the flow patented invention variables lose significance once these firm characteristics are explicitly included.

Table 4.4: Removing firm fixed effects

	Dependent variable: Distance$_t$			
	(1) OLS	(2) OLS	(3) OLS	(4) OLS
log InitialStockGreenInnov$_{t0}$	0.0843	0.0487	0.0841	0.0487
	(0.0731)	(0.0709)	(0.0732)	(0.0709)
log InitialStockGreenInnov$_{t0}$	0.0738**	-0.00124	0.0738**	-0.00124
	(0.0315)	(0.0308)	(0.0315)	(0.0308)
log GreenInnov$_{t-1}$	-0.281	-0.214	-0.280	-0.214
	(0.204)	(0.200)	(0.204)	(0.200)
log Innov$_{t-1}$	0.0838	0.0698	0.0838	0.0698
	(0.0823)	(0.0809)	(0.0823)	(0.0809)
Stringency $_{t-1}$		-1.395		-1.397
		(9.726)		(9.738)
Installation Closed $_t$		-0.144		-0.148
		(0.282)		(0.283)
Installation Opened $_t$		-0.259		-0.263
		(0.251)		(0.251)
log Size$_t$		0.141***		0.141***
		(0.00749)		(0.00749)
Firm FE	No	No	No	No
Year FE	No	No	Yes	Yes
Country-Year FE	No	No	No	No
Adjusted R^2	0.0195	0.0823	0.0187	0.0815
F-statistic	9.756	49.03	4.396	30.21
Observations	5232	5232	5232	5232

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standards errors are reported in parentheses.***, ** and * indicate significance at the one, five and ten percent levels respectively.

Logit specification. Here, we investigate an alternative specification in which, rather than examining a firm's distance to the previous year's technological frontier, we assess the probability that a firm displaces this frontier—i.e., that at time t, it is beyond the frontier constructed for $t-1$. Our dependent variable is a binary variable that takes the value of 1 if the firm is beyond the $t-1$ frontier and 0 otherwise. This prompts a switch to a logit specification. As discussed in the empirical strategy section, flows

of patent families are more appropriate for capturing discrete shifts—or "jumps"—in a firm's technological position. Table 4.5 presents the results of the logit regression. The sample size decreases substantially because the estimation can only be conducted for firms that have displaced the frontier at least once due to the inclusion of firm fixed effects.

Focusing on the results reported in column (5) of Table 4.5, which include the full set of controls, shows that the coefficient associated with the logarithm of the flow of low-carbon patent families is estimated at -1.6 and is statistically significant at the 10% confidence level. This result implies that an increase in low-carbon patenting activity is associated with a drop in the likelihood that a firm displaces the technological frontier. In contrast, the coefficients on the remaining covariates are not statistically significant, indicating that they do not contribute meaningfully to explaining variation in frontier displacement. This result aligns with our earlier findings.

Table 4.5: Logit specification results

	Dependent variable: P(Displacement)$_t$				
	(1)	(2)	(3)	(4)	(5)
	Logit	Logit	Logit	Logit	Logit
log GreenInnov$_{t-1}$	-1.868**		-1.845**		-1.603*
	(0.913)		(0.917)		(0.943)
log Innov$_{t-1}$		-0.551		-0.552	-0.402
		(0.340)		(0.340)	(0.349)
Stringency $_{t-1}$			43.37	42.26	43.26
			(32.32)	(32.03)	(32.25)
Installation Closed $_t$			2.094	2.301	2.131
			(2.114)	(2.027)	(2.095)
Installation Opened $_t$			-0.501	-0.456	-0.474
			(0.839)	(0.838)	(0.839)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Country-Year FE	No	No	No	No	No
Pseudo R^2	0.0277	0.0251	0.0319	0.0295	0.0338
Log likelihood	-353.6	-354.6	-352.1	-352.9	-351.4
Observations	917	917	917	917	917

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standards errors are reported in parentheses. Errors are corrected for clustering at the sector-year level.***, ** and * indicate significance at the one, five and ten percent levels respectively.

To ensure the robustness of the results presented in Table 4.3, three additional tests are conducted. Their results are provided in Appendix 4.C.

Robustness – CPC weighting. As presented in the data section, the patented inventions stock variables are constructed by weighting patent families belonging to both the low-carbon and non-low-carbon patent categories. Consequently, patent families belonging to a single category are implicitly given twice the weight of their bi-category peers. To assess whether this weighting scheme introduces bias into our estimates, we re-estimate the baseline specification using unweighted patent family stock measures, treating all patent families equally regardless of category overlaps. The results are reported in Appendix 4.C, Table 4.8. All the results presented in Table 4.3 are robust to this new weighting of patent counts. The only difference is that the magnitude of the coefficient for the low-carbon stock of patented inventions is reduced from around 0.34 to 0.24.

The smaller coefficient for the stock of low-carbon patented inventions in the robustness test may reflect the different informational content of mono- versus dual-category patents. Patents classified exclusively as low-carbon or non-low-carbon are likely to be more thematically focused, potentially yielding a stronger and more targeted impact on firm-level efficiency outcomes. In contrast, dual-category patents may embody more general-purpose inventions, whose benefits are diffused across multiple dimensions and thus less potent in any single domain. Equal weighting might mitigate the bias introduced by over-weighting such dual-purpose inventions, potentially reducing measurement error and enhancing statistical precision.

Robustness – Patent depreciation. The patented inventions stock variables are defined as the cumulative sums of patent families over time. This construction entails two key features that may introduce bias in the estimation. First, the stock variable never decreases since it captures only positive increments in patent counts. Second, all patents are weighted equally, irrespective of their filing year. As a result, older patents—for instance, those filed in 2014—contribute equally to the stock in 2020 as more recent ones, filed in 2018, despite possible differences in their current relevance or technological value. These features highlight a limitation of the stock measure: it does not account for knowledge depreciation or the dynamic nature of the technological frontier, wherein past innovation does not necessarily translate into sustained technological leadership (de Rassenfosse & Jaffe, 2018). Following (Huang & Diewert, 2011) we construct stock variables as weighted depreciated sums of past flows, applying an exponential decay to account for temporal distance. Each year's contribution is weighted by $1/(1+\delta)^{\text{age}}$, where $\delta = 0.05$ and age reflects the number of years that have passed since a patent was filed.

Re-estimating the baseline specification using the "depreciated" version of the patent stock variables yields the results displayed in Appendix 4.C, Table 4.9. These results do not depart from the preferred specification, either in sign or significance. There is however a slight change in the magnitude of the coefficients—from 0.34 to 0.27—which is similar to the one observed in the previous robustness check with the unweighted version of the stock of patented inventions (Appendix 4.C, Table 4.8).

Robustness – Reduced sample. Finally, there is a possibility that our estimation is affected by the fact that many observations in our sample have a value of zero for the main variable of interest—green patented inventions counts. 82% of the firms we observe never filed a patent in the period covered by our data. This might cause some statistical issues due to zero inflation (Czado et al., 2007).

To test for this bias, we run the baseline specification on a subsample of firms that have filed at least one patent between 2013 and 2020. The results for this test are reported in Appendix 4.C, Table 4.10. This regression can be understood as studying the intensive effect of the stock of green patented inventions on firms' distance to the previous year's frontier. The magnitude of the coefficient for the stock of green patented inventions increases slightly in magnitude—from 0.34 to 0.37—and decreases in significance—from a 1% to a 5% confidence level.

4.7 Discussion

The results presented in the previous section can be summarized as two key insights: (1) there is a high level of heterogeneity in the dispersion of efficiency levels between sectors; (2) green patenting is inversely related to technical progress. This section discusses some possible explanations and policy implications for each of these results.

Heterogeneity of dispersion in efficiency. The dispersion of efficiency within a sector can be interpreted as an indicator of its potential for emission reductions. Greater dispersion suggests that the least efficient firms are significantly lagging behind the most efficient ones, implying a higher opportunity for efficiency gains and corresponding emission cuts. Using a back-of-the-envelope calculation of efficiency[15] and potential emission reductions[16], we can evaluate this potential at the sectoral level.

Figure 4.10 illustrates that there is considerable variation across sectors in both the mean efficiency score and the total potential for emission reductions. The cement sector

[15]Efficiency is computed as $1/(1 + \text{distance}_{it})$.

[16]Potential emission cuts within a sector are computed as $\sum_{i=1}^{N} \text{emissions}_{it} \cdot (1 - \text{efficiency}_{it})$.

stands out, with the highest estimated potential for emission reductions—approximately 9 $MtCO_2$—despite exhibiting a relatively high average efficiency of 83%. This is largely due to the sector's inherently high emission intensity. Lime and plaster, along with Chemicals, follow as the sectors with the next highest reduction potential. In contrast, the EAF Iron and steel sector has the highest mean efficiency at 92%, but also the lowest potential for emission reductions, at just 0.2 $MtCO_2$, reflecting its significantly lower carbon intensity.

These findings offer valuable insights for policymakers regarding the emission reduction potential achievable through existing technologies. Overall, the analysis suggests that the scope for further reductions through efficiency improvements alone is limited. Even in the case of cement production—the sector with the greatest potential—the estimated reduction accounts for only about 10% of its total emissions. While this is not negligible, it highlights the critical need for technological innovation. To achieve climate targets, policy efforts should focus on transformative solutions that enable deep decarbonization beyond what incremental efficiency gains can deliver.

Figure 4.10: Mean efficiency and total potential emission reductions by sector (2020)



Green patenting and efficiency. At first glance, the finding that green patenting is associated with reduced firm-level efficiency may seem counterintuitive. However, we offer

an explanation grounded in the broader economic and technological context, which—while supported by existing literature—warrants further empirical testing.

Our argument builds on the theory of carbon-intensive technology lock-in, as proposed by Acemoglu et al. (2012) and empirically supported by Aghion et al. (2016) and Janipour et al. (2020). Firms relying on brown technologies benefit from decades of accumulated knowledge, infrastructure, and learning-by-doing. In contrast, firms shifting toward green technologies face higher costs, technical uncertainty, and weaker performance relative to the established norm. As a result, green inventive firms may appear less efficient in relative terms, simply because their brown-technology peers are improving at a faster rate within the current paradigm.

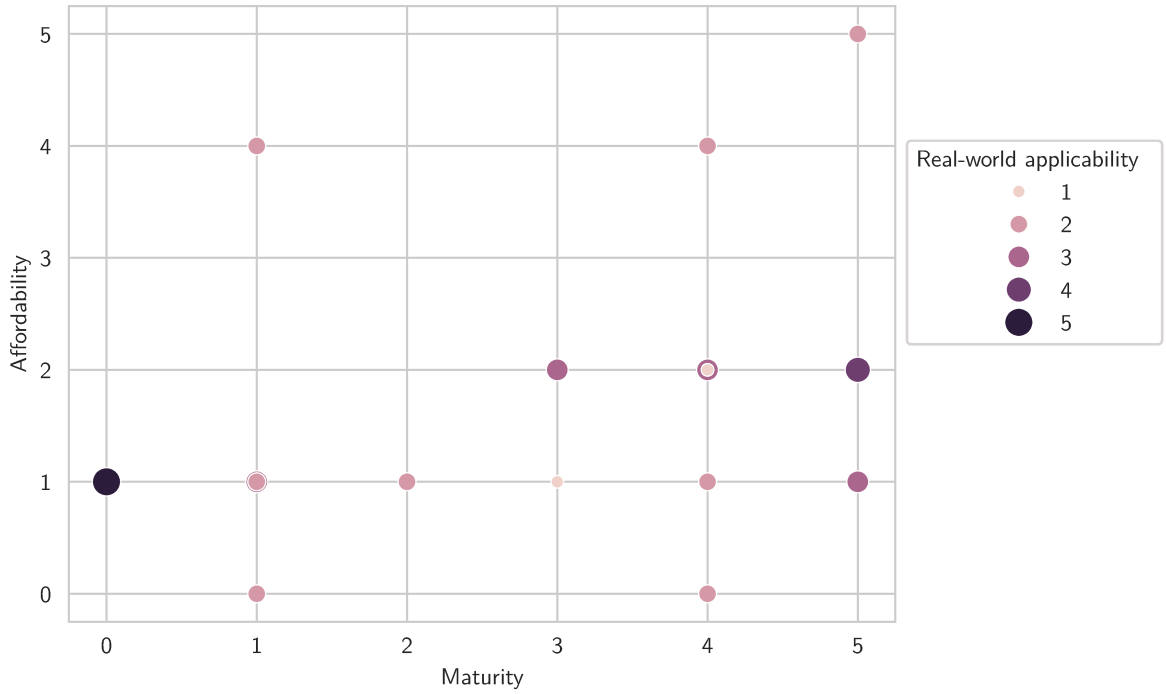
This explanation is particularly relevant in the context of heavy industry, where green alternatives remain largely immature. Even where mature technologies exist, they tend to be costlier than conventional options or face practical constraints, limiting their adoption. A recent review by Diesing et al. (2025) finds that none of the available low-carbon technologies across major industrial sectors—Iron and steel, Cement, Chemicals, Glass, and Pulp and paper—score above 3 (on a 1–5 scale) across all three dimensions of maturity, affordability, and applicability (Figure 4.11). This suggests that, despite investment in green patenting, these technologies are not yet ready for widespread deployment. It also underscores that patents protect inventions which may take a long time before being profitable or even never succeed . Additionally, heavy industrial assets are long-lived, and are typically not retired before the end of their life cycle, which slows the pace at which cleaner technologies can be adopted.

There is also a methodological consideration related to how we define the technological frontier. Our directional distance function treats a 1% increase in output as equivalent to a 1% decrease in emissions. This implies that firms can improve efficiency by reducing emissions, increasing output, or both. In this context, green patenting might lead to better environmental performance while having no effect—or even a negative effect—on production-side efficiency. This interpretation aligns with findings from Xiang and Geng (2024), who also report mixed impacts of green patenting on firm efficiency in Chinese industry and it challenges the strong version of the Porter hypothesis (Porter & van der Linde, 1995).

Several macro-level studies offer similar insights, showing that green inventions alone may not reduce emissions unless accompanied by strong prior economic growth and complementary enabling factors (Du et al., 2019; Sahoo et al., 2022). A similar dynamic may be present in our data.

To test this hypothesis more directly, further studies could adjust the directional vector in the TFA to assign more weight either to emissions or to output. If green

Figure 4.11: Viability of low-carbon heavy industry technologies



Source: Authors based on Diesing et al. (2025)

patenting shows a negative effect when output is prioritized, but a positive effect when emissions are prioritized, this would lend further support to the idea that green patented inventions boost environmental efficiency but not necessarily productive efficiency.

An alternative explanation is that our study period may simply be too short to capture the effects of green patenting. The transition from invention to commercialization is often slow and incremental, especially in capital-intensive sectors. As such, the benefits of green patenting might not yet be fully observable. A longer time horizon or the use of a model that explicitly captures delayed effects, such as a Nonlinear Autoregressive Distributed Lag model could help uncover these lagged relationships and better account for the cumulative impact of green patented inventions over time.

4.8 Conclusion

This paper has examined the relationship between firm-level efficiency, green patenting, technological progress, and the potential for emission reductions in the context of heavy industry sectors regulated by the EU ETS. Our findings highlight several key insights with important implications for both research and policy.

First, we observe substantial heterogeneity in the dispersion of efficiency scores across firms within sectors. This variation translates into differing levels of emission reductions

that can be achieved solely through improvements in inefficiency. However, the overall picture suggests that incremental efficiency gains alone are insufficient. Most sectors will require more profound shifts in production technologies to achieve the deep decarbonization necessary to meet climate targets.

Second, our analysis shows that technological progress is driven by a small number of firms within each sector. This suggests the presence of a strong leader–laggard dynamic. From a policy perspective, this raises two distinct and potentially complementary strategic options: policymakers can either support the sectoral "champions" that are already innovating and leading in technical change, or they can adopt a broader approach that promotes technological diffusion by supporting a wider base of firms to stimulate more inclusive and competitive innovation.

Finally, our findings indicate that green patenting does not directly imply improvements in firm-level efficiency, even when the measure of efficiency includes both emission and output in its measure. This challenges the interpretation of earlier studies such as Calel and Dechezleprêtre (2014) and Calel (2020), which primarily measure the effect of the EU ETS on green patenting activity. Our results suggest that green patents do not necessarily translate into effective or implemented decarbonization technologies—at least in the short run that is analyzed in this paper. Consequently, policymakers should be cautious in using patent-based indicators to evaluate the success of climate policy. Greater emphasis should instead be placed on direct measures of technological change and real-world emission reductions at the firm level.

Future research can extend and refine the conclusions found in this paper. Other methodologies could be applied to measure firm-level efficiencies, namely Bayesian modeling which this paper has identified as the most promising and flexible methodology available, despite its heavy computational needs. Additionally, to further understand the effect of green patenting on firm-level efficiency outcomes, it could be useful to study innovation in sectors that are either upstream or downstream of the regulated heavy industry sectors. It could be that the green patenting that really matters to reduce emissions comes from these sectors instead of directly from the regulated sector.

Ultimately, achieving deep decarbonization in heavy industries will require a dual focus on accelerating technological breakthroughs among sectoral leaders while ensuring broader diffusion of innovations and process changes across lagging firms. Policymakers must also look beyond patent-based metrics and prioritize direct evidence of emission reductions when evaluating the effectiveness of climate regulations.

Appendix

4.A Sector-NACE correspondence table

Table 4.6: Aggregated Manufacturing Descriptions and Associated Codes

Aggregated sector code	N° firms	4-digit NACE code	N° firms
Manufacture of articles of paper and paperboard	42	Manufacture of veneer sheets and wood-based panels	3
		Wholesale of wood, construction materials and sanitary equipment	7
		Manufacture of paper stationery	1
		Manufacture of other articles of paper and paperboard	5
		Manufacture of articles of paper and paperboard	4
		Manufacture of paper and paper products	1
		Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	18
		Manufacture of wallpaper	1
		Manufacture of other products of wood; manufacture of articles of cork, straw and plaiting materials	1
		Silviculture and other forestry activities	1
Manufacture of basic iron and steel and of ferro-alloys	60	Manufacture of basic iron and steel and of ferro-alloys	60
Manufacture of bricks, tiles and construction products, in baked clay	70	Manufacture of bricks, tiles and construction products, in baked clay	70

Table 4.6: Aggregated Manufacturing Descriptions and Associated Codes

Aggregated sector code	N° firms	4-digit NACE code	N° firms
Manufacture of cement	43	Manufacture of cement	43
Manufacture of ceramic tiles and flags	96	Manufacture of ceramic tiles and flags	96
Manufacture of hollow glass	45	Manufacture of hollow glass	45
Manufacture of household and sanitary goods	26	Manufacture of household and sanitary goods and of toilet requisites	26
Manufacture of lime and plaster	59	Manufacture of plaster products for construction purposes	7
		Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate	8
		Manufacture of lime and plaster	44
Manufacture of other basic chemicals	34	Manufacture of fertilisers and nitrogen compounds	10
		Manufacture of other inorganic basic chemicals	12
		Manufacture of other organic basic chemicals	12
Manufacture of other basic metals	29	Manufacture of basic precious and other non-ferrous metals	1
		Lead, zinc and tin production	6
		Manufacture of basic metals	1
		Mining of other non-ferrous metal ores	2
		Wholesale of metals and metal ores	1
		Copper production	8
		Aluminium production	10
Manufacture of other chemical products n.e.c.	59	Manufacture of dyes and pigments	2

Table 4.6: Aggregated Manufacturing Descriptions and Associated Codes

Aggregated sector code	N° firms	4-digit NACE code	N° firms
		Manufacture of basic chemicals, fertilisers and nitrogen compounds, plastics and synthetic rubber in primary forms	2
		Manufacture of plastics in primary forms	17
		Wholesale of chemical products	3
		Manufacture of chemicals and chemical products	3
		Manufacture of industrial gases	4
		Manufacture of paints, varnishes and similar coatings, printing ink and mastics	14
		Manufacture of basic pharmaceutical products	1
		Manufacture of synthetic rubber in primary forms	1
		Manufacture of other chemical products n.e.c.	10
		Manufacture of glues	2
Manufacture of other glass products	42	Manufacture of glass and glass products	7
		Shaping and processing of flat glass	2
		Manufacture of flat glass	14
		Manufacture and processing of other glass, including technical glassware	6
		Manufacture of glass fibres	13
Manufacture of other non-metallic mineral products n.e.c.	48	Cutting, shaping and finishing of stone	1
		Manufacture of other articles of concrete, plaster and cement	2
		Manufacture of other ceramic products	4

Table 4.6: Aggregated Manufacturing Descriptions and Associated Codes

Aggregated sector code	N° firms	4-digit NACE code	N° firms
		Manufacture of other non-metallic mineral products n.e.c.	19
		Manufacture of refractory products	10
		Manufacture of concrete products for construction purposes	5
		Manufacture of ceramic sanitary fixtures	7
Manufacture of paper and paperboard	160	Manufacture of paper and paperboard	156
		Manufacture of pulp, paper and paperboard	4
Manufacture of pulp	21	Manufacture of pulp	21
Processing of metals	45	Other non-ferrous metal production	1
		Manufacture of wire products, chain and springs	1
		Forging, pressing, stamping and roll-forming of metal; powder metallurgy	12
		Manufacture of railway locomotives and rolling stock	1
		Casting of iron	7
		Manufacture of other taps and valves	1
		Cold drawing of wire	2
		Manufacture of fabricated metal products, except machinery and equipment	1
		Casting of steel	4
		Treatment and coating of metals	1
		Manufacture of other fabricated metal products n.e.c.	4

Table 4.6: Aggregated Manufacturing Descriptions and Associated Codes

Aggregated sector code	N° firms	4-digit NACE code	N° firms
		Cold forming or folding	1
		Casting of metals	1
		Casting of light metals	1
		Casting of other non-ferrous metals	2
		Manufacture of tubes, pipes, hollow profiles and related fittings, of steel	2
		Manufacture of metal structures and parts of structures	2
		Manufacture of other products of first processing of steel	1

4.B Summary of TFA literature on European heavy industry

Table 4.7: Literature applying TFA to European heavy industry secto

Paper	# DMU	Geographical Coverage	Observation Level	Sectoral Coverage	Time Coverage	Method
Löschel et al. (2019)	473	Germany	Firm	4 manuf.	2003-2012	SFA
Baudry and Faure (forthcoming)	249	EU	Firm	9 manuf.	2012-2021	LP
Morfeldt and Silveira (2014)	15	EU	Country	Iron and steel	1992-2010	DEA

Note: DMU stands for Decision-Making Unit.

Table 4.7: Literature applying TFA to European heavy industry secto

Paper	# DMU	Geographical Coverage	Observation Level	Sectoral Coverage	Time Coverage	Method
Bostian et al. (2018)	46	Sweden	Firm	Pulp and paper	2002-2008	DEA
Lundgren et al. (2015)	90	Sweden	Firm	Pulp and paper	1998-2002	DEA
Oggioni et al. (2011)	21	Global	Country	Cement	2005-2008	DEA
Dzemydaitė and Naruševičius (2023)	22	EU	Country	Chemicals	2000-2019	SFA

Note: DMU stands for Decision-Making Unit.

Table 4.7: Literature applying TFA to European heavy industry secto

Paper	# DMU	Geographical Coverage	Observation Level	Sectoral Coverage	Time Coverage	Method
Rekker et al. (2023)	24	EU	Firm	Chemicals	2015-2020	Deterministic LP
Zurano-Cervelló et al. (2018)	14	EU	EU	14 manufacturing sectors	2009	DEA

Note: DMU stands for Decision-Making Unit.

4.C Econometric robustness checks

Table 4.8: Unweighted CPC class

	Dependent variable: Distance$_t$				
	(1)	(2)	(3)	(4)	(5)
	OLS	OLS	OLS	OLS	OLS
log unweightStockGreenInnov$_{t-1}$	0.240***		0.241***		0.243***
	(0.0777)		(0.0778)		(0.0822)
log unweightStockInnov$_{t-1}$		0.0434*		0.0443*	-0.00265
		(0.0224)		(0.0224)	(0.0230)
Stringency $_{t-1}$			0.177	0.195	0.179
			(0.529)	(0.528)	(0.530)
Installation Closed $_t$			-0.119*	-0.120*	-0.119*
			(0.0605)	(0.0614)	(0.0607)
Installation Opened $_t$			-0.0265	-0.0240	-0.0263
			(0.0177)	(0.0177)	(0.0175)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Country-Year FE	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.945	0.945	0.945	0.945	0.945
F-statistic	9.535	3.767	3.275	2.081	2.624
Observations	6104	6104	6104	6104	6104

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standards errors are reported in parentheses. Errors are corrected for clustering at the sector-year level.***, ** and * indicate significance at the one, five and ten percent levels respectively.

Table 4.9: Patent stock variables with depreciation

	Dependent variable: Distance$_t$				
	(1)	(2)	(3)	(4)	(5)
	OLS	OLS	OLS	OLS	OLS
log DeprecStockGreenInnov$_{t-1}$	0.269***		0.270***		0.270***
	(0.0798)		(0.0798)		(0.0833)
log DeprecStockInnov$_{t-1}$		0.0461**		0.0470**	-0.0000499
		(0.0228)		(0.0229)	(0.0237)
Stringency $_{t-1}$			0.184	0.196	0.184
			(0.529)	(0.529)	(0.530)
Installation Closed $_t$			-0.118*	-0.119*	-0.118*
			(0.0605)	(0.0613)	(0.0607)
Installation Opened $_t$			-0.0266	-0.0238	-0.0266
			(0.0176)	(0.0177)	(0.0175)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Country-Year FE	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.945	0.945	0.945	0.945	0.945
F-statistic	11.34	4.077	3.675	2.168	2.943
Observations	6104	6104	6104	6104	6104

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standards errors are reported in parentheses. Errors are corrected for clustering at the sector-year level.***, ** and * indicate significance at the one, five and ten percent levels respectively.

Table 4.10: Reduced Sample

	Dependent variable: Distance$_t$				
	(1)	(2)	(3)	(4)	(5)
	OLS	OLS	OLS	OLS	OLS
log StockGreenInnov$_{t-1}$	0.374**		0.367**		0.355**
	(0.145)		(0.145)		(0.145)
log StockInnov$_{t-1}$		0.0525*		0.0569*	0.0349
		(0.0312)		(0.0308)	(0.0313)
Stringency $_{t-1}$			4.540**	4.769**	4.576**
			(2.248)	(2.203)	(2.249)
Installation Closed $_t$			-0.182	-0.204	-0.194
			(0.200)	(0.196)	(0.199)
Installation Opened $_t$			-0.109	-0.0916	-0.112
			(0.0896)	(0.0931)	(0.0899)
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No
Country-Year FE	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.931	0.930	0.931	0.930	0.931
F-statistic	6.625	2.833	2.350	2.440	2.142
Observations	1092	1092	1092	1092	1092

The dependent variable is a continuous variable representing a firm's distance to the previous year's technological frontier. Heteroskedasticity-robust standards errors are reported in parentheses. Errors are corrected for clustering at the sector-year level.***, ** and * indicate significance at the one, five and ten percent levels respectively.

Conclusion

C.1 Revisiting Dr. Competition and Mr. Climate

This thesis began by interrogating a central tension in the EU's climate policy: can industrial decarbonization and competitiveness be complementary forces, or must policymakers sacrifice one to pursue the other? Framed through the lens of "Dr. Competition" and "Mr. Climate", the question becomes whether the EU can harmonize these two objectives into a cohesive strategy—and if yes, how?— or if the bloc will remain trapped in a Jekyll-and-Hyde struggle which ends like Robert Louis Stevenson's novel, with the death of the main character.

To avoid this ill fate, the EU has set itself the goal of being a front-runner in addressing climate change. Policymakers have recognized the opportunities presented by the green transition to bolster the EU's economic resilience and to become a leader in the new green economy (Draghi, 2024; European Commission, 2019; Tagliapietra et al., 2019). Despite these aspirations, the reality falls short: climate policy stringency levels are currently not high enough to achieve deep enough cuts in emissions to achieve carbon neutrality by 2050 (EEA, 2024a, 2024b; IPCC, 2023).

One major reason for this discrepancy between climate objectives and implemented policies is the threat of carbon leakage. Policymakers are weary of imposing very stringent climate policies which would lead their industries to lose market shares to less regulated competition and relocate their production outside of the regulated region (Markusen, 1975; Markusen et al., 1993). This is an especially strong risk in a world of fragmented climate policies (Clausing & Wolfram, 2023; Weber et al., 2025).

Recent geopolitical shifts— namely resurgent protectionism, China's clean tech dominance, and the U.S.'s climate policy reversal—have intensified this tension, reframing decarbonization as both an ecological imperative and a geopolitical contest. The EU's response, epitomized by initiatives like the Competitiveness Compass, reflects the precarious balancing act of pursuing climate neutrality without ceding industrial leadership.

C.2 Summary of findings and contributions

General contributions. This thesis moves beyond policy debates by empirically testing the competition-climate nexus in EU heavy industries. Through sector- and firm-level analyses of carbon leakage risks, corporate performance, and technological frontiers, it reveals a critical insight: the relationship between decarbonization and competitiveness is not universal but contingent on market structure, innovation pathways, and policy design. While some sectors (e.g., steel) demonstrate compatibility, others (e.g., cement) face acute trade-offs, challenging the notion of a one-size-fits-all industrial strategy.

Taken as a whole, this thesis contributes to scholarly and policy understanding of the links between EU climate policy and industrial competitiveness through four key contributions: first, a systematic synthesis of existing literature to identify gaps and contradictions; second, a static analysis of carbon leakage mechanisms in the EU ETS' third phase; third, a forward-looking examination of how technological shifts can reshape long-term industrial competitiveness; and fourth, a new and open-source method to match micro-level databases that do not have a common identifier. Through these contributions, the thesis challenges oversimplified assumptions about the relationship between industrial decarbonization and competitiveness and provides actionable policy recommendations.

Chapter 1. Chapter 1 is the first systematic review of the economic literature on carbon leakage across all channels and methodologies applied to study it. This analysis highlights three main results in this literature: (1) the first two phases of the EU ETS have not caused carbon leakage because its stringency has not been high enough, but this may change as stringency increases; (2) the energy channel has not yet caused any noticeable leakage, but is predicted to cause significant leakage in *ex ante* models, thus requiring continued evaluation; (3) policymakers are not currently exploiting the innovation channel much, despite its potential to reduced emissions domestically and abroad.

This chapter also identifies gaps in this literature which are addressed in the rest of the thesis. These include: (1) the gap in carbon leakage estimates between *ex ante* and *ex post* literature; (2) how the EU ETS' impacts have changed following stringency increases after Phase II; and (3) how green innovation can change long-term competitiveness and decarbonization dynamics in the EU's heavy industry.

Chapter 2. Chapter 2 studies one of the reasons for the gap between *ex ante* and *ex post* estimates of carbon leakage, namely by integrating market structure into an *ex ante* estimation of carbon leakage. Most *ex ante* models assume perfect competition in their models, while *ex post* literature reflects the true, less than perfectly competitive

conditions of industrial markets. This chapter applies a tool from competition economics, the hypothetical monopolist test (or SSNIP test) to account for market structure at the product level.

The analysis reveals three key results: (1) clinker exhibits the highest leakage risk, driven by relatively low product differentiation and trade costs; (2) hydraulic cement faces moderate leakage risk, whereas flat steel has a relatively low risk of leakage, reflecting regional specialization patterns; (3) EU producers' limited ability to compete in foreign markets suggests that fears about carbon pricing disproportionately harming industrial exporters may be overstated. These findings collectively emphasize the importance of designing anti-leakage policies that account for differences in product-specific market dynamics and competitive structures.

Chapter 3. Chapter 3 addresses the need for research on the decarbonization-competitiveness nexus in the EU ETS' third phase. Most research has so far focused on the carbon market's first two phases due to data limitations, as highlighted in Chapter 1. Chapter 3 makes three key contributions: (1) proposing a new measure of carbon intensity that is based on production volumes rather than value as has been the case in previous literature; (2) expanding and updating the firm-level matching between the EU Transaction Log and ORBIS through a Natural Language Processing approach; and (3) analyzing climate-economic performance linkages at the firm level specifically for Phase III of the EU ETS.

The main result of this chapter is that firms that reduced their emission intensity during Phase III did not worsen their financial performance as a result. In some cases, their financial performance was even slightly improved. This indicates that there have been no short-term losses in competitiveness, even in trade-exposed and carbon-intensive sectors.

Chapter 4. Chapter 4 moves away from the static and short-term approaches of Chapters 2 and 3 by looking into the technological change of EU heavy industries firms during the EU ETS' third phase. Its main contributions are (1) the use of a parametric quadratic-linear minimization program for technological frontier analysis, which overcomes the inconsistent handling of emissions in other parametric methodologies; (2) linking firm-level patent data (PATSTAT) with EU ETS data on emissions (EU Transaction Log) and financial and economic results (ORBIS); and (3) focusing on the whole of the EU ETS' third phase, during which stringency increased.

This study reveals three key insights on efficiency trends and technological change in EU ETS-regulated heavy industries. First, while firm-level efficiency improvements have

the potential to yield some emission reductions, deep decarbonization requires transformative technological shifts, as incremental gains are insufficient. Second, innovation is currently concentrated in a few 'leader' firms, suggesting policies must accelerate breakthroughs by these champions and foster broader diffusion across lagging firms. Finally, green patenting does not reliably signal short-term efficiency gains or implemented decarbonization, urging policymakers to prioritize direct emission metrics over patent counts when evaluating climate policy effectiveness.

C.3 Policy lessons

The findings of this thesis can be distilled into four main policy lessons.

First, policy design must prioritize granularity and real-world impact assessments to accurately target emission reductions and leakage risks. This applies to the EU's Carbon Border Adjustment Mechanism, which will be most effective if it uses product-level and origin-dependent carbon content data (Chapter 1), as well as *ex ante* measures of carbon leakage risk (Chapter 2). While aggregate measures can be a first start to implement policies, efforts should also be made to develop granular data reporting and infrastructure. Proxy data such as green patenting can also serve as preliminary indicators in policy evaluations, but they must always be supplemented with direct assessments of real-world emission reductions to verify that intended decarbonization outcomes are fully achieved (Chapter 4).

Second, innovation diffusion must be actively supported as technological progress remains unevenly distributed both within the EU and between EU and non-EU countries. While a small subset of firms drives green patenting in EU ETS firms (Chapter 4), broader adoption of low-carbon technologies is necessary for meaningful emission reductions. Policymakers should facilitate knowledge transfers, both within regulated sectors and across supply chains, to ensure that breakthroughs in low-carbon technologies are widely implemented. At the global level, reinvesting CBAM revenues into an international green technology fund could accelerate this process (Chapter 1).

Third, climate policy must re-balance competitiveness concerns with decarbonization effectiveness. Evidence suggests that the EU ETS has not significantly harmed firms' financial performance (Chapter 3). This indicates room to reduce the generosity of leakage mitigation policies and to strengthen incentives and support for structural decarbonization. Moreover, historical over-estimations of leakage risk suggest that policies should complement the focus on shielding industry competitiveness with ensuring measurable emission reductions (Chapter 1).

Finally, policies must remain adaptive and globally coordinated. Technological change and shifting economic dynamics require continuous monitoring and flexibility in policy implementation. Since both competitiveness and climate challenges are inherently global, regional measures alone—such as the EU ETS or CBAM—are insufficient. Policymakers must pursue multilateral cooperation to align industrial strategies, carbon pricing, and green innovation efforts across borders.

By combining granular policy design, proactive technology diffusion, a stronger emphasis on real-world decarbonization, and sustained international engagement, the EU can more effectively steer its heavy industry toward deep emission reductions without sacrificing economic resilience.

C.4 Limitations and avenues for future research

As with all research, this thesis has some inherent limitations which open up avenues for future research. I will highlight three of these limitations and future research avenues in this section, choosing those which are the most relevant for EU policymaking and most closely related to the topic of this thesis, namely the climate-competitiveness nexus.

C.4.1 Granular and timely data

Limitation. A fundamental limitation of this thesis lies in the data that has been used. Despite significant efforts to compile relevant datasets to study the interactions between climate policy and competitiveness at a detailed level, the works presented here do not study fully representative samples and observations do not go beyond 2020 for the most part. This is because existing databases often have data gaps (even proprietary ones such as ORBIS), are fragmented, insufficiently structured, or incomplete in their coverage.

Future research directions. An essential step forward is the development of publicly and easily accessible, structured firm-level datasets that can facilitate empirical research in this field. Policymakers are starting to work towards this. For instance, the European Commission is developing an alternative to ORBIS available to researchers through its CompNet initiative,[17] and the OECD is working on firm-level climate data through its IFCMA program.[18] Independent researchers have also contributed by collecting, structuring, and opening access to relevant datasets—for instance, Jan Abrell's work on the

[17] More information available on the CompNet website: https://www.comp-net.org/.

[18] More information available on the IFCMA's website: https://www.oecd.org/en/about/programmes/inclusive-forum-on-carbon-mitigation-approaches.html.

EU ETS Transaction Log (EUTL) [19] and the open-source matching between ORBIS and the EUTL developed in this thesis in partnership with the European Commission's DG GROW.[20] Other initiatives, such as Climate TRACE's remote-sensing approach to installation-level emission measurement, demonstrate the potential for novel methodologies to bridge existing data gaps.[21] While many initiatives are ongoing in this domain, there is still a long way to go before data is easily available and these different sources can be linked together at the firm level. Promoting open-source research and linkages between institutions and researchers can help bridge this gap. This type of data is essential for policymakers to develop effective policies that achieve deep emission reductions while retaining competitiveness.

C.4.2 Time scope of study

Limitation. This thesis primarily examines developments up to 2020, yet the post-2020 period has introduced profound changes that merit further investigation. The EU's heavy industry landscape has been shaped by major shocks, including a steep increase in the EU ETS' price of allowances, the COVID-19 recovery, the implementation of the Carbon Border Adjustment Mechanism, the Russian invasion of Ukraine and the resulting energy crisis, as well as shifting geopolitical dynamics, such as the return to power of President Trump in the U.S. These developments create a distinct policy and economic environment that this thesis does not fully capture.

Future research directions. Several questions emerge in the post-2020 context. First, the implementation of the world's first large-scale CBAM warrants empirical analyses of its impacts on domestic and foreign emissions. Specific research questions that should be explored include: will the switch from free allowances to a CBAM change incentives for industrial producers? Will a CBAM cause reshuffling? Or create demand for greener products that other countries will try to address? Additionally, researchers could look into the CBAM's impacts on the global climate policy landscape. These questions could be addressed through the application of geo-spatial econometrics combined with trade models.

Second, the existence of and interaction between different channels of carbon leakage remains poorly understood. It will be particularly important to watch for the development of the energy channel, which has been highlighted as a risk of major carbon leakage by

[19] More information on the website developed by Jan Abrell: https://www.euets.info/.

[20] More information on the website dedicated to this matching: https://single-market-economy.ec.europa.eu/single-market/services/economic-analysis/matching-eu-transaction-log-orbis-database_en?prefLang=cs.

[21] More information available on Climate TRACE's website: https://climatetrace.org/.

ex ante modeling. Monitoring price shocks on energy markets as a result of climate policy developments through time series analysis or event studies can contribute to this. Additionally, it will be essential to monitor and promote negative carbon leakage through the innovation channel by better understanding the chain of causality between climate policies, innovation and emission reductions. Studying unintended effects like rebound or waterbed effects is of particular importance to ensure that emission cuts actually happen.

C.4.3 Transformative changes for deep decarbonization

Limitation. This thesis does not fully address the long-term structural changes that are needed to achieve deep decarbonization in heavy industry sectors. Since most of the work presented here is empirical and these changes have yet to be implemented in most heavy industries, their impact on competitiveness has not been assessed. Examples of such changes include shifting toward lower overall consumption patterns, using more alternative construction materials, developing hydrogen-based production and carbon capture and utilization/storage. These changes go far beyond marginal improvements in material or energy efficiency, and are likely to redefine industrial competitiveness in ways that traditional economic indicators cannot capture.

Future research directions. Addressing this limitation requires a fundamental rethinking of current analytical frameworks. Metrics such as profit, turnover, and cost-competitiveness may be inadequate when entire industries are undergoing significant transformations—some even contracting or disappearing, while others emerge. Future research should explore new conceptual models that move beyond simply preserving competitiveness in existing industries and instead focus on understanding how societies can best meet all their needs—including ecological needs. This may involve developing more comprehensive metrics of industrial competitiveness as has been proposed by the Beyond GDP strand of research in the context of growth metrics (Bleys, 2012; Chancel et al., 2014). Developing measures of the utility of an industrial good, or of its carbon intensity in terms of functional units rather than volume or value are examples of this. The more work is done to shift away from purely economic values of competitiveness towards social welfare values, the easier the transition will be.

C.5 Final remarks

This thesis has aimed to demonstrate that addressing climate change and maintaining the competitiveness of heavy industry in the EU need not be a zero sum game. Sector-

specific pathways can be developed to harmonize both objectives. However, this will require efficient, holistic, and balanced policies that are backed by science, a tremendous amount of political courage and public support, and enough flexibility to adapt to a constantly change geopolitical landscape.

To make things even more complex, the questions posed in this thesis are just one piece of a much larger puzzle. The trade-offs between climate action and competitiveness are part of a broader set of tensions—between climate action and social justice, democracy, global equity, security, and autonomy, to name just a few. A truly sustainable transition requires a holistic approach, balancing decarbonization with all the societal goals that EU citizens aspire to.

Bibliography

Abrell, J. (2022). Database for the European Union Transaction Log.

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. *American Economic Review*, *102*(1), 131–166. Retrieved March 9, 2021, from https://www.aeaweb.org/articles?id=10.1257/aer.102.1.131

Acemoglu, D., & Autor, D. (2011). Skills, Tasks and Technologies: Implications for Employment and Earnings*. In D. Card & O. Ashenfelter (Eds.), *Handbook of Labor Economics* (pp. 1043–1171, Vol. 4). Elsevier. https://doi.org/10.1016/S0169-7218(11)02410-5

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., & Van Reenen, J. (2016). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry [Publisher: The University of Chicago Press]. *Journal of Political Economy*, *124*(1), 1–51. https://doi.org/10.1086/684581

Agnolucci, P., & Arvanitopoulos, T. (2019). Industrial characteristics and air emissions: Long-term determinants in the UK manufacturing sector. *Energy Economics*, *78*, 546–566. https://doi.org/10.1016/j.eneco.2018.12.005

Ahmad, M. F., Ahmad, F. A., Alsayegh, A. A., Zeyaullah, M., AlShahrani, A. M., Muzammil, K., Saati, A. A., Wahab, S., Elbendary, E. Y., Kambal, N., Abdelrahman, M. H., & Hussain, S. (2024). Pesticides impacts on human health and the environment with their mechanisms of action and possible countermeasures. *Heliyon*, *10*(7), e29128. https://doi.org/10.1016/j.heliyon.2024.e29128

Aichele, R., & Felbermayr, G. (2015). Kyoto and Carbon Leakage: An Empirical Analysis of the Carbon Content of Bilateral Trade. *Review of Economics & Statistics*, *97*(1), 104–115. https://doi.org/10.1162/REST_a_00438

Albertini, E. (2013). Does Environmental Management Improve Financial Performance? A Meta-Analytical Review [Publisher: SAGE Publications Inc]. *Organization & Environment*, *26*(4), 431–457. https://doi.org/10.1177/1086026613510301

Alexeeva-Talebi, V., Böhringer, C., Löschel, A., & Voigt, S. (2012). The value-added of sectoral disaggregation: Implications on competitive consequences of climate change policies. *Energy Economics*, *34*, S127–S142. https://doi.org/10.1016/j.eneco.2012.10.001

Ambec, S., Cohen, M. A., Elgie, S., & Lanoie, P. (2013). The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Review of Environmental Economics and Policy*, *7*(1), 2–22. https://doi.org/10.1093/reep/res016

Ambec, S., Esposito, F., & Pacelli, A. (2024). The economics of carbon leakage mitigation policies. *Journal of Environmental Economics and Management*, *125*, 102973. https://doi.org/10.1016/j.jeem.2024.102973

Anderson, J. E., & van Wincoop, E. (2003). Gravity with Gravitas: A Solution to the Border Puzzle. *American Economic Review*, *93*(1), 170–192. https://doi.org/10.1257/000282803321455214

Anderson, J. E., & van Wincoop, E. (2004). Trade Costs. *Journal of Economic Literature*, *42*(3), 691–751. https://doi.org/10.1257/0022051042177649

Anderson, J. E., & Yotov, Y. V. (2010). The Changing Incidence of Geography. *American Economic Review*, *100*(5), 2157–2186. https://doi.org/10.1257/aer.100.5.2157

Angelucci, S., Hurtado-Albir, F. J., & Volpe, A. (2018). Supporting global initiatives on climate change: The EPO's "Y02-Y04S" tagging scheme. *World Patent Information*, *54*, S85–S92. https://doi.org/10.1016/j.wpi.2017.04.006

Antimiani, A., Costantini, V., Kuik, O., & Paglialunga, E. (2016). Mitigation of adverse effects on competitiveness and leakage of unilateral EU climate policy: An assessment of policy instruments. *Ecological Economics*, *128*, 246–259. https://doi.org/10.1016/j.ecolecon.2016.05.003

Antimiani, A., Costantini, V., Martini, C., Salvatici, L., & Tommasino, M. C. (2013). Assessing alternative solutions to carbon leakage. *Energy Economics*, *36*, 299–311. https://doi.org/10.1016/j.eneco.2012.08.042

Armington, P. S. (1969). A Theory of Demand for Products Distinguished by Place of Production [Publisher: Palgrave Macmillan Journals]. *Staff Papers (International Monetary Fund)*, *16*(1), 159–178. https://doi.org/10.2307/3866403

Arroyo-Currás, T., Bauer, N., Kriegler, E., Schwanitz, V. J., Luderer, G., Aboumahboub, T., Giannousakis, A., & Hilaire, J. (2015). Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. *Technological Forecasting and Social Change*, *90*, 192–203. https://doi.org/10.1016/j.techfore.2013.10.002

Assaf, A. G., & Josiassen, A. (2016). Frontier Analysis: A State-of-the-Art Review and Meta-Analysis [Publisher: SAGE Publications Inc]. *Journal of Travel Research*, *55*(5), 612–627. https://doi.org/10.1177/0047287515569776

Atkinson, S. E., & Tsionas, M. G. (2018). Shadow directional distance functions with bads: GMM estimation of optimal directions and efficiencies. *Empirical Economics*, *54*(1), 207–230. https://doi.org/10.1007/s00181-017-1233-6

Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics*, *65*(2), 421–445. https://doi.org/10.1016/j.jinteco.2004.01.003

Bacchus, J. (2019). *What is a climate response measure? : Breaking the trade taboo in confronting climate change* (tech. rep. No. No. 220). Centre for International Governance Innovation.

Bajzik, J., Havranek, T., Irsova, Z., & Schwarz, J. (2020). Estimating the Armington elasticity; The importance of study design and publication bias. *Journal of International Economics*, *127*.

Balistreri, E., Al-Qahtani, A., & Dahl, C. (2010). Oil and Petroleum Product Armington Elasticities: A New-Geography-of-Trade Approach to Estimation. *The Energy Journal*, *31*(3), 167–179.

Balistreri, E. J., Kaffine, D. T., & Yonezawa, H. (2019). Optimal Environmental Border Adjustments Under the General Agreement on Tariffs and Trade. *Environmental and Resource Economics*, *74*(3), 1037–1075. https://doi.org/10.1007/s10640-019-00359-2

Balistreri, E. J., & Rutherford, T. F. (2012). Subglobal carbon policy and the competitive selection of heterogeneous firms. *Energy Economics*, *34*, S190–S197. https://doi.org/10.1016/j.eneco.2012.08.002

Barrows, G., & Ollivier, H. (2021). Foreign demand, developing country exports, and CO2 emissions: Firm-level evidence from India [Publisher: Elsevier]. *Journal of Development Economics*, *149*(100). Retrieved January 31, 2022, from https://econpapers.repec.org/article/eeedeveco/v_3a149_3ay_3a2021_3ai_3ac_3as0304387820301620.htm

Bas, M., Fontagné, L., Martin, P., & Mayer, T. (2015). *A la recherche des parts de marché perdues* (tech. rep. No. 23). Conseil d'Analyse Economique. Paris.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, *187*, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Baudry, M. (2022). The Porter's Hypothesis and its Implications for the Acceptability of Ambitious National Climate Policies. In K. F. Zimmermann (Ed.), *Handbook of Labor, Human Resources and Population Economics* (pp. 1–20). Springer International Publishing. https://doi.org/10.1007/978-3-319-57365-6_259-1

Baudry, M., & Dumont, B. (2021). Is the dragon going green? Insights into the leadership of Chna in low-carbon patents. *Mimeo*.

Baudry, M., & Faure, A. (2021). Technological progress and carbon price formation: An analysis of EU-ETS plants. *FAERE Working Paper*.

Baudry, M., & Faure, A. (N.d.). Decarbonization of EU-ETS firms: Myth or reality?

Bednar-Friedl, B., Schinko, T., & Steininger, K. W. (2012). The relevance of process emissions for carbon leakage: A comparison of unilateral climate policy options with and without border carbon adjustment. *Energy Economics*, *34*, S168–S180. https://doi.org/10.1016/j.eneco.2012.08.038

Bellocchi, A., Travaglini, G., & Vitali, B. (2023). How capital intensity affects technical progress: An empirical analysis for 17 advanced economies. *Metroeconomica*, *74*(3), 606–631. https://doi.org/10.1111/meca.12421

Berthou, A., & Emlinger, C. (2011). *The Trade Unit Value Database* (Working Papers No. 2011-10). CEPII. http://www.cepii.fr/CEPII/en/publications/wp/abstract.asp?NoDoc=3304

Bhawsar, P., & Chattopadhyay, U. (2015). Competitiveness: Review, Reflections and Directions [Publisher: SAGE Publications India]. *Global Business Review*, *16*(4), 665–679. https://doi.org/10.1177/0972150915581115

Bleys, B. (2012). Beyond GDP: Classifying Alternative Measures for Progress. *Social Indicators Research*, *109*(3), 355–376. https://doi.org/10.1007/s11205-011-9906-6

Boeters, S., & Bollen, J. (2012). Fossil fuel supply, leakage and the effectiveness of border measures in climate policy. *Energy Economics*, *34*, S181–S189. https://doi.org/10.1016/j.eneco.2012.08.017

Bogetoft, P., & Otto, L. (2011). *Benchmarking with DEA, SFA, and R* (Vol. 157). Springer New York. https://doi.org/10.1007/978-1-4419-7961-2

Böhringer, C., Balistreri, E. J., & Rutherford, T. F. (2012). The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29). *Energy Economics*, *34*, S97–S110. https://doi.org/10.1016/j.eneco.2012.10.003

Böhringer, C., Bye, B., Fæhn, T., & Rosendahl, K. E. (2012). Alternative designs for tariffs on embodied carbon: A global cost-effectiveness analysis. *Energy Economics*, *34*, S143–S153. https://doi.org/10.1016/j.eneco.2012.08.020

Böhringer, C., Bye, B., Fæhn, T., & Rosendahl, K. E. (2017). Targeted carbon tariffs: Export response, leakage and welfare. *Resource and Energy Economics*, *50*, 51–73. https://doi.org/10.1016/j.reseneeco.2017.06.003

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2012). Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Economics*, *34*, S208–S217. https://doi.org/10.1016/j.eneco.2012.09.011

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2016). The Strategic Value of Carbon Tariffs. *American Economic Journal: Economic Policy*, *8*(1), 28–51. https://doi.org/10.1257/pol.20130327

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2018). Embodied Carbon Tariffs [Publisher: Wiley-Blackwell]. *Scandinavian Journal of Economics*, *120*(1), 183–210. https://doi.org/10.1111/sjoe.12211

Böhringer, C., Fischer, C., Rosendahl, K. E., & Rutherford, T. F. (2022). Potential impacts and challenges of border carbon adjustments [Number: 1 Publisher: Nature Publishing Group]. *Nature Climate Change*, *12*(1), 22–29. https://doi.org/10.1038/s41558-021-01250-z

Borghesi, S., Cainelli, G., & Mazzanti, M. (2015). Linking emission trading to environmental innovation: Evidence from the Italian manufacturing industry. *Research Policy*, *44*(3), 669–683. https://doi.org/10.1016/j.respol.2014.10.014

Borghesi, S., Franco, C., & Marin, G. (2020). Outward Foreign Direct Investment Patterns of Italian Firms in the European Union's Emission Trading Scheme. *The Scandinavian Journal of Economics*, *122*(1), 219–256. https://doi.org/10.1111/sjoe.12323

Bostian, M., Färe, R., Grosskopf, S., Lundgren, T., & Weber, W. L. (2018). Time substitution for environmental performance: The case of Swedish manufacturing. *Empirical Economics*, *54*(1), 129–152. https://doi.org/10.1007/s00181-016-1180-7

Branger, F., & Quirion, P. (2014). Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. *Ecological Economics*, *99*, 29–39. https://doi.org/10.1016/j.ecolecon.2013.12.010

Branger, F., Quirion, P., & Chevallier, J. (2016). Carbon Leakage and Competitiveness of Cement and Steel Industries Under the EU ETS: Much Ado About Nothing. *The Energy Journal*, *37*(3), 109–135. https://doi.org/10.5547/01956574.37.3.fbra

Brozen, Y. (1951). Invention, Innovation, and Imitation. *The American Economic Review*, *41*(2), 239–257. Retrieved March 25, 2025, from https://www.jstor.org/stable/1910798

Burniaux, J.-M., & Oliveira Martins, J. (2012). Carbon leakages: A general equilibrium view. *Economic Theory*, *49*(2). Retrieved November 7, 2020, from https://search-proquest-com.acces-distant.sciencespo.fr/docview/916304952?accountid=13739&rfr_id=info%3Axri%2Fsid%3Aprimo

Busch, T., & Lewandowski, S. (2018). Corporate Carbon and Financial Performance: A Meta-analysis. *Journal of Industrial Ecology*, *22*(4), 745–759. https://doi.org/10.1111/jiec.12591

Calel, R. (2020). Adopt or Innovate: Understanding Technological Responses to Cap-and-Trade. *American Economic Journal: Economic Policy*, *12*(3), 170–201. https://doi.org/10.1257/pol.20180135

Calel, R., Colmer, J., Dechezleprêtre, A., & Glachant, M. (2021). *Do Carbon Offsets Offset Carbon?* (SSRN Scholarly Paper No. ID 3950103). Social Science Research Network. Rochester, NY. https://doi.org/10.2139/ssrn.3950103

Calel, R., & Dechezleprêtre, A. (2014). Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *The Review of Economics and Statistics*, *98*(1), 173–191. https://doi.org/10.1162/REST_a_00470

Caliendo, L., & Parro, F. (2015). Estimates of the Trade and Welfare Effects of NAFTA. *The Review of Economic Studies*, *82*(1), 1–44. https://doi.org/10.1093/restud/rdu035

Cambridge Dictionary. (2025). Heavy industry.

Cameron, A. (2025). Mind the Market: A Novel Measure of Carbon Leakage Risk. *Climate Economics Chair*. https://www.chaireeconomieduclimat.org/en/publications-en/20341/

Cameron, A., & Baudry, M. (2023). The case for carbon leakage and border adjustments: Where do economists stand? *Environmental Economics and Policy Studies*. https://doi.org/https://doi.org/10.1007/s10018-023-00366-0

Cameron, A., & Garrone, M. (2024). Carbon Intensity and Corporate Performance: A Micro-Level Study of EU ETS Industrial Firms. *Single Market Economics Conference Papers*, *[Working Paper]*. https://doi.org/10.2873/188206

Cameron, A., & Ho, V. (2024). *Matching the EU Transaction Log and ORBIS: A Natural Language Processing approach. Working paper.* (tech. rep.). European Commission, DG GROW, Chief Economist Team. Brussels.

Carbon Market Watch. (2015). *Carbon leakage myth buster* (tech. rep.). Carbon Market Watch. Brussels.

Carbone, J. C., & Rivers, N. (2017). The Impacts of Unilateral Climate Policy on Competitiveness: Evidence From Computable General Equilibrium Models. *Review of Environmental Economics and Policy*, *11*(1), 24–42. https://doi.org/10.1093/reep/rew025

Caron, J. (2012). Estimating carbon leakage and the efficiency of border adjustments in general equilibrium — Does sectoral aggregation matter? *Energy Economics*, *34*, S111–S126. https://doi.org/10.1016/j.eneco.2012.08.015

Caron, J. (2022). Empirical evidence and projections of carbon leakage: Some, but not too much, probably. In *Handbook on Trade Policy and Climate Change* (p. 360). Edward Elgar Publishing.

Carvalho, A. d., & Sekiguchi, N. (2015). *The structure of steel exports: Changes in specialisation and the role of innovation* (tech. rep.). OECD. Paris. https://doi.org/10.1787/5jrxfmstf0xt-en

Chambers, R. G., Chung, Y., & Färe, R. (1998). Profit, Directional Distance Functions, and Nerlovian Efficiency. *Journal of Optimization Theory and Applications*, *98*(2), 351–364. https://doi.org/10.1023/A:1022637501082

Chancel, L., Thiry, G., & Demailly, D. (2014). Beyond-GDP indicators: To what end? [Lecture 6].

Chikán, A. (2008). National and firm competitiveness: A general research model (A. Chikán, Ed.) [Publisher: Emerald Group Publishing Limited]. *Competitiveness Review: An International Business Journal*, *18*(1/2), 20–28. https://doi.org/10.1108/10595420810874583

Clausing, K. A., & Wolfram, C. (2023). Carbon Border Adjustments, Climate Clubs, and Subsidy Races When Climate Policies Vary [Lecture 11]. https://doi.org/10.3386/w31310

Climate Action Tracker. (2024). Climate Action Tracker Thermometer | Country profile EU. Retrieved April 15, 2024, from https://climateactiontracker.org/countries/eu/

Clò, S. (2010). Grandfathering, auctioning and Carbon Leakage: Assessing the inconsistencies of the new ETS Directive. *Energy Policy*, *38*(5), 2420–2430. https://doi.org/10.1016/j.enpol.2009.12.035

Cludius, J., de Bruyn, S., Schumacher, K., & Vergeer, R. (2020). Ex-post investigation of cost pass-through in the EU ETS - an analysis for six industry sectors. *Energy Economics*, *91*.

Cohen, M., & Tubb, A. (2018). The Impact of Environmental Regulation on Firm and Country Competitiveness: A Meta-analysis of the Porter Hypothesis [Publisher: University of Chicago Press]. *Journal of the Association of Environmental and Resource Economists*, *5*(2), 371–399. Retrieved November 19, 2021, from https://econpapers.repec.org/article/ucpjaerec/doi_3a10.1086_2f695613.htm

Colmer, J., Martin, R., Muûls, M., & Wagner, U. J. (2023). Does Pricing Carbon Mitigate Climate Change? Firm-Level Evidence from the European Union Emissions Trading Scheme. *SSRN Electronic Journal*, *CEPR Discussion Paper*(Discussion Paper No. 232). https://doi.org/10.2139/ssrn.3725482

Commission, E. (2016). Use of international credits. Retrieved December 23, 2020, from https://ec.europa.eu/clima/policies/ets/credits_en

Conte, M., Cotterlaz, P., & Mayer, T. (2022). The CEPII Gravity Database.

Cook, G. (2011). *Cement Industry Characteristics* (tech. rep.). Climate Strategies. Retrieved November 8, 2024, from https://www.jstor.org/stable/resrep15960.4

Correia, S., Guimarães, P., & Zylkin, T. (2020). Ppmlhdfe: Fast Poisson Estimation with High-Dimensional Fixed Effects. *The Stata Journal: Promoting communications on statistics and Stata*, *20*(1), 95–115. https://doi.org/10.1177/1536867X20909691

Cosbey, A., Droege, S., Fischer, C., & Munnings, C. (2019). Developing Guidance for Implementing Border Carbon Adjustments: Lessons, Cautions, and Research Needs from the Literature [Publisher: The University of Chicago Press]. *Review of Environmental Economics and Policy*, *13*(1), 3–22. https://doi.org/10.1093/reep/rey020

Curzi, D., Garrone, M., & Olper, A. (2021). Import Competition and Firm Markups in the Food Industry. *American Journal of Agricultural Economics*, *103*(4), 1433–1453. https://doi.org/10.1111/ajae.12175

Czado, C., Erhardt, V., Min, A., & Wagner, S. (2007). Zero-inflated generalized Poisson models with regression effects on the mean, dispersion and zero-inflation level applied to patent outsourcing rates [Publisher: SAGE Publications India]. *Statistical Modelling*, *7*(2), 125–153. https://doi.org/10.1177/1471082X0700700202

Dagoumas, A. S., & Polemis, M. L. (2020). Carbon pass-through in the electricity sector: An econometric analysis. *Energy Economics*, *86*, 104621. https://doi.org/10.1016/j.eneco.2019.104621

Dakpo, K. H., Jeanneaux, P., & Latruffe, L. (2016). Modelling pollution-generating technologies in performance benchmarking: Recent developments, limits and future prospects in the nonparametric framework. *European Journal of Operational Research*, *250*(2), 347–359. https://doi.org/10.1016/j.ejor.2015.07.024

D'Arcangelo, F. M., & Galeotti, M. (2022). Environmental Policy and Investment Location: The Risk of Carbon Leakage in the EU ETS. https://doi.org/10.2139/ssrn.4240927

D'Arcangelo, F. M., Kruse, T., Pisu, M., & Tomasi, M. (2023). The effect of climate policies on firms' financing and investment: New evidence and policy options. Retrieved November 17, 2023, from https://cepr.org/voxeu/columns/effect-climate-policies-firms-financing-and-investment-new-evidence-and-policy

De Bruyn, S., Markowska, A., De Jong, F., & Bles, M. (2010). Does the energy intensive industry obtain windfall profits through the EU ETS? An econometric analysis for products from the refineries, iron and steel and chemical sectors. Retrieved September 15, 2023, from https://www.osti.gov/etdeweb/biblio/21338966

De Vivo, N., & Marin, G. (2018). How neutral is the choice of the allocation mechanism in cap-and-trade schemes? Evidence from the EU-ETS. *Argomenti*, (9), 21–44. https://doi.org/10.14276/1971-8357.1062

Dechezleprêtre, A., Dussaux, D., & Vona, F. (2020). Carbon offshoring: Evidence from French manufacturing companies. *OFCE Working Paper*, *23*.

Dechezleprêtre, A., Gennaioli, C., Martin, R., Muûls, M., & Stoerk, T. (2022). Searching for carbon leaks in multinational companies. *Journal of Environmental Economics and Management*, *112*, 102601. https://doi.org/10.1016/j.jeem.2021.102601

Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., & Ménière, Y. (2011). Invention and Transfer of Climate Change–Mitigation Technologies: A Global Analysis. *Review of Environmental Economics and Policy*, *5*(1), 109–130. https://doi.org/10.1093/reep/req023

Dechezleprêtre, A., Koźluk, T., Kruse, T., Nachtigall, D., & de Serres, A. (2019). Do Environmental and Economic Performance Go Together? A Review of Micro-level Empirical Evidence from the Past Decade or So. *International Review of Environmental and Resource Economics*, *13*(1-2), 1–118. https://doi.org/10.1561/101.00000106

Dechezleprêtre, A., & Kruse, T. (2018). A review of the empirical literature combining economic and environmental performance data at the micro-level [Publisher: OECD]. https://doi.org/10.1787/45d269b2-en

Dechezleprêtre, A., Nachtigall, D., & Venmans, F. (2023). The joint impact of the European Union emissions trading system on carbon emissions and economic performance. *Journal of Environmental Economics and Management*, *118*, 102758. https://doi.org/10.1016/j.jeem.2022.102758

Dechezleprêtre, A., & Sato, M. (2017). The Impacts of Environmental Regulations on Competitiveness. *Review of Environmental Economics and Policy*, *11*(2), 183–206. https://doi.org/10.1093/reep/rex013

Demailly, D., & Quirion, P. (2006). CO2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: Grandfathering versus output-based allocation. *Climate Policy*, *6*(1), 93–113. https://doi.org/10.1080/14693062.2006.9685590

Demailly, D., & Quirion, P. (2008). European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry. *Energy Economics*, *30*(4), 2009–2027. https://doi.org/10.1016/j.eneco.2007.01.020

de Perthuis, C., & Trotignon, R. (2014). Governance of CO2 markets: Lessons from the EU ETS. *Energy Policy*, *75*, 100–106. https://doi.org/10.1016/j.enpol.2014.05.033

de Rassenfosse, G., & Jaffe, A. B. (2018). Econometric evidence on the depreciation of innovations. *European Economic Review*, *101*, 625–642. https://doi.org/10.1016/j.euroecorev.2017.11.005

Di Maria, C., & Van Der Werf, E. (2008). Carbon leakage revisited: Unilateral climate policy with directed technical change. *Environmental and Resource Economics*, *39*(2), 55–74. https://doi.org/10.1007/s10640-007-9091-x

Diesing, P., Lopez, G., Blechinger, P., & Breyer, C. (2025). From knowledge gaps to technological maturity: A comparative review of pathways to deep emission reduction for energy-intensive industries. *Renewable and Sustainable Energy Reviews*, *208*, 115023. https://doi.org/10.1016/j.rser.2024.115023

Dong, Y., Ishikawa, M., & Hagiwara, T. (2015). Economic and environmental impact analysis of carbon tariffs on Chinese exports. *Energy Economics*, *50*, 80–95. https://doi.org/10.1016/j.eneco.2015.04.008

Draghi, M. (2024). *The future of European competitiveness: A competitiveness strategy for Europe* (tech. rep.).

Du, K., Li, P., & Yan, Z. (2019). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technological Forecasting and Social Change*, *146*, 297–303. https://doi.org/10.1016/j.techfore.2019.06.010

Dupont, C., Moore, B., Boasson, E. L., Gravey, V., Jordan, A., Kivimaa, P., Kulovesi, K., Kuzemko, C., Oberthür, S., Panchuk, D., Rosamond, J., Torney, D., Tosun, J., & von Homeyer, I. (2024). Three decades of EU climate policy: Racing toward climate neutrality? *WIREs Climate Change*, *15*(1), e863. https://doi.org/10.1002/wcc.863

Dzemydaitė, G., & Naruševičius, L. (2023). Exploring efficiency growth of advanced technology-generating sectors in the European Union: A stochastic frontier analysis [Number: 6]. *Journal of Business Economics and Management*, *24*(6), 976–995. https://doi.org/10.3846/jbem.2023.20688

Eberhard, T., Casillas, G., Zarus, G. M., & Barr, D. B. (2024). Systematic review of microplastics and nanoplastics in indoor and outdoor air: Identifying a framework and data needs for quantifying human inhalation exposures [Publisher: Nature Publishing Group]. *Journal of Exposure Science & Environmental Epidemiology*, *34*(2), 185–196. https://doi.org/10.1038/s41370-023-00634-x

EEA. (2024a). Greenhouse gas emissions by source sector. https://doi.org/https://doi.org/10.2908/ENV_AIR_GGE

EEA. (2024b). *Trends and projections in Europe 2024*. Publications Office. Retrieved March 15, 2025, from https://data.europa.eu/doi/10.2800/7574066

Ellerman, A. D., & Buchner, B. K. (2008). Over-Allocation or Abatement? A Preliminary Analysis of the EU ETS Based on the 2005–06 Emissions Data. *Environmental and Resource Economics*, *41*(2), 267–287. https://doi.org/10.1007/s10640-008-9191-2

Ellerman, A. D., Convery, F. J., & de Perthuis, C. (2010). Ouvertures Internationales. In *Le prix du carbone: Les enseignements du marché européen du CO2*. Pearson Education France.

Eskander, S., & Fankhauser, S. (2021). The impact of climate legislation on trade-related carbon emissions, 1997–2017. *Grantham Institute Working Paper*. Retrieved February 2, 2022, from https://www.lse.ac.uk/granthaminstitute/publication/the-impact-of-climate-legislation-on-trade-related-carbon-emissions-1997-2017/

European Commission. (2006). Communication from the Commission to the Council and to the European Parliament on the assessment of national allocation plans for the allocation of greenhouse gas emission allowances in the second period of the EU

Emissions Trading Scheme. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0725&from=EN

European Commission. (2012). Communication from the Commission — Guidelines on certain State aid measures in the context of the greenhouse gas emission allowance trading scheme post-2012 (SWD(2012) 130 final) (SWD(2012) 131 final) Text with EEA relevance. Retrieved November 17, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52012XC0605%2801%29

European Commission. (2015). EU ETS Handbook.

European Commission. (2018). Preliminary Carbon Leakage List, 2021-2030. Retrieved January 20, 2025, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=oj:JOC_2018_162_R

European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Committee of the Regions; The European Green Deal. Retrieved January 31, 2024, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

European Commission. (2021a). Commission Staff Working Document: Impact Assessment Report accompanying the document Proposal for a regulation of the European Parliament and of the Council establishing a carbon border adjustment mechanism.

European Commission. (2021b). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: 'Fit for 55': Delivering the EU's 2030 Climate Target on the way to climate neutrality.

European Commission. (2023a). Commission Delegated Regulation (EU) 2019/856 of 26 February 2019 supplementing Directive 2003/87/EC of the European Parliament and of the Council with regard to the operation of the Innovation Fund. Retrieved March 26, 2025, from http://data.europa.eu/eli/reg_del/2019/856/2023-11-21/eng

European Commission. (2023b). *Progress Report 2023 Climate Action: Shifting gears: Increasing the pace of progress towards a green and prosperous future* (tech. rep.).

European Commission. (2025a). The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation.

European Commission. (2025b). A Competitiveness Compass for the EU.

European Investment Bank. (2024). Chapter 5: Investing in green transformation [OCLC: 1424496025]. In *EIB investment report 2023/2024: Transforming for competitiveness*.

European Parliament and Council. (2003). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Di-

rective 96/61/EC (Text with EEA relevance). Retrieved September 15, 2023, from http://data.europa.eu/eli/dir/2003/87/oj/eng

European Parliament and Council. (2013). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (Text with EEA relevance). Retrieved November 17, 2023, from http://data.europa.eu/eli/dir/2003/87/2013-07-01/eng

European Parliament and Council. (2015). Decision (EU) 2015/1814 of the European Parliament and of the Council of 6 October 2015 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and amending Directive 2003/87/EC (Text with EEA relevance). Retrieved September 15, 2023, from http://data.europa.eu/eli/dec/2015/1814/oj/eng

European Parliament and Council. (2023). Regulation (EU) 2023/956 of the European Parliament and of the Council of 10 May 2023 establishing a carbon border adjustment mechanism (Text with EEA relevance). Retrieved November 17, 2023, from http://data.europa.eu/eli/reg/2023/956/oj/eng

European Parliament and Council. (2024). Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (Text with EEA relevance). Retrieved March 26, 2025, from http://data.europa.eu/eli/dir/2003/87/oj/eng

European Securities and Markets Authority. (2022). *Final Report: Emission allowances and associated derivatives* (tech. rep. No. ESMA70-445-38). ESMA. Paris.

Fabra, N., & Reguant, M. (2014). Pass-Through of Emissions Costs in Electricity Markets. *American Economic Review*, *104*(9), 2872–2899. https://doi.org/10.1257/aer.104.9.2872

Fagan-Watson, B., Elliott, B., & Watson, T. (2015). Lobbying by Trade Associations on EU Climate Policy, 116.

Färe, R., Grosskopf, S., Noh, D.-W., & Weber, W. (2005). Characteristics of a polluting technology: Theory and practice. *Journal of Econometrics*, *126*(2), 469–492. https://doi.org/10.1016/j.jeconom.2004.05.010

Feenstra, R. C. (1994). New Product Varieties and the Measurement of International Prices [Publisher: American Economic Association]. *The American Economic Review*, *84*(1), 157–177. Retrieved December 6, 2024, from https://www.jstor.org/stable/2117976

Fernández, C., Koop, G., & Steel, M. (2000). A Bayesian analysis of multiple-output production frontiers. *Journal of Econometrics*, *98*(1), 47–79. https://doi.org/10.1016/S0304-4076(99)00074-3

Fischer, C., & Fox, A. (2012). Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates. *Journal of Environmental Economics and Management*, *64*, 199–216.

Fischer, C., & Fox, A. K. (2018). How Trade Sensitive Are Energy-Intensive Sectors? *AEA Papers and Proceedings*, *108*, 130–135. https://doi.org/10.1257/pandp.20181088

Fontagné, L., Guimbard, H., & Orefice, G. (2019). Product-Level Trade Elasticities: Worth Weighting For. *CEPII Working Paper*, *2019-17*. Retrieved June 3, 2022, from https://www.cesifo.org/en/publikationen/2020/working-paper/product-level-trade-elasticities-worth-weighting

Fontagné, L., Martin, P., & Orefice, G. (2023). The Many Channels of Firm's Adjustment to Energy Shocks: Evidence from France. *Banque de France publications*. https://doi.org/10.2139/ssrn.4506334

Fowlie, M., & Reguant, M. (2018). Challenges in the Measurement of Leakage Risk [Publisher: American Economic Association]. *AEA Papers and Proceedings*, *108*, 124–129. Retrieved October 11, 2022, from http://www.jstor.org/stable/26452718

Fowlie, M. L., & Reguant, M. (2022). Mitigating Emissions Leakage in Incomplete Carbon Markets [Publisher: The University of Chicago Press]. *Journal of the Association of Environmental and Resource Economists*, *9*(2), 307–343. https://doi.org/10.1086/716765

Fragkos, P., & Paroussos, L. (2018). Employment creation in EU related to renewables expansion. *Applied Energy*, *230*, 935–945. https://doi.org/10.1016/j.apenergy.2018.09.032

Franco, C., & Marin, G. (2017). The Effect of Within-Sector, Upstream and Downstream Environmental Taxes on Innovation and Productivity [Publisher: Springer]. *Environmental & Resource Economics*, *66*(2), 261–291. https://doi.org/10.1007/s10640-015-9948-3

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneth, A., Arora, V., Bates, N. R., ... Zaehle, S. (2020). Global Carbon Budget 2020 [Publisher: Copernicus GmbH]. *Earth System Science Data*, *12*(4), 3269–3340. https://doi.org/10.5194/essd-12-3269-2020

Friman, M., & Strandberg, G. (2014). Historical responsibility for climate change: Science and the science–policy interface. *WIREs Climate Change*, *5*(3), 297–316. https://doi.org/10.1002/wcc.270

Gagg, C. R. (2014). Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Engineering Failure Analysis*, *40*, 114–140. https://doi.org/10.1016/j.engfailanal.2014.02.004

Gal, P. N. (2013). *Measuring Total Factor Productivity at the Firm Level using OECD-ORBIS* (tech. rep.). OECD. Paris. https://doi.org/10.1787/5k46dsb25ls6-en

Ganapati, S., Shapiro, J. S., & Walker, R. (2020). Energy Cost Pass-Through in US Manufacturing: Estimates and Implications for Carbon Taxes. *American Economic Journal: Applied Economics*, *12*(2), 303–342. https://doi.org/10.1257/app.20180474

Gaulier, G., & Zignago, S. (2010). *BACI: International Trade Database at the Product-Level. The 1994-2007 Version* (Working Papers No. 2010-23). CEPII. http://www.cepii.fr/CEPII/fr/publications/wp/abstract.asp?NoDoc=2726

Gelles, D., Friedman, L., & Plumer, B. (2025). 'Full on Fight Club': How Trump Is Crushing U.S. Climate Policy. *The New York Times*. Retrieved March 16, 2025, from https://www.nytimes.com/2025/03/02/climate/trump-us-climate-policy-changes.html

Gerlagh, R., & Kuik, O. (2014). Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Economics*, *45*, 381–388. https://doi.org/10.1016/j.eneco.2014.07.017

Ghosh, M., Luo, D., Siddiqui, M. S., & Zhu, Y. (2012). Border tax adjustments in the climate policy context: CO2 versus broad-based GHG emission targeting. *Energy Economics*, *34*, S154–S167. https://doi.org/10.1016/j.eneco.2012.09.005

Gibson, M. (2019). Regulation-Induced Pollution Substitution. *The Review of Economics and Statistics*, *101*(5), 827–840.

Gielen, D. (2021). *Critical Materials for the Energy Transition* (Technical Report No. 5). International Renewable Energy Agency. Abu Dhabi.

Global Energy Monitor. (2024). Global Steel Plant Tracker. https://globalenergymonitor.org/projects/global-steel-plant-tracker/

Gopinath, G., Kalemli-Özcan, Ş., Karabarbounis, L., & Villegas-Sanchez, C. (2017). Capital Allocation and Productivity in South Europe. *The Quarterly Journal of Economics*, *132*(4), 1915–1967. https://doi.org/10.1093/qje/qjx024

Grubb, M., Jordan, N. D., Hertwich, E., Neuhoff, K., Das, K., Bandyopadhyay, K. R., Van Asselt, H., Sato, M., Wang, R., Pizer, W. A., & Oh, H. (2022). Carbon Leakage, Consumption, and Trade. *Annual Review of Environment and Resources*, *47*(1), 753–795. https://doi.org/10.1146/annurev-environ-120820-053625

Gruebel, H. G., & Lloyd, P. J. (1975). *Intra-industry trade : The theory and measurement of international trade in differentiated products*. Macmillan.

Hepburn, C., Grubb, M., Neuhoff, K., Matthes, F., & Tse, M. (2006). Auctioning of EU ETS phase II allowances: How and why? [Publisher: Taylor & Francis _eprint: https://www.tandfonline.com/doi/pdf/10.1080/14693062.2006.9685592]. *Climate Policy*, *6*(1), 137–160. https://doi.org/10.1080/14693062.2006.9685592

Herfort, D., Moir, G., Johansen, V., Sorrentino, F., & Arceo, H. (2010). The chemistry of Portland cement clinker. *Advances in Cement Research*, *22*(4), 187–194. https://doi.org/10.1680/adcr.2010.22.4.187

Hicks, J., R. (1932). *The Theory of Wages* (First edition). Macmillan.

Hoel, M. (1991). Global environmental problems: The effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management*, *20*(1), 55–70. https://doi.org/10.1016/0095-0696(91)90023-C

Hoel, M. (1996). Should a carbon tax be differentiated across sectors? *Journal of Public Economics*, *59*(1), 17–32. https://doi.org/10.1016/0047-2727(94)01490-6

Holm, S. (1979). A Simple Sequentially Rejective Multiple Test Procedure [Publisher: [Board of the Foundation of the Scandinavian Journal of Statistics, Wiley]]. *Scandinavian Journal of Statistics*, *6*(2), 65–70. Retrieved April 17, 2024, from https://www.jstor.org/stable/4615733

Horváthová, E. (2010). Does environmental performance affect financial performance? A meta-analysis. *Ecological Economics*, *70*(1), 52–59. https://doi.org/10.1016/j.ecolecon.2010.04.004

Horváthová, E. (2012). The impact of environmental performance on firm performance: Short-term costs and long-term benefits? *Ecological Economics*, *84*, 91–97. https://doi.org/10.1016/j.ecolecon.2012.10.001

Hourcade, J.-C., Demailly, D., Neuhoff, K., Sato, M., Grubb, M., Matthes, F., & Graichen, V. (2007). *Differentiation and dynamics of EU ETS industrial competitiveness impacts: Final Report* (tech. rep.). Climate Strategies. Retrieved June 1, 2022, from https://climatestrategies.org/publication/differentiation-and-dynamics-of-eu-ets-industrial-competitiveness-impacts-final-report/

Huang, N., & Diewert, E. (2011). Estimation of R&D depreciation rates: A suggested methodology and preliminary application. *Canadian Journal of Economics/Revue canadienne d'économique*, *44*(2), 387–412. https://doi.org/10.1111/j.1540-5982.2011.01638.x

Huang, P., Negro, S. O., Hekkert, M. P., & Bi, K. (2016). How China became a leader in solar PV: An innovation system analysis. *Renewable and Sustainable Energy Reviews*, *64*, 777–789. https://doi.org/10.1016/j.rser.2016.06.061

Huppmann, D., & Egging, R. (2014). Market power, fuel substitution and infrastructure – A large-scale equilibrium model of global energy markets. *Energy*, *75*, 483–500. https://doi.org/10.1016/j.energy.2014.08.004

International Carbon Action Partnership. (2023). Allowance Price Explorer. Retrieved November 11, 2023, from https://icapcarbonaction.com/en/ets-prices

International Energy Agency. (2020). *Iron and Steel Technology Roadmap* (tech. rep.).

International Energy Agency. (2024). *World Energy Outlook 2024* (tech. rep.). International Energy Agency. Paris.

IPCC. (2022). Annex I: Glossary. In *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (1st ed.). Cambridge University Press. Retrieved March 9, 2025, from https://www.cambridge.org/core/product/identifier/9781009157940/type/book

IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (tech. rep.) ([Core Writing Team, H. Lee and J. Romero (eds.)].). IPCC. Geneva. Retrieved March 16, 2025, from https://www.ipcc.ch/report/ar6/syr/

Jaffe, A. B., Peterson, S. R., Portney, P. R., & Stavins, R. N. (1995). Environmental Regulation and the Competitiveness of U.S. Manufacturing: What Does the Evidence Tell Us? [Publisher: American Economic Association]. *Journal of Economic Literature*, *33*(1), 132–163. Retrieved April 16, 2024, from https://www.jstor.org/stable/2728912

Janipour, Z., de Nooij, R., Scholten, P., Huijbregts, M. A. J., & de Coninck, H. (2020). What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. *Energy Research & Social Science*, *60*, 101320. https://doi.org/10.1016/j.erss.2019.101320

Jaraite, J., Kurtyka, O., & Ollivier, H. (2021). *Take a Ride on the Green Side: How Do CDM Projects Affect Indian Manufacturing Firms' Environmental Performance?* (SSRN Scholarly Paper No. ID 3760586). Social Science Research Network. Rochester, NY. https://doi.org/10.2139/ssrn.3760586

Jensen, S., Mohlin, K., Pittel, K., & Sterner, T. (2020). An Introduction to the Green Paradox: The Unintended Consequences of Climate Policies [Publisher: The University of Chicago Press]. *Review of Environmental Economics and Policy*. https://doi.org/10.1093/reep/rev010

Joltreau, E., & Sommerfeld, K. (2019). Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms' competitiveness? Empirical findings from the literature. *Climate Policy*, *19*(4), 453–471. https://doi.org/10.1080/14693062.2018.1502145

Kaldor, N. (1957). A Model of Economic Growth. *The Economic Journal*, *67*(268), 591–624. https://doi.org/10.2307/2227704

Kalemli-Ozcan, S., Sorensen, B., Villegas-Sanchez, C., Volosovych, V., & Yesiltas, S. (2015). *How to Construct Nationally Representative Firm Level Data from the Orbis Global Database: New Facts and Aggregate Implications* (tech. rep.). National Bureau of Economic Research. Cambridge, MA. https://doi.org/10.3386/w21558

Karkatsoulis, P., Capros, P., Fragkos, P., Paroussos, L., & Tsani, S. (2016). First-mover advantages of the European Union's climate change mitigation strategy. *International Journal of Energy Research*, *40*(6), 814–830. https://doi.org/10.1002/er.3487

Kirchherr, J., & Urban, F. (2018). Technology transfer and cooperation for low carbon energy technology: Analysing 30 years of scholarship and proposing a research agenda. *Energy Policy*, *119*, 600–609. https://doi.org/10.1016/j.enpol.2018.05.001

Kirk, J., Contrepois, S., & Jefferys, S. (2012). Approaching Regional and Identity Change in Europe. In J. Kirk, S. Contrepois, & S. Jefferys (Eds.), *Changing Work and Community Identities in European Regions: Perspectives on the Past and Present* (pp. 1–22). Palgrave Macmillan UK. Retrieved March 22, 2025, from https://doi.org/10.1057/9780230353916_1

Knittel, C., Metaxoglou, K., Soderbery, A., & Trindade, A. (2018). Does the US Export Global Warming? Coal Trade and the Shale Gas Boom. *MIT CEEPR Working Paper*, *013*, 70. http://ceepr.mit.edu/files/papers/2018-013.pdf

Koch, N., & Mama, H. B. (2019). Does the EU Emissions Trading System induce investment leakage? Evidence from German multinational firms. *Energy Economics*, *81*, 479–492. https://doi.org/10.1016/j.eneco.2019.04.018

Kossoy, A., & Ambrosi, P. (2010). *State and Trends of the Carbon Market 2010* (tech. rep.). World Bank.

Krugman, P. (1994). Competitiveness: A Dangerous Obsession Essay. *Foreign Affairs*, *73*(2), 28–44. Retrieved March 9, 2025, from https://heinonline.org/HOL/P?h=hein.journals/fora73&i=226

Kruse, T., Teusch, J., D'Arcangelo, F. M., & Pisu, M. (2024). *Carbon prices, emissions and international trade in sectors at risk of carbon leakage: Evidence from 140 countries* (tech. rep.). OECD. Paris. https://doi.org/10.1787/116248f5-en

Kuik, O., & Hofkes, M. (2010). Border adjustment for European emissions trading: Competitiveness and carbon leakage. *Energy Policy*, *38*(4), 1741–1748. https://doi.org/10.1016/j.enpol.2009.11.048

Kumar, A., Tiwari, A. K., & Milani, D. (2024). Decarbonizing hard-to-abate heavy industries: Current status and pathways towards net-zero future. *Process Safety and Environmental Protection*, *187*, 408–430. https://doi.org/10.1016/j.psep.2024.04.107

Kurdowski, W. (2014). Cement Kinds and Principles of their Classification. In *Cement and Concrete Chemistry* (pp. 1–20). Springer Netherlands. https://doi.org/10.1007/978-94-007-7945-7_1

Laing, T., Sato, M., Grubb, M., & Comberti, C. (2014). The effects and side-effects of the EU emissions trading scheme. *WIREs Climate Change*, *5*(4), 509–519. https://doi.org/10.1002/wcc.283

Lanzi, E., Chateau, J., & Dellink, R. (2012). Alternative approaches for levelling carbon prices in a world with fragmented carbon markets. *Energy Economics*, *34*, S240–S250. https://doi.org/10.1016/j.eneco.2012.08.016

Larch, M., & Wanner, J. (2017). Carbon tariffs: An analysis of the trade, welfare, and emission effects. *Journal of International Economics*, *109*, 195–213. https://doi.org/10.1016/j.jinteco.2017.09.003

Le Cacheux, J., & Laurent, É. (2009). Le marché européen du carbone en quête de stabilité [Publisher: La Découverte]. *Regards croisés sur l'economie*, *n° 6*(2), 117–127. Retrieved December 21, 2020, from https://www-cairn-info.acces-distant.sciencespo.fr/revue-regards-croises-sur-l-economie-2009-2-page-117.htm

Letout, S. (2021). Firm level data in the EU ETS (JRC-EU ETS-FIRMS) [Publisher: European Commission, Joint Research Centre (JRC)]. Retrieved October 25, 2023, from http://data.europa.eu/89h/bdd1b71f-1bc8-4e65-8123-bbdd8981f116

Letta, E. (2024). *Much more than a market: Speed, security, solidarity. Empowering the Single Market to deliver a sustainable future and prosperity for all EU Citizens* (tech. rep.).

Levinson, A., & Taylor, M. S. (2008). Unmasking the Pollution Haven Effect. *International Economic Review*, *49*(1), 223–254. https://doi.org/https://doi.org/10.1111/j.1468-2354.2008.00478.x

Li, Y., Tao, L., Wang, Q., Wang, F., Li, G., & Song, M. (2023). Potential Health Impact of Microplastics: A Review of Environmental Distribution, Human Exposure, and Toxic Effects [Publisher: American Chemical Society]. *Environment & Health*, *1*(4), 249–257. https://doi.org/10.1021/envhealth.3c00052

Liu, G. (2020). Data quality problems troubling business and financial researchers: A literature review and synthetic analysis. *Journal of Business & Finance Librarianship*, *25*(3-4), 315–371. https://doi.org/10.1080/08963568.2020.1847555

Löfgren, Å., Wråke, M., Hagberg, T., & Roth, S. (2014). Why the EU ETS needs reforming: An empirical analysis of the impact on company investments [Publisher: Taylor & Francis _eprint: https://doi.org/10.1080/14693062.2014.864800]. *Climate Policy*, *14*(5), 537–558. https://doi.org/10.1080/14693062.2014.864800

Löschel, A., Lutz, B. J., & Managi, S. (2019). The impacts of the EU ETS on efficiency and economic performance – An empirical analyses for German manufacturing firms. *Resource and Energy Economics*, *56*, 71–95. https://doi.org/10.1016/j.reseneeco.2018.03.001

Lundgren, T., Marklund, P.-O., Samakovlis, E., & Zhou, W. (2015). Carbon prices and incentives for technological development. *Journal of Environmental Management*, *150*, 393–403. https://doi.org/10.1016/j.jenvman.2014.12.015

Magacho, G., Espagne, E., & Godin, A. (2024). Impacts of the CBAM on EU trade partners: Consequences for developing countries [Publisher: Taylor & Francis _eprint:

https://doi.org/10.1080/14693062.2023.2200758]. *Climate Policy*, *24*(2), 243–259. https://doi.org/10.1080/14693062.2023.2200758

Marcu, A., Mehling, M., & Cosbey, A. (2020). *Border Carbon Adjustments in the EU: Issues and Options* (tech. rep.). European Roundtable on Climate Change and Sustainable Transitions.

Mari, E., Sourisseau, S., Bouxin, A., Borde, C., Padilla, S., & Gourdon, T. (2021). Plan de transition sectoriel de l'industrie cimentière en France. *ADEME*, 40.

Markusen, J. R. (1975). International externalities and optimal tax structures. *Journal of International Economics*, *5*(1), 15–29. https://doi.org/10.1016/0022-1996(75)90025-2

Markusen, J. R., Morey, E. R., & Olewiler, N. D. (1993). Environmental Policy when Market Structure and Plant Locations Are Endogenous. *Journal of Environmental Economics and Management*, *24*(1), 69–86. https://doi.org/10.1006/jeem.1993.1005

Marmier, A. (2023). *Decarbonisation options for the cement industry*. Publications Office of the European Union. Retrieved September 1, 2023, from https://data.europa.eu/doi/10.2760/174037

Martin, R., Muûls, M., de Preux, L. B., & Wagner, U. J. (2014). Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme. *American Economic Review*, *104*(8), 2482–2508. https://doi.org/10.1257/aer.104.8.2482

Martinez, C. (2010). *Insight into Different Types of Patent Families* (OECD Science, Technology and Industry Working Papers No. 2010/02) (Series: OECD Science, Technology and Industry Working Papers Volume: 2010/02). OECD. Paris. https://doi.org/10.1787/5kml97dr6ptl-en

Mathiesen, L., & Maestad, O. (2004). Climate Policy and the Steel Industry: Achieving Global Emission Reductions by an Incomplete Climate Agreement. *The Energy Journal*, *25*(4). https://doi.org/10.5547/ISSN0195-6574-EJ-Vol25-No4-5

Mattoo, A., Subramanian, A., van der Mensbrugghe, D., & He, J. (2009). Reconciling Climate Change and Trade Policy. https://doi.org/10.2139/ssrn.1516053

McCallum, J. (1995). National Borders Matter: Canada-U.S. Regional Trade Patterns [Publisher: American Economic Association]. *The American Economic Review*, *85*(3), 615–623. Retrieved August 30, 2022, from http://www.jstor.org/stable/2118191

Mckibbin, W. J., Wilcoxen, P. J., Braathen, N. A., Tao, (H., & Levinson, A. (2008). The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy [with Comments] [Publisher: Brookings Institution Press]. *Brookings Trade Forum*, 1–34. Retrieved March 25, 2025, from https://www.jstor.org/stable/20799647

Mehling, M. A., Asselt, H. v., Das, K., Droege, S., & Verkuijl, C. (2019). Designing Border Carbon Adjustments for Enhanced Climate Action [Publisher: Cambridge University Press]. *American Journal of International Law*, *113*(3), 433–481. https://doi.org/10.1017/ajil.2019.22

Melitz, M. J. (2003). The Impact of Trade on Intra-Industry Reallocations and Aggregate Industry Productivity. *Econometrica*, *71*(6), 1695–1725. Retrieved September 11, 2020, from https://www.jstor.org/stable/1555536

Misch, F., & Wingender, P. (2021). Revisiting Carbon Leakage. *IMF, Working Papers*. Retrieved September 7, 2023, from https://www.imf.org/en/Publications/WP/Issues/2021/08/06/Revisiting-Carbon-Leakage-462148

Monash University. (2025). Heavy industry.

Monjon, S., & Quirion, P. (2011a). Addressing leakage in the EU ETS: Border adjustment or output-based allocation? *Ecological Economics*, *70*(11), 1957–1971. https://doi.org/10.1016/j.ecolecon.2011.04.020

Monjon, S., & Quirion, P. (2011b). A border adjustment for the EU ETS: Reconciling WTO rules and capacity to tackle carbon leakage. *Climate Policy*, *11*(5), 1212–1225. https://doi.org/10.1080/14693062.2011.601907

Morfeldt, J., & Silveira, S. (2014). Capturing energy efficiency in European iron and steel production—comparing specific energy consumption and Malmquist productivity index. *Energy Efficiency*, *7*(6), 955–972. https://doi.org/10.1007/s12053-014-9264-8

Naegele, H., & Zaklan, A. (2019). Does the EU ETS cause carbon leakage in European manufacturing? *Journal of Environmental Economics and Management*, *93*, 125–147. https://doi.org/10.1016/j.jeem.2018.11.004

Oberthür, S., & Dupont, C. (2021). The European Union's international climate leadership: Towards a grand climate strategy? *Journal of European Public Policy*, *28*(7), 1095–1114. https://doi.org/10.1080/13501763.2021.1918218

OECD. (2024). Towards more accurate, timely, and granular product-level carbon intensity metrics. *OECD Publishing, Inclusive Forum on Carbon Mitigation Approaches Papers*. https://doi.org/https://doi.org/10.1787/4de3422f-en

Oggioni, G., Riccardi, R., & Toninelli, R. (2011). Eco-efficiency of the world cement industry: A data envelopment analysis. *Energy Policy*, *39*(5), 2842–2854. https://doi.org/10.1016/j.enpol.2011.02.057

Ossa, R. (2015). Why trade matters after all. *Journal of International Economics*, *97*(2), 266–277. https://doi.org/10.1016/j.jinteco.2015.07.002

Oxford Languages. (2025). Heavy industry.

Paltsev, S. V. (2001). The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage [Publisher: SAGE Publications]. *The Energy Journal*, *22*(4), 53–79. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol22-No4-3

Paroussos, L., Fragkos, P., Capros, P., & Fragkiadakis, K. (2015). Assessment of carbon leakage through the industry channel: The EU perspective. *Technological Forecasting and Social Change*, *90*, 204–219. https://doi.org/10.1016/j.techfore.2014.02.011

Parrado, R., & De Cian, E. (2014). Technology spillovers embodied in international trade: Intertemporal, regional and sectoral effects in a global CGE framework. *Energy Economics*, *41*, 76–89. https://doi.org/10.1016/j.eneco.2013.10.016

Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., & Cournapeau, D. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*(85), 2825–2830.

Peltonen, T. A., Skala, M., Santos Rivera, A., & Pula, G. (2008). Imports and Profitability in the Euro Area Manufacturing Sector: The Role of Emerging Market Economies. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1157774

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008 [Publisher: National Academy of Sciences Section: Biological Sciences]. *Proceedings of the National Academy of Sciences*, *108*(21), 8903–8908. https://doi.org/10.1073/pnas.1006388108

Peterson, E. B., & Schleich, J. (2007). *Economic and environmental effects of border tax adjustments* (Working Paper No. S1/2007). Working Paper Sustainability and Innovation. Retrieved March 25, 2025, from https://www.econstor.eu/handle/10419/28514

Popp, D. (2019). Environmental Policy and Innovation: A Decade of Research. https://doi.org/10.3386/w25631

Porter, M. (1991). America's green strategy. *Scientific American*, *264*(4), 168.

Porter, M. E., & van der Linde, C. (1995). Toward a New Conception of the Environment - Competitiveness Relationship. *Journal of Economic Perspectives*, *9*(4), 97–118. https://doi.org/10.1257/jep.9.4.97

Probst, B., Touboul, S., Glachant, M., & Dechezleprêtre, A. (2021). Global trends in the invention and diffusion of climate change mitigation technologies. *Nature Energy*, *6*, 1077–1086. https://doi.org/https://doi.org/10.1038/s41560-021-00931-5

Rekker, L., Kesina, M., & Mulder, M. (2023). Carbon abatement in the European chemical industry: Assessing the feasibility of abatement technologies by estimating firm-level marginal abatement costs. *Energy Economics*, *126*, 106889. https://doi.org/10.1016/j.eneco.2023.106889

Rexhäuser, S., & Rammer, C. (2014). Environmental Innovations and Firm Profitability: Unmasking the Porter Hypothesis. *Environmental and Resource Economics*, *57*(1), 145–167. https://doi.org/10.1007/s10640-013-9671-x

Rigby, D. L., & Essletzbichler, J. (1997). Evolution, Process Variety, and Regional Trajectories of Technological Change in U.S. Manufacturing. *Economic Geography*, *73*(3), 269–284. https://doi.org/10.1111/j.1944-8287.1997.tb00089.x

Robaina-Alves, M., Moutinho, V., & Macedo, P. (2015). A new frontier approach to model the eco-efficiency in European countries. *Journal of Cleaner Production*, *103*, 562–573. https://doi.org/10.1016/j.jclepro.2015.01.038

Rubashkina, Y., Galeotti, M., & Verdolini, E. (2015). Environmental regulation and competitiveness: Empirical evidence on the Porter Hypothesis from European manufacturing sectors. *Energy Policy*, *83*, 288–300. https://doi.org/10.1016/j.enpol.2015.02.014

Ryan, S. P. (2012). The Costs of Environmental Regulation in a Concentrated Industry. *Econometrica*, *80*(3), 1019–1061. https://doi.org/10.3982/ECTA6750

Sahoo, B., Behera, D. K., & Rahut, D. (2022). Decarbonization: Examining the role of environmental innovation versus renewable energy use. *Environmental Science and Pollution Research*, *29*(32), 48704–48719. https://doi.org/10.1007/s11356-022-18686-1

Sardain, E. (2023). Why could steel industry de-carbonisation be long and difficult?

Sato, M., Neuhoff, K., Graichen, V., Schumacher, K., & Matthes, F. (2015). Sectors Under Scrutiny: Evaluation of Indicators to Assess the Risk of Carbon Leakage in the UK and Germany. *Environmental and Resource Economics*, *60*(1), 99–124. https://doi.org/10.1007/s10640-014-9759-y

Sato, M., Rafaty, R., Calel, R., & Grubb, M. (2022). Allocation, allocation, allocation! The political economy of the development of the European Union Emissions Trading System. *WIREs Climate Change*, *13*(5), e796. https://doi.org/10.1002/wcc.796

Schmalensee, R. (1993). *The costs of environmental protection* (Working Paper). MIT Center for Energy and Environmental Policy Research. Retrieved May 28, 2024, from https://dspace.mit.edu/handle/1721.1/50210

Schmidt, T. S., Schneider, M., Rogge, K. S., Schuetz, M. J. A., & Hoffmann, V. H. (2012). The effects of climate policy on the rate and direction of innovation: A survey of the EU ETS and the electricity sector. *Environmental Innovation and Societal Transitions*, *2*, 23–48. https://doi.org/10.1016/j.eist.2011.12.002

Schuman, R. (1950). Schuman Declaration.

Shephard, R. W., & Färe, R. (1974). The Law of Diminishing Returns [Publisher: Springer]. *Zeitschrift für Nationalökonomie / Journal of Economics*, *34*(1/2), 69–90. Retrieved February 18, 2025, from https://www.jstor.org/stable/41797657

Shephard, R. W. (1970). *Theory of Cost and Production Functions*. Princeton University Press.

Shepherd, W. G. (1972). The Elements of Market Structure [Publisher: The MIT Press]. *The Review of Economics and Statistics*, *54*(1), 25–37. https://doi.org/10.2307/1927492

Sijm, J., Neuhoff, K., & Chen, Y. (2006). CO2 cost pass-through and windfall profits in the power sector. *Climate Policy*, *6*(1), 49–72. https://doi.org/10.1080/14693062.2006.9685588

Simon, F. (2010). France details plans for 'carbon inclusion mechanism'. *Euractiv*. Retrieved December 22, 2020, from https://www.euractiv.com/section/trade-society/news/france-details-plans-for-carbon-inclusion-mechanism/

Sinn, H.-W. (2012). *The Green Paradox: A Supply-Side Approach to Global Warming* [Google-Books-ID: NnwCVOso9vgC]. MIT Press.

Skevas, I. (2025). Technical and environmental inefficiency measurement in agriculture using a flexible by-production stochastic frontier model. *Journal of Agricultural Economics*, *76*(1), 164–181. https://doi.org/10.1111/1477-9552.12619

Soliman, F. S. (2020). Intrafirm Leakage. *CESifo Working Papers*, *8619*.

Somers, J. (2022). *Technologies to decarbonise the EU steel industry* [ISBN: 9789276471479 ISSN: 1831-9424]. Publications Office of the European Union. https://doi.org/10.2760/069150

Sourisseau, S. (2018). The Global Iron and Steel Industry: From a Bilateral Oligopoly to a Thwarted Monopsony. *Australian Economic Review*, *51*(2), 232–243. https://doi.org/10.1111/1467-8462.12264

Springmann, M. (2012). A look inwards: Carbon tariffs versus internal improvements in emissions-trading systems. *Energy Economics*, *34*, S228–S239. https://doi.org/10.1016/j.eneco.2012.08.039

Steel Plate & Sections. (2024). Steel from Around the World: Types of Steel. Retrieved November 22, 2024, from https://sps-bmsteel.co.uk/article/steel-from-around-the-world

Stern, N. (2008). The Economics of Climate Change. *American Economic Review*, *98*(2), 1–37. https://doi.org/10.1257/aer.98.2.1

Tagliapietra, S., & Veugelers, R. (2023). Industrial policy in Europe: Past and future. In *Sparking Europe's new Industrial Revolution*. Bruegel.

Tagliapietra, S., Zachmann, G., Edenhofer, O., Glachant, J.-M., Linares, P., & Loeschel, A. (2019). The European union energy transition: Key priorities for the next five years. *Energy Policy*, *132*, 950–954. https://doi.org/10.1016/j.enpol.2019.06.060

Tan, X., Liu, Y., Cui, J., & Su, B. (2018). Assessment of carbon leakage by channels: An approach combining CGE model and decomposition analysis. *Energy Economics*, *74*, 535–545. https://doi.org/10.1016/j.eneco.2018.07.003

Taylor, J. (2020). Fuzzy matching at scale. Retrieved October 25, 2023, from https://towardsdatascience.com/fuzzy-matching-at-scale-84f2bfd0c536

Teixidó, J., Verde, S. F., & Nicolli, F. (2019). The impact of the EU Emissions Trading System on low-carbon technological change: The empirical evidence. *Ecological Economics*, *164*, 106347. https://doi.org/10.1016/j.ecolecon.2019.06.002

Tietenberg, T., & Lewis, L. (2024). *Environmental and Natural Resource Economics* (12th Edition). Routledge. Retrieved April 4, 2024, from https://www.routledge.com/Environmental-and-Natural-Resource-Economics/Tietenberg-Lewis/p/book/9781032101187

Trinks, A., & Hille, E. (2023). Carbon Costs and Industrial Firm Performance: Evidence From International Microdata. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4422275

Trinks, A., Mulder, M., & Scholtens, B. (2020). An Efficiency Perspective on Carbon Emissions and Financial Performance. *Ecological Economics*, *175*, 106632. https://doi.org/10.1016/j.ecolecon.2020.106632

Trotignon, R. (2011). Combining cap-and-trade with offsets: Lessons from CER use in the EU ETS in 2008 and 2009. *Climate Economics Chair*. Retrieved December 23, 2020, from http://inis.iaea.org/Search/search.aspx?orig_q=RN:49103952

United States Geological Survey. (2011). *2011 Minerals Yearbook* (tech. rep.). USGS. https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

United States Geological Survey. (2016). *2016 Minerals Yearbook* (tech. rep.). USGS. https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

United States Geological Survey. (2021). *2021 Minerals Yearbook* (tech. rep.). https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information

van Leeuwen, G., & Mohnen, P. (2017). Revisiting the Porter hypothesis: An empirical analysis of Green innovation for the Netherlands. *Economics of Innovation and New Technology*, *26*(1-2), 63–77. https://doi.org/10.1080/10438599.2016.1202521

Veith, S., Werner, J. R., & Zimmermann, J. (2009). Capital market response to emission rights returns: Evidence from the European power sector. *Energy Economics*, *31*(4), 605–613. https://doi.org/10.1016/j.eneco.2009.01.004

Verde, S. F. (2020). The Impact of the EU Emissions Trading System on Competitiveness and Carbon Leakage: The Econometric Evidence. *Journal of Economic Surveys*, *34*(2), 320–343. https://doi.org/10.1111/joes.12356

Verde, S. F., Teixidó, J., Marcantonini, C., & Labandeira, X. (2019). Free allocation rules in the EU emissions trading system: What does the empirical literature show? *Climate Policy*, *19*(4), 439–452. https://doi.org/10.1080/14693062.2018.1549969

Verhoeven, D., Bakker, J., & Veugelers, R. (2016). Measuring technological novelty with patent-based indicators. *Research Policy*, *45*(3), 707–723. https://doi.org/10.1016/j.respol.2015.11.010

von der Leyen, U. (2019). Press remarks by President von der Leyen on the occasion of the adoption of the European Green Deal Communication.

Wagner, M., & Blom, J. (2011). The reciprocal and non-linear relationship of sustainability and financial performance. *Business Ethics: A European Review*, *20*(4), 418–432. https://doi.org/10.1111/j.1467-8608.2011.01622.x

Wagner, U. J., Muûls, M., Martin, R., & Colmer, J. (2014). The Causal Effect of the European Union Emissions Trading Scheme: Evidence from French Manufacturing Plants. *Working Paper*.

Walheer, B. (2024). Meta-frontier: Literature review and toolkit. *Operational Research*, *24*(2), 20. https://doi.org/10.1007/s12351-024-00830-z

Walley, N., & Whitehead, B. (1994). It's Not Easy Being Green [Section: Sustainable business practices]. *Harvard Business Review*. Retrieved May 28, 2024, from https://hbr.org/1994/05/its-not-easy-being-green

Wang, Q., Chen, X., Jha, A. N., & Rogers, H. (2014). Natural gas from shale formation – The evolution, evidences and challenges of shale gas revolution in United States. *Renewable and Sustainable Energy Reviews*, *30*, 1–28. https://doi.org/10.1016/j.rser.2013.08.065

Weber, P.-F., Afota, A., Attinasi, M.-G., Boeckelmann, L., Brueggemann, A., De Gaye, A., Dieppe, A., Faubert, V., Grieco, F., Le Roux, J., Meunier, B., Munteanu, B., Nobletz, C., Norring, A., Reininger, T., Skackauskaite, I., Suárez-Varela, M., Svartzman, R., Valadier, C., ... Zaghini, A. (2025). *The intersection between climate transition policies and geoeconomic fragmentation: A report of the International Relations Committee Network on climate change* (Research Report No. 366) (ISBN: 9789289970099). European Central Bank. https://doi.org/10.2866/0850763

Weitzel, M., Hübler, M., & Peterson, S. (2012). Fair, optimal or detrimental? Environmental vs. strategic use of border carbon adjustment. *Energy Economics*, *34*, S198–S207. https://doi.org/10.1016/j.eneco.2012.08.023

Werden, G. J. (2003). The 1982 merger guidelines and the ascent of the hypothetical monopolist paradigm [Publisher: American Bar Association]. *Antitrust Law Journal*, *71*(1), 253–275. Retrieved September 6, 2022, from http://www.jstor.org/stable/40843587

Winchester, N., Paltsev, S., & Reilly, J. M. (2011). Will Border Carbon Adjustments Work? [Publisher: De Gruyter]. *The B.E. Journal of Economic Analysis & Policy*, *11*(1). https://doi.org/10.2202/1935-1682.2696

World Bank. (2023). *State and Trends of Carbon Pricing: International Carbon Markets* (tech. rep.). World Bank. Washington, DC. http://hdl.handle.net/10986/40700

WorldSteel. (2023). *Steel Statistical Yearbook 2023* (tech. rep.). World Steel Association. Brussels. https://worldsteel.org/steel-topics/statistics/steel-statistical-yearbook/

Xiang, X., & Geng, Y. (2024). Assessing the impact of green patents on pollution reduction: A micro-level study of Chinese industrial firms. *Journal of Environmental Management*, *368*, 122193. https://doi.org/10.1016/j.jenvman.2024.122193

Xu, B., & Wang, J. (2000). Trade, FDI, and International Technology Diffusion [Publisher: Center for Economic Integration, Sejong University]. *Journal of Economic Integration*, *15*(4), 585–601. Retrieved August 17, 2021, from https://www.jstor.org/stable/23000438

Yotov, Y., Roberta, P., José-Antonio, M., & Mario, L. (2016). An Advanced Guide to Trade Policy Analysis: The Structural Gravity Model. Retrieved June 27, 2022, from https://www.wto.org/english/res_e/publications_e/advancedguide2016_e.htm

Zhang, K., Zhang, Z.-Y., & Liang, Q.-M. (2017). An empirical analysis of the green paradox in China: From the perspective of fiscal decentralization. *Energy Policy*, *103*, 203–211. https://doi.org/10.1016/j.enpol.2017.01.023

Zurano-Cervelló, P., Pozo, C., Mateo-Sanz, J. M., Jiménez, L., & Guillén-Gosálbez, G. (2018). Eco-efficiency assessment of EU manufacturing sectors combining input-output tables and data envelopment analysis following production and consumption-based accounting approaches. *Journal of Cleaner Production*, *174*, 1161–1189. https://doi.org/10.1016/j.jclepro.2017.10.178

Abstract

Decarbonizing heavy industry is essential for the EU to meet its climate goals yet concerns over competitiveness and carbon leakage have hindered the adoption of more ambitious policy measures. **This thesis explores whether decarbonization and competitiveness can coexist in the EU's heavy industry**. Using sector- and firm-level data, it employs econometric analysis, deterministic programming, economic modeling, and a systematic literature review. The findings show that carbon leakage risks during Phase 3 of the EU Emissions Trading Scheme were minimal, and that standard *ex ante* assessments often overestimate leakage by ignoring market structure. Additionally, the analysis reveals that neither green patenting nor efficiency gains alone are sufficient for firms to meet climate targets given current technological trends. Together, these results suggest that a balanced and targeted policy approach is needed to drive deep decarbonization without sacrificing industrial competitiveness.

Résumé

L'UE doit rapidement décarboner son industrie lourde pour atteindre ses objectifs climatiques. A ce jour, les craintes de fuites de carbone ont freiné l'adoption de politiques climatiques assez ambitieuses. **Cette thèse s'interroge sur la possibilité de concilier décarbonation et compétitivité industrielle**. Elle s'appuie sur des données sectorielles et d'entreprise, et mobilise des méthodes variées : analyse économétrique, programmation déterministe, modélisation économique et revue systématique de la littérature. Les résultats indiquent un risque faible de fuites de carbone durant la Phase 3 du marché du carbone européen, et que les évaluations *ex ante* surestiment souvent ce risque en négligeant la structure des marchés. L'analyse montre aussi que les brevets verts et les gains d'efficacité technique ne suffisent actuellement pas aux objectifs climatiques de l'UE. Ces résultats plaident pour une politique ciblée capable de concilier ambition climatique et compétitivité industrielle.