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Magnitudes, Directions, and Policy Implications

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Emissions Embodied in International Trade

Magnitudes, Directions, and Policy Implications

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TU Delft

Emissions Embodied in International Trade

Magnitudes, Directions, and Policy Implications

Dissertation

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For my parents.

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Summary

The global CO_2 emissions from fuel combustion in production and consumption activities, which comprise the majority of global Greenhouse Gas (GHG) emissions, have continued to rise in the past decades. This is a cause for concern, as limiting the global warming to below 1.5°C (even worse, 2°C) requires a deep and rapid reduction in the current level of global CO_2 emissions. However, the pattern of the CO_2 emissions at the level of individual countries are less straightforward than the pattern of global CO_2 emissions. Studies have documented that the territorial CO_2 emissions are increasing in most developing countries while decreasing in most developed countries. In general, most developed countries are net importers of CO_2 emissions and most developing countries are net exporters of CO_2 emissions. This evidence has led to a hypothesis that the international trade has enabled the developed countries to reduce their domestic CO_2 emissions – while maintaining an acceptable rate of economic growth – by means of production outsourcing to the developing countries. This is particularly the case because the global CO_2 emissions embodied in international trade has also increased in the past decades and indicated no sign of slowing down. This hypothesis, however, is inconclusive, as the international CO_2 emission transfer patterns could also be driven by the cross-country differences in production technology. In particular, in the presence of technology differences, the exchange of identical products at equal prices between two countries would result in one country generating more emissions than the other.

This dissertation investigates whether the decrease in territorial CO_2 emissions reported by the developed countries have indeed been associated with the emissions increases in the developing countries. In particular, it examines to what extent a country's participation in international trade affects both foreign and domestic CO_2 emissions. In doing so, this dissertation implements the Environmentally-Extended Multi-Regional Input-Output (EE MRIO) as the primary model to measure emissions embodied in final demand, proposes a novel method to standardize the production technology at the world average level, and interprets the resulting 'technology-adjusted' emission concepts. The EE MRIO analysis is

a tractable mathematical model capable of analyzing how resources are flowing within and between countries and in what way the emissions are discharged along the production and consumption activities.

Given the need to understand the cross-border dynamics of CO_2 emissions, the need arises to explore regulation mechanisms that can address the issue of global CO_2 increases. Carbon taxation policy represents one such mechanism. By holding polluters accountable for their CO_2 emissions, a carbon tax creates a direct financial incentive for the polluters to reduce CO_2 emission footprints associated with their economic activities. Carbon taxation is preferred for its ability to generate tax revenues necessary to finance other climate mitigation and adaptation programs. In the long run, carbon taxation may also stimulate polluters to either substitute emission-intensive for less-polluting energy sources and/or to increase the efficiency of energy use. Carbon taxation, however, faces a greater challenge for its short-run economic consequences. Carbon tax immediately increases the prices of CO_2-intensive energy sources, which will increase the prices of other commodities. The economy-wide price increases would disproportionately place heavier burden on low-income households. There have been various evidences across the world when public demonstrates fierce resistances to the price-increasing energy and climate policy initiatives. For this reason, this dissertation also seeks to understand the distributional implications of a carbon taxation policy on households. Indonesia is selected as a case study for carbon tax and cash transfer policy implementation. Although still addressing a challenge of reducing CO_2 while maintaining its development objectives, Indonesia has set a target to introduce carbon taxation policy in the near future.

This dissertation has three primary objectives. First, it seeks to understand to what extent the reductions in territorial CO_2 emissions in the developed countries are associated with the CO_2 emissions increases in the developing countries. In particular, it evaluates to what extent a country's participation in international trade is associated with the emission increases in the rest of the world. Secondly, it evaluates whether some countries have experienced an absolute 'decoupling' between the domestic CO_2 emissions and economic growth, in that they have significantly reduced domestic CO_2 emissions while maintaining meaningful economic growth. In doing so, this dissertation appraises the net effect of participation in international trade on domestic CO_2 emissions. Thirdly, this dissertation seeks to understand the potential implications arising from the implementations of carbon taxation and fiscal transfer initiatives on households in Indonesia. The objectives of this dissertation are synthesized into the following main research question:

To what extent does a country's participation in international trade affect domestic and foreign CO_2 emissions, and how does the carbon taxation policy – as an instrument to stimulate carbon emissions reduction – affects the income of households in developing countries?

In answering this main research question, a combination of theoretical thought experiments derived from trade theory and multiple mathematical models are used in the analysis. At the heart of this research is the mathematical model called the environmentally-extended multi-regional input-output (EE MRIO) analysis. The EE MRIO analysis serves as the primary model to measure the direct and indirect CO_2 emissions embodied in final demand. To understand the effect of a country's trade on foreign emissions, this study proposes a novel 'technology-adjusted' emission accounting scheme and offers a perspective to interpret the emissions 'avoided' by exports and imports. To appraise the distributional impacts of a carbon tax and cash transfer policy on households in Indonesia, this dissertation combines the EE MRIO and household survey data of Indonesia.
The main research question is answered by subdividing it into three research sub-questions:

1. ***How does a country's participation in international trade affect carbon emissions in the rest of the world?***

Many developed countries are reported to have reduced a substantial level of domestic CO_2 emissions while maintaining an adequate level of economic growth. However, at the same time, the domestic CO_2 emissions documented by many developing countries, and in general the global CO_2 emissions, are increasing. These facts have led to a common interpretation that the developed countries have managed to reduce domestic CO_2 emissions by means of production 'outsoucing' to the developing countries. The developed countries' absolute 'decoupling' between domestic CO_2 emissions and economic growth, therefore, is a mere 'delusion', as the domestic CO_2 emission increases in developing countries will not translate into overall global emissions reductions. This paper intends to investigate whether developed countries 'decoupling' is indeed genuine. It does so by investigating to what extent a country's participation in international trade affects foreign CO_2 emissions.

Appraising the impact of a country's participation in international trade on foreign CO_2 emissions requires taking into consideration the foreign CO_2 emissions generated by imports and foreign emissions avoided by exports. The concept of emissions avoided by exports is hypothetical, it is derived from asking a question: "What would the emissions be if a country ceased participation in trade?". In a counterfactual scenario where a certain commodity had not been exported by the country in question, the least demanding assumption is that the focus country's exports were produced by the 'world-average' technology. The impact of a country's trade on foreign emissions is then measured by comparing the foreign emissions embodied in imports and the foreign emissions avoided by exports. The difference between the former and the latter implies the 'net weak carbon leakage'. A country is said to net-avoid foreign emissions if it documents a positive net weak carbon leakage, and otherwise net-generates foreign emissions if it documents negative net weak carbon leakage.

This study finds that a large-trade deficit countries like the USA net-generates foreign CO_2 emissions. This means that the USA generates more than it avoids foreign emissions. China records an opposing trend to the USA: China net-avoids foreign CO_2 emissions, meaning China avoids more than it generates foreign emissions. The patterns of net weak carbon leakage vary across countries, yet a general pattern can be inferred from the results. In general, most developed countries net-avoid CO_2 emissions, meaning they avoid more than they generate foreign CO_2 emissions. Most developing countries, on the other hand, net-generate CO_2 emissions, meaning they generate more than they avoid foreign CO_2 emissions. This study observes a positive cross-country correlation between net weak carbon leakage and per-capita income.

To investigate whether 'economy-emission' decoupling in the developed countries are valid, this study analyzes the cross-country trends in production-based emissions (PBE) and the technology-adjusted consumption-based emissions (TCBE). The 'decoupling' can be found if, assuming the developed countries' economies are growing at an acceptable rate, both PBE and TCBE are decreasing. If one of these conditions are not met, the 'decoupling' is just a mirage. PBE and TCBE are indeed decreasing in many developed countries. This means that the PBE decreases reported by the developed countries are not associated with the emission increases in the rest of the world. All the developing countries in the sample show increasing PBE and TCBE.

2. ***How does participation in international trade affect a country's domestic carbon emissions?***

When a country participates in international trade, it 'onshores' emissions to produce exports and 'offshores' emissions to produce imports. When a country generates more emissions for exports than it generates emissions to produce imports, its participation in international trade implies a net increase in its territorial emissions. On the other hand, when a country generates more emissions to produce imports than it generates for exports, its participation in international trade results in a net reduction in its territorial emissions. In general, the developed countries offshore emissions in net terms while the developing countries onshore emissions in net terms. The participation in international trade is said to have allowed some developed countries to reduce their domestic CO_2 emissions while achieving an adequate level of economic growth – the 'economy-emission' decoupling – with the cost of increasing domestic CO_2 emissions in some developing countries. This paper investigates to what extent a country participation in international trade affects domestic emissions.

To assess the effect of a country's trade participation on domestic emissions, one should consider not only the domestic emissions the focus country generates to produce exports but also the domestic emissions it avoids by importing from the rest of the world. The domestic emissions to produce exports are essentially the emissions embodied in exports, or the emissions onshoring. The domestic emissions avoided by imports assumes that the imports were to be produced using domestic production technology. The 'net onshoring' of emissions measures the net impact of a country's participation in trade on domestic emissions, calculated by the difference between the emissions onshoring and the emissions avoided by imports. A country with positive 'net onshoring' onshores more than it offshores emissions. A country with negative 'net onshoring' offshores more than it onshores emissions.

There has been a spatio-temporal variation of 'net onshoring' for the sample countries. The USA and China once again exercise an opposing trend. The USA is net offshoring emissions, meaning the USA offshores more than it onshores emissions. China, on the other hand, is net onshoring emissions, meaning it onshores more than it offshores emissions. For the large trade-surpluses countries like China and Germany, the change in net onshoring reflectes the change in trade balance across the study period. For Japan, the increasingly negative trend of net onshoring between 2003-2012 is likely driven by the influx of foreign fuel which peaks in 2008 and 2012 when global oil prices were 2-3 times higher than the previous decades. India is net offshoring emissions throughout the analysis period because the country exports services with low emission intensity and imports high-intensity manufactured goods. There is a positive cross-country correlation between net onshoring and per-capita income.

To appraise the reported 'decoupling' success, this study proposes a domestic emission metric that takes into account the net onshoring of emissions, the domestic-technology CBE. The 'decoupling' is a genuine success if both PBE and the domestic-technology CBE are decreasing in parallel with the growth in economy. The 'decoupling' is a 'delusion' if one of these conditions cannot be satisfied. This study finds that both PBE and the domestic-technology CBE are decreasing in most developed countries and increasing in many developing countries. Out of 66 sample countries and over the period 1995-2015, PBE are decreasing in 20 countries and the domestic-technology CBE are decreasing in 21 countries. Most of these countries are developed countries. The developed countries' 'decoupling' is an actual success.

3. ***How are the households across income levels affected by the implementation of carbon taxation policy?***

This study considers the carbon taxation policy to be accompanied by the cash transfer initiative and defines them as 'carbon policy reform'. The relative net impact of a carbon policy reform on households is measured by the ratio of the net expenditure after carbon tax and cash transfer to the initial expenditure of that particular household. By selecting Indonesia as a case study, this study finds that the carbon policy reform has a tendency to be progressive. This is indicated by the relative net impact that is (positively) higher for low-income than high-income households. However, this is not indicative of whether the post-reform net expenditure levels of all households have recovered to the pre-reform expenditure levels. This study discovers that without an accompanying cash transfer initiative, the carbon tax in Indonesia is neither progressive nor regressive.

If the carbon tax is levied on all sectors in the national economy (national carbon tax) and the entire tax revenue is uniformly recycled to all households, the bottom 60% of households would recover and net benefit from the carbon policy reform. In the same taxation scenario but with a $100 existing cash transfer program in Indonesia, only the first 10% of households in the income decile would recover and net benefit from the reform. If the imported products are subject to carbon border adjustment, bottom 60% would net benefit in the uniform cash transfer initiative.

To investigate the drivers of carbon tax burden, consumption items are aggregated into four categories (electricity, fuel, foods, and others). This study finds that a carbon tax in Indonesia mainly affects households across income levels through the price increase in electricity and fuel. However, the monetary size of electricity and fuel consumption does not seem to be the primary drivers of the magnitude of carbon tax burden. Instead, it is just that both products are intensive in emissions. This is because both products only comprise a tiny portion of households' expenditures. Gas electricity is the biggest source of carbon tax burden, followed by coal electricity and diesel electricity.

The EE MRIO incorporates a number of underlying assumptions and limitations. Acknowledging these assumptions and limitations is necessary when interpreting the analysis results generated by the model. The most fundamental assumption pertaining the EE MRIO analysis is that production in a Leontief input-output system operates under the *constant return to scale*. This assumption implies that the intermediate inputs are in constant proportions of the output of the purchasing industry. In addition, a Leontief IO system assumes that a sector uses input in fixed proportions. The assumption of constant returns to scale and fixed input proportions means that the model implicitly assumes an absence of technological change. Therefore, the results do not account for changes in productivity and efficiency that could arise from the technological progress. In consequence, the assumptions could lead to either an overestimation or underestimation of environmental impact or economic value of different sectors.

To measure the impacts of carbon tax on households, this dissertation relies on a short-run, static model. As a short-term model, it assumes that both producer and consumer have limited room to respond to the change brought about by carbon policy reform. Specifically, it assumes that the producer and consumer price elasticity of demand functions to be zero. While this assumption is practical to predict the immediate impact of carbon policy reform, this assumption does not accurately reflect the real-world economic behavior of both producer and consumer. In consequence, this assumption could again could result in overestimation or underestimation of the impact of carbon taxation policy in Indonesia. The model also assumes that the received cash from the cash transfer program is spent entirely and in the same proportion as to the previous structure of consumption of the corresponding household.

It might be of interest for the future research to explore what could possibly drive the international patterns of the 'net weak carbon leakage'. This type of analysis, which is beyond the scope of this dissertation, could be carried out by structural decomposition analysis. As for the carbon policy reform analysis, it might be a worthwhile enterprise to introduce price elasticity of demand of producer and consumer. This will consequentially transform the static model into dynamic model and increase the complexities and uncertainties of the model.

To the main research question, by participating in trade, most developed countries net-avoid CO2 emissions. This means that most developed countries avoid more than they generate foreign CO2 emissions. In contrast, most developing countries net-generate CO2 emissions. This means that most developing countries generate more than they avoid foreign CO2 emissions. There has actually been a positive cross-country correlation between net weak carbon leakage and per-capita income and between net onshoring and per-capita income. Most developed countries (the USA is one of the exceptions) net onshore emissions, meaning they generate more emissions by exporting than they avoid by importing. In contrast, most developing countries (China is one of the exceptions) net offshore emissions. This means they avoid more emissions by importing than they generate by exporting. The decoupling between economic growth and domestic CO2 emissions observed in developed countries is an actual success. In the context of carbon taxation policy, taking into account the emissions embodied in imports (for instance if carbon border adjustment were to be implemented in Indonesia) increases the impact of carbon tax on households in Indonesia, irrespective of the income level.

Samenvatting

De wereldwijde CO_2-emissies door brandstofverbranding in productie- en consumptieactiviteiten, die het grootste deel van de wereldwijde broeikasgasemissies (GHG) uitmaken, zijn de afgelopen decennia blijven stijgen. Dit is een reden tot zorg, aangezien het beperken van de opwarming van de aarde tot onder de 1,5°C (en nog erger, 2°C) een diepe en snelle vermindering van het huidige niveau van wereldwijde CO_2-emissies vereist. Echter, het patroon van de CO_2-emissies op het niveau van individuele landen is minder eenduidig dan het patroon van wereldwijde CO_2-emissies. Studies hebben gedocumenteerd dat de territoriale CO_2-emissies in de meeste ontwikkelingslanden toenemen, terwijl ze in de meeste ontwikkelde landen afnemen. Over het algemeen zijn de meeste ontwikkelde landen netto-importeurs van CO_2-emissies en zijn de meeste ontwikkelingslanden netto-exporteurs van CO_2-emissies. Dit bewijs heeft geleid tot de hypothese dat de internationale handel de ontwikkelde landen in staat heeft gesteld hun binnenlandse CO_2-emissies te verminderen – terwijl ze een acceptabele economische groei behouden – door middel van productie-uitbesteding aan ontwikkelingslanden. Dit is met name het geval omdat de wereldwijde CO_2-emissies die in de internationale handel zijn belichaamd, ook in de afgelopen decennia zijn toegenomen en geen tekenen van vertraging vertonen. Deze hypothese is echter niet sluitend, aangezien de patronen van internationale CO_2-emissietransfers ook kunnen worden gedreven door de verschillen in productietechnologie tussen landen. In het bijzonder, in de aanwezigheid van technologieverschillen, zou de uitwisseling van identieke producten tegen gelijke prijzen tussen twee landen resulteren in dat het ene land meer emissies genereert dan het andere.

Dit proefschrift onderzoekt of de afname van territoriale CO_2-emissies die door de ontwikkelde landen is gerapporteerd, daadwerkelijk is geassocieerd met de toename van emissies in de ontwikkelingslanden. In het bijzonder observeert dit proefschrift in hoeverre de deelname van een land aan de internationale handel zowel buitenlandse als binnenlandse CO_2-emissies beïnvloedt. Hierbij implementeert dit proefschrift de Environmentally-Extended Multi-Regional Input-Output (EE MRIO) als het primaire model om de emissies belichaamd

in de finale vraag te meten, stelt een nieuwe methode voor om de productietechnologie te standaardiseren op het wereldgemiddelde niveau, en interpreteert de resulterende ’technologie-aangepaste’ emissieconcepten. De EE MRIO-analyse is een hanteerbaar wiskundig model dat in staat is om te analyseren hoe hulpbronnen binnen en tussen landen stromen en op welke manier de emissies worden vrijgegeven langs de productie- en consumptieactiviteiten.

Gezien de noodzaak om de grensoverschrijdende dynamiek van CO_2-emissies te begrijpen, ontstaat de behoefte om reguleringsmechanismen te verkennen die het probleem van wereldwijde toenames in CO_2-emissies kunnen aanpakken. Een koolstofbelastingbeleid vertegenwoordigt zo’n mechanisme. Door vervuilers verantwoordelijk te houden voor de CO_2-emissies die ze hebben gegenereerd, creëert een koolstofbelasting een directe financiële prikkel voor de vervuilers om de CO_2-emissievoetafdrukken die geassocieerd zijn met hun economische activiteiten te verminderen. Koolstofbelasting wordt geprefereerd vanwege het vermogen om belastinginkomsten te genereren die nodig zijn om andere klimaatmitigatie- en aanpassingsprogramma’s te financieren. Op de lange termijn kan koolstofbelasting vervuilers ook stimuleren om emissie-intensieve energiebronnen te vervangen door minder vervuilende of de efficiëntie van energiegebruik te verhogen. Koolstofbelasting staat echter voor een grotere uitdaging vanwege de kortetermijneconomische gevolgen. Een koolstofbelasting verhoogt onmiddellijk de prijzen van CO_2-intensieve energiebronnen, wat de prijzen van andere goederen zal verhogen. De economiebrede prijsstijgingen zouden onevenredig zwaarder drukken op huishoudens met een laag inkomen. Er zijn verschillende bewijzen over de hele wereld wanneer het publiek hevige weerstand biedt tegen het verhogen van de prijs van energie- en klimaatbeleidsinitiatieven. Om deze reden streeft dit proefschrift ernaar de distributieve implicaties van een koolstofbelastingbeleid voor huishoudens te begrijpen. Indonesië is geselecteerd als casestudy voor de implementatie van koolstofbelasting en cash transfer beleid. Hoewel het nog steeds een uitdaging is om CO_2 te verminderen terwijl het zijn ontwikkelingsdoelstellingen handhaaft, heeft Indonesië als doel gesteld om in de nabije toekomst een koolstofbelastingbeleid in te voeren.

Dit proefschrift heeft drie primaire doelstellingen. Ten eerste tracht dit proefschrift te begrijpen in hoeverre de afnames in territoriale CO_2-emissies in de ontwikkelde landen geassocieerd zijn met de toenames van CO_2-emissies in de ontwikkelingslanden. In het bijzonder evalueert het in hoeverre de deelname van een land aan de internationale handel geassocieerd is met de emissietoename in de rest van de wereld. Ten tweede tracht dit proefschrift te evalueren of sommige landen een absolute ’ontkoppeling’ tussen de binnenlandse CO_2-emissies en economische groei hebben ervaren, in die zin dat ze de binnenlandse CO_2-emissies aanzienlijk hebben verminderd terwijl ze betekenisvolle economische groei hebben behouden. Hierbij beoordeelt dit proefschrift het netto-effect van deelname aan de internationale handel op binnenlandse CO_2-emissies. Ten derde tracht dit proefschrift de potentiële implicaties te begrijpen die voortvloeien uit de implementaties van koolstofbelasting en fiscale overdrachtsinitiatieven op huishoudens in Indonesië. De doelstellingen van dit proefschrift zijn samengevat in de volgende onderzoeksvraag:

In hoeverre beïnvloedt de deelname van een land aan internationale handel de binnenlandse en buitenlandse CO_2-emissies, en hoe beïnvloedt het koolstofbelastingbeleid – als instrument om de reductie van koolstofemissies te stimuleren – het inkomen van huishoudens in ontwikkelingslanden?

Bij het beantwoorden van deze hoofdonderzoeksvraag wordt gebruik gemaakt van een combinatie van theoretische gedachte-experimenten en meerdere wiskundige modellen in de analyse. Centraal in dit proefschrift staat de analyse van de Environmentally-Extended Multi-Regional Input-Output (EE MRIO). De EE MRIO-analyse dient als het primaire model om de directe en indirecte CO_2-emissies belichaamd in de finale vraag te meten. Om het effect van de handel van een land op buitenlandse emissies te begrijpen, stelt dit proefschrift een nieuw 'technologie-aangepast' emissieboekhoudingsschema voor en biedt het een perspectief om de emissies 'vermeden' door export en import te interpreteren. Om de distributieve impact van een koolstofbelasting en cash transfer beleid op huishoudens in Indonesië te taxeren, combineert dit proefschrift de EE MRIO en huishoudensenquêtegegevens van Indonesië.

De hoofdonderzoeksvraag wordt beantwoord door deze op te delen in drie onderzoeksvragen:

1. ***Hoe beïnvloedt de deelname van een land aan internationale handel de koolstofemissies in de rest van de wereld?***

Veel ontwikkelde landen worden gemeld een substantieel niveau van binnenlandse CO_2-emissies te hebben verminderd terwijl ze een adequaat niveau van economische groei handhaven. Echter, tegelijkertijd nemen de binnenlandse CO_2-emissies zoals gedocumenteerd door veel ontwikkelingslanden, en in het algemeen de wereldwijde CO_2-emissies, toe. Deze feiten hebben geleid tot de indruk dat de ontwikkelde landen erin zijn geslaagd om binnenlandse CO_2-emissies te verminderen door middel van productie 'outsourcing' naar de ontwikkelingslanden. De absolute 'ontkoppeling' tussen binnenlandse CO_2-emissies en economische groei van de ontwikkelde landen, is daarom een loutere 'illusie', aangezien de toename van binnenlandse CO_2-emissies in ontwikkelingslanden niet zal resulteren in een algehele vermindering van wereldwijde emissies. Dit proefschrift is bedoeld om te bevestigen of de 'ontkoppeling' van de ontwikkelde landen inderdaad waar is. Dit doet het door te onderzoeken in hoeverre de deelname van een land aan internationale handel buitenlandse CO_2-emissies beïnvloedt.

Het beoordelen van de impact van de deelname van een land aan internationale handel op buitenlandse CO_2-emissies vereist dat rekening wordt gehouden met de buitenlandse CO_2-emissies gegenereerd door import en buitenlandse emissies vermeden door export. Het concept van door export vermeden emissies is hypothetisch, het is afgeleid van de vraag: "Wat zouden de emissies zijn als een land zou stoppen met deelnemen aan de handel?". In een tegenfeitelijk scenario waarin een bepaald goed niet door het betreffende land was geëxporteerd, is de minst veeleisende aanname dat de export van het focusland werd geproduceerd met de 'wereldgemiddelde' technologie. De impact van de handel van een land op buitenlandse emissies wordt dan gemeten door de buitenlandse emissies belichaamd in importen te vergelijken met de buitenlandse emissies vermeden door export. Het verschil tussen het eerste en het laatste impliceert de 'netto zwakke koolstoflekkage'. Er wordt gezegd dat een land buitenlandse emissies netto vermijdt als het een positieve netto zwakke koolstoflekkage documenteert, en andersom netto buitenlandse emissies genereert als het een negatieve netto zwakke koolstoflekkage documenteert.

Deze studie vindt dat landen met een groot handelstekort, zoals de USA, netto buitenlandse CO_2-emissies genereren. Dit betekent dat de USA meer buitenlandse emissies genereert dan het vermijdt. China laat een tegengestelde trend zien ten opzichte van de USA: China vermijdt netto buitenlandse CO_2-emissies, wat betekent dat China meer buitenlandse emissies vermijdt dan het genereert. De patronen van netto zwakke koolstoflekkage variëren per land, maar uit de resultaten kan een algemeen patroon worden afgeleid. Over het algemeen vermijden de meeste ontwikkelde landen netto CO_2-emissies, wat betekent dat ze meer buitenlandse CO_2-emissies vermijden dan ze genereren. De meeste ontwikkelingslanden daarentegen genereren netto CO_2-emissies, wat betekent dat ze meer genereren dan ze buitenlandse CO_2-emissies vermijden. Deze studie observeert een positieve correlatie tussen landen wat betreft netto zwakke koolstoflekkage en inkomen per hoofd van de bevolking.

Om te bevestigen of de economie-emissie' ontkoppeling in de ontwikkelde landen geldig is, analyseert deze studie de trends tussen landen in production-based emissions (PBE) en de technology-adjusted consumption-based emissions (TCBE). De ontkoppeling' kan worden bevestigd als, uitgaande van het feit dat de economieën van de ontwikkelde landen groeien tegen een acceptabel tarief, zowel PBE als TCBE afnemen. Als een van deze voorwaarden niet wordt voldaan, is de 'ontkoppeling' slechts een luchtspiegeling. PBE en TCBE nemen inderdaad af in veel ontwikkelde landen. Dit betekent dat de afnames van PBE gerapporteerd door de ontwikkelde landen niet geassocieerd zijn met de emissietoenames in de rest van de wereld. Alle ontwikkelingslanden in de steekproef registreren toenemende

PBE en TCBE.

2. ***Hoe beïnvloedt deelname aan internationale handel de binnenlandse koolstofemissies van een land?***

Wanneer een land deelneemt aan internationale handel, haalt het emissies binnen' om export te produceren en zet het emissies buiten' wanneer het export produceert. Wanneer een land meer emissies genereert voor export dan het emissies genereert om import te produceren, impliceert zijn deelname aan internationale handel een netto toename van zijn territoriale emissies. Aan de andere kant, wanneer een land meer emissies genereert om import te produceren dan het genereert voor export, resulteert zijn deelname aan internationale handel in een netto vermindering van zijn territoriale emissies. Over het algemeen exporteren de ontwikkelde landen netto emissies terwijl de ontwikkelingslanden netto emissies binnenhalen. Er wordt gezegd dat deelname aan internationale handel sommige ontwikkelde landen in staat heeft gesteld hun binnenlandse CO_2-emissies te verminderen terwijl ze een adequaat niveau van economische groei bereiken – de economie-emissie' ontkoppeling – ten koste van het verhogen van binnenlandse CO_2-emissies in sommige ontwikkelingslanden. Dit proefschrift onderzoekt opnieuw of het geval van economie-emissie' ontkoppeling waargenomen in sommige ontwikkelde landen geldig is. Dit keer onderzoekt dit proefschrift in hoeverre deelname van een land aan internationale handel binnenlandse emissies beïnvloedt.

Om het effect van de deelname van een land aan handel op binnenlandse emissies te beoordelen, moet men niet alleen de binnenlandse emissies overwegen die het focusland genereert om export te produceren, maar ook de binnenlandse emissies die het vermijdt door te importeren uit de rest van de wereld. De binnenlandse emissies om export te produceren zijn in wezen de emissies belichaamd in export, of de emissies die binnengehaald worden. De binnenlandse emissies vermeden door import gaan ervan uit dat de importen geproduceerd zouden worden met behulp van binnenlandse productietechnologie. Het netto binnenhalen' van emissies meet de netto impact van de deelname van een land aan handel op binnenlandse emissies, berekend door het verschil tussen de binnengehaalde emissies en de door import vermeden emissies. Een land met positief netto binnenhalen' haalt meer emissies binnen dan het naar buiten brengt. Een land met negatief 'netto binnenhalen' brengt meer emissies naar buiten dan het binnenhaalt.

Er is een spatio-temporele variatie van 'netto binnenhalen' voor de steekproeflanden. De USA en China vertonen weer een tegenovergestelde trend. De USA is netto emissies aan het binnenhalen, wat betekent dat de USA meer buiten zet dan binnenhaalt aan emissies. China, daarentegen, is netto emissies aan het binnenhalen, wat betekent dat het meer binnenhaalt dan het buiten zet aan emissies. Voor landen met grote handelsoverschotten zoals China en Duitsland weerspiegelt de verandering in netto binnenhalen de verandering in de handelsbalans gedurende de studieperiode. Voor Japan wordt de steeds negatievere trend van netto binnenhalen tussen 2003-2012 waarschijnlijk gedreven door de toestroom van buitenlandse brandstof, die piekt in 2008 en 2012 toen de wereldwijde olieprijzen 2-3 keer hoger waren dan in de voorgaande decennia. India is gedurende de hele analyseperiode netto emissies aan het buiten zetten, omdat het land diensten exporteert met een lage emissie-intensiteit en goederen met een hoge intensiteit importeert. Er is een positieve correlatie tussen landen van netto binnenhalen en het inkomen per hoofd van de bevolking.

Om het gerapporteerde ontkoppelings' succes te beoordelen, stelt deze studie een binnenlandse emissiemetric voor die rekening houdt met het netto binnenhalen van emissies, de trade-adjusted PBE (TPBE). De ontkoppeling' is een echt succes als zowel PBE als TPBE parallel aan de economische groei afnemen. De ontkoppeling' is een illusie' als een van deze voorwaarden niet kan worden voldaan. Deze studie vindt dat zowel PBE als TPBE in de meeste ontwikkelde landen afnemen en in veel ontwikkelingslanden toenemen. Van de 66 onderzochte landen en over de periode 1995-2015, nemen PBE af in 20 landen en TPBE in 21 landen. De meeste van deze landen zijn ontwikkelde landen. De meeste van deze landen zijn ontwikkelde landen. De 'ontkoppeling' van de ontwikkelde landen zou een daadwerkelijk succes kunnen zijn.

3. ***Hoe worden huishoudens over de inkomensniveaus heen beïnvloed door de implementatie van een koolstofbelastingbeleid?***

Deze studie beschouwt het koolstofbelastingbeleid als vergezeld van het initiatief voor geldoverdrachten en definieert deze als 'hervorming van het koolstofbeleid'. De relatieve netto-impact van een hervorming van het koolstofbeleid op een huishouden wordt gemeten door de verhouding van de netto-uitgaven na koolstofbelasting en geldoverdracht tot de initiële uitgaven van dat specifieke huishouden. Door Indonesië als een studiegeval te selecteren, vindt deze studie dat de hervorming van het koolstofbeleid de neiging heeft progressief te zijn. Dit wordt aangegeven door de relatieve netto-impact die (positief) hoger is voor huishoudens met een laag inkomen dan voor huishoudens met een hoog inkomen. Dit is echter niet indicatief voor of de netto-uitgavenniveaus na de hervorming van alle huishoudens zijn hersteld naar de niveaus van uitgaven voor de hervorming. Deze studie ontdekt dat zonder een begeleidend initiatief voor geldoverdrachten, de koolstofbelasting in Indonesië noch progressief noch regressief is.

Als de koolstofbelasting wordt geheven op alle sectoren in de nationale economie (nationale koolstofbelasting) en de gehele belastingopbrengst uniform aan alle huishoudens wordt gerecycled, zouden de onderste 60% van de huishoudens herstellen en netto profiteren van de hervorming van het koolstofbeleid. In hetzelfde belastingscenario maar met een bestaand cash transfer-programma van $100 in Indonesië, zouden alleen de eerste 10% van de huishoudens in het inkomensdecile herstellen en netto profiteren van de hervorming. Als de geïmporteerde producten onderworpen zijn aan koolstofgrensaanpassing, zou de onderste 60% netto profiteren bij het uniforme cash transfer-initiatief.

Om de drijfveren van de koolstofbelastinglast te onderzoeken, worden consumptiegoederen geaggregeerd in vier categorieën (elektriciteit, brandstof, voedsel en overige). Deze studie vindt dat een koolstofbelasting in Indonesië huishoudens over inkomensniveaus voornamelijk beïnvloedt door de prijsstijging in elektriciteit en brandstof. Echter, de monetaire grootte van het verbruik van elektriciteit en brandstof lijkt niet de primaire drijfveren te zijn van de omvang van de koolstofbelastinglast. In plaats daarvan is het gewoon zo dat beide producten emissie-intensief zijn. Dit komt omdat beide producten slechts een klein deel uitmaken van de uitgaven van huishoudens. Gas-elektriciteit is de grootste bron van koolstofbelastinglast, gevolgd door kolen-elektriciteit en diesel-elektriciteit.

De EE MRIO omvat een aantal onderliggende aannames en beperkingen. Het erkennen van deze aannames en beperkingen is noodzakelijk bij het interpreteren van de analyse resultaten die door het model worden gegenereerd. De meest fundamentele aanname met betrekking tot de EE MRIO-analyse is dat de productie in een Leontief input-output systeem functioneert onder het principe van 'constante opbrengsten naar schaal'. Deze aanname impliceert dat de intermediaire inputs in constante proporties zijn van de output van de kopende industrie. Daarnaast neemt een Leontief IO-systeem aan dat een sector input gebruikt in vaste proporties. De aanname van constante opbrengsten naar schaal en vaste inputverhoudingen betekent dat het model impliciet aanneemt dat er geen technologische verandering plaatsvindt. Daarom houden de resultaten geen rekening met veranderingen in productiviteit en efficiëntie die kunnen voortvloeien uit technologische vooruitgang. Bijgevolg kunnen de aannames leiden tot een over- of onderschatting van de milieueffecten of economische waarde van verschillende sectoren.

Om de impacten van koolstofbelasting op huishoudens te meten, vertrouwt deze dissertatie op een kortetermijn, statisch model. Als kortetermijnmodel wordt aangenomen dat zowel producent als consument beperkte ruimte hebben om te reageren op de verandering die wordt teweeggebracht door de hervorming van het koolstofbeleid. Specifiek wordt aangenomen dat de prijselasticiteit van de vraagfuncties van producent en consument perfect inelastisch zijn. Hoewel deze aanname praktisch is om de onmiddellijke impact van de hervorming van het koolstofbeleid te voorspellen, weerspiegelt deze aanname niet nauwkeurig het reële economische gedrag van zowel producent als consument. Bijgevolg kan deze aanname opnieuw leiden tot een over- of onderschatting van de impact van het koolstofbelastingbeleid in Indonesië. Het model neemt ook aan dat het ontvangen geld van het cash transfer programma volledig en in dezelfde verhouding wordt uitgegeven als de vorige structuur van consumptie van het overeenkomstige huishouden.

Het kan van belang zijn voor toekomstig onderzoek om te verkennen wat mogelijk de internationale patronen van de 'net weak carbon leakage' zou kunnen drijven. Dit type analyse, dat buiten de reikwijdte van deze dissertatie valt, zou uitgevoerd kunnen worden door structurele decompositie analyse. Wat betreft de analyse van de hervorming van het koolstofbeleid, zou het waardevol kunnen zijn om prijselasticiteit van de vraag van producent en consument te introduceren. Dit zal vervolgens het statische model transformeren in een dynamisch model en de complexiteiten en onzekerheden van het model verhogen.

Op de hoofdonderzoeksvraag, door deel te nemen aan de handel, vermijden de meeste ontwikkelde landen netto CO2-emissies. Dit betekent dat de meeste ontwikkelde landen meer buitenlandse CO2-emissies vermijden dan ze genereren. In tegenstelling tot de meeste ontwikkelingslanden genereren netto CO2-emissies. Dit betekent dat de meeste ontwikkelingslanden meer genereren dan ze buitenlandse CO2-emissies vermijden. Er is daadwerkelijk een positieve grensoverschrijdende correlatie waargenomen tussen netto zwakke koolstoflekkage en het inkomen per hoofd van de bevolking en tussen netto binnenhalen en het inkomen per hoofd van de bevolking. De meeste ontwikkelde landen (de VS is een van de uitzonderingen) nemen netto emissies op, wat betekent dat ze meer emissies genereren door te exporteren dan ze vermijden door te importeren. In tegenstelling tot de meeste ontwikkelingslanden (China is een van de uitzonderingen) voeren netto emissies af. Dit betekent dat ze meer emissies vermijden door te importeren dan ze genereren door te exporteren. De ontkoppeling tussen economische groei en binnenlandse CO2-emissies waargenomen in ontwikkelde landen is een daadwerkelijk succes. In de context van het koolstofbelastingbeleid, rekening houdend met de emissies belichaamd in importen (bijvoorbeeld als koolstofgrensaanpassing zou worden geïmplementeerd in Indonesië) verhoogt de impact van de koolstofbelasting op huishoudens in Indonesië, ongeacht het inkomensniveau.

Units and Abbreviations

Units

Mass	
t	metric tonne
Gt	gigatonne
CO_2-eq	carbon dioxide equivalent

Temperature	
°C	degree Celcius

Abbreviations

ASEAN	The Association of Southeast Asian Nations
BEET	Balance of Emissions Embodied in Trade
BLT	Bantuan Langsung Tunai
BTA	Border Tax Adjustment
CBE	Consumption-Based Emissions
CGE	Computable General Equilibrium
CO_2	Carbon Dioxide
EAM	Emissions Avoided by Imports
EE	Environmentally-Extended MRIO
EEBT	Emissions-Embodied in Bilateral Trade
EEIO	Emissions Embodied in Input-Output
EEM	Emissions Embodied in Imports
EEX	Emissions Embodied in Exports
EAM	Emissions Avoided by Imports
ESDM	Energi dan Sumber Daya Mineral
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
ICIO	Inter-Country Input-Output
IEA	International Energy Agency
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
LPG	Liquefied Petroleum Gas
MRIO	Multi-Regional Input-Output
NetOn	Net Onshoring of Emissions
OECD	The Organisation for Economic Co-operation and Development
OLS	Ordinary Least Square
PBE	Production-Based Emissions
PHH	Pollution-Haven Hypothesis
PLN	Perusahaan Listrik Negara
PPP	Purchasing Power Parity

PWT10	Penn World Table Version 10
ROW	Rest of the World
SUSENAS	Survey Ekonomi Nasional
TBEET	Technology-adjusted BEET
TEEX	Technology-adjusted EEX
UN	United Nations
USD	United States Dollar
WTO	World Trade Organization

Chapter 1

Introduction

1.1 Background

In the midst of the increasing pressure to limit the adverse effects caused by global warming, global anthropogenic greenhouse gas (GHG) emissions have continued to rise over time and have already led to 1°C increase in average global mean surface temperature relative to the pre-industrial period (see Figure 1.1).

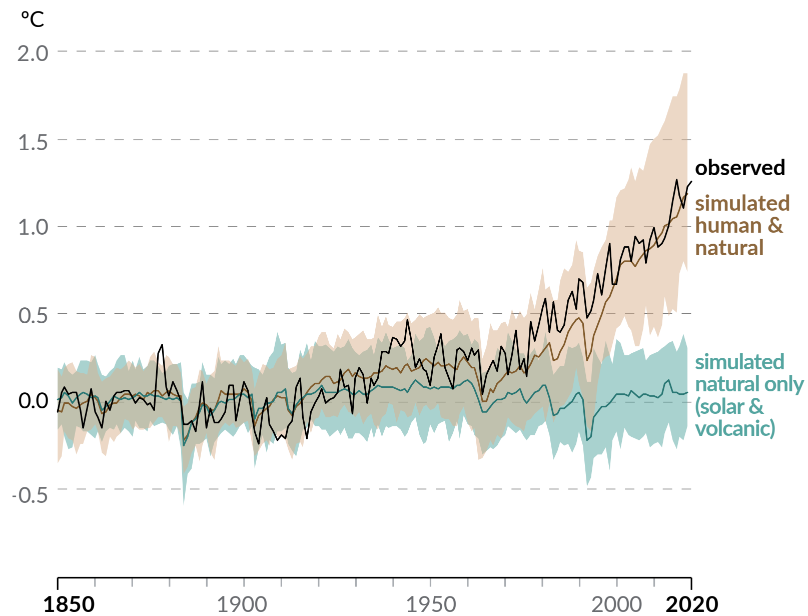


Figure 1.1: Change in global mean surface temperature (in °C) relative to 1850-1900

Source: IPCC (2023) https://www.ipcc.ch/report/ar6/wg1/figures/summary-for-policymakers/figure-spm-1

The IPCC (2023) Synthesis Report documents that global GHG emissions were around 59±6 $GtCO_2$-eq in 2019, which were about 12% higher than in 2010, and about 54% higher than in 1990. Mitigating the impact of climate change requires not only curbing the increase in global GHG emissions but also immediately bringing the current levels down, because an average temperature increase in excess of 1.5°C (or worse, 2°C) may lead to irreversible geophysical changes which lock the Earth into an unstoppable warming (Steffen et al., 2018). To limit the warming to 2°C, the world would require an estimated 26% reduction in global GHG emissions (relative to 2019 level) by 2030, or even an estimated reduction of 43% by 2030 if we are to limit the temperature increase to below 1.5°C (IPCC, 2023). The reduction of global GHG emissions would involve reduction in the current levels of the global CO_2 emissions. This is because not only does CO_2 emissions constitute the majority[1] of all GHG

[1]The most abundant GHG emission in the atmosphere is CO_2, followed by CH_4 and N_2O (IPCC, 2023).

emissions, but the global CO_2 emissions have also been increasing at an unprecedented rate in recent decades. Stadler et al. (2021) estimate that the global CO_2 emissions from fuel combustion in production and consumption activities, which account for around 70% of total global CO_2 emissions, increased from 22.0 to 38.9 Gt of CO_2 between 1995 and 2021 (see Figure 1.2).

The rise in global CO_2 emissions from fuel combustion calls for effective climate policies to meet the global GHG reduction targets. Formulating such policies requires a comprehensive understanding of the factors causing the growth of global CO_2 emissions. However, while the available global emission accounts offer greater clarity on trends at the aggregate level, it is less clear to what extent CO_2 emissions at the level of individual countries or regions are associated with these aggregate emission trends. In particular, a complication arises from the fact that while some countries have recorded a decreasing trend of CO_2 emissions and maintained acceptable rates of economic growth, global CO_2 emissions continue to escalate (Figure 1.2). At the same time, a significant portion of the global CO_2 emissions embodied in trade are increasing. Between 1995 and 2021, the total CO_2 emissions embodied in international trade increased from 3.9 to 8.4 $GtCO_2$, comprising around 20-22% of the global CO_2 emissions (Stadler et al., 2021).

This evidence raises concerns that the increase in global CO_2 emissions in the past decades may be partly attributed to the internationalization of global value chains. In other words, international trade might have enabled countries to reduce domestic emissions by relocating emission-intensive production activities to other countries. As a result, the global CO_2 emissions continue to escalate amid the decreasing trend of CO_2 emissions at the level of individual countries and regions. This would hinder the global effort in reducing CO_2 emissions. Understanding how the participation in international trade is related to the rise in global CO_2 emissions is essential if we are to develop an emission accounting framework that could serve as a guidance for climate policy (Kander et al., 2015). In particular, extensive insights in how and where the resources are used and the emissions are released is required as a basis to design such climate policy (Stadler et al., 2018).

1.1.1 Participation in International Trade and Emission Transfers

Multiple studies implementing the multi-regional input-output (MRIO) analysis have documented that the production-based or territorial emissions[2] are increasing in most developing countries, while these production-based emissions are decreasing in most developed countries (Quéré et al., 2019; Yamano and Guilhoto, 2020; Stadler et al., 2021; Friedlingstein et al., 2022). Between 1995-2021, most developed countries recorded decreases while most

[2]Territorial emissions are the emissions occurring within a country's territory.

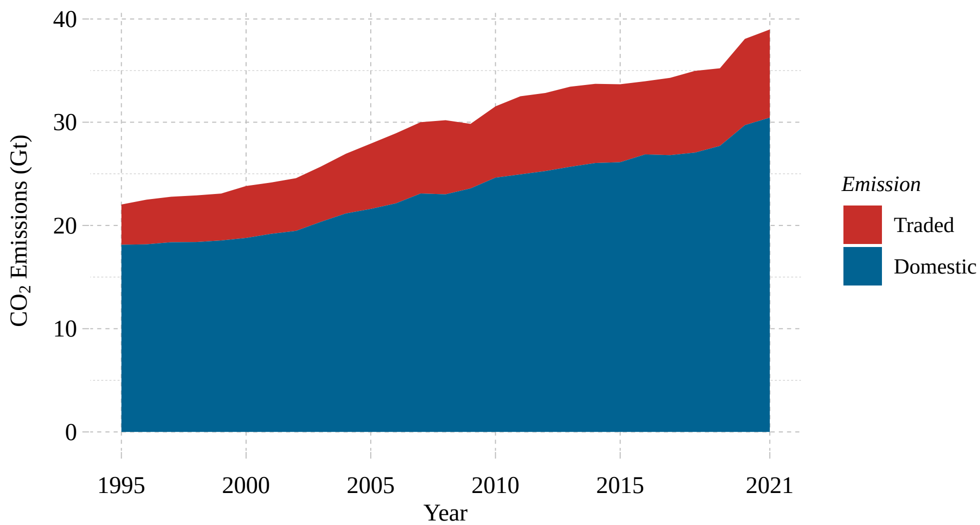


Figure 1.2: Global CO_2 emissions generated from the combustion of fuel in production and consumption activities

Notes: The figure is generated based on the EXIOBASE 3.8.2 regional CO_2 emissions data (Stadler et al., 2021). Domestic emission constitutes the emissions generated domestically to produce goods and services for domestic consumption. Traded emissions constitutes the emissions embodied in internationally traded products. Together, domestic and traded emissions indicate the total global CO_2 emissions generated from the combustion of fuel in production and consumption activities.

developing countries recorded increases in territorial CO_2 emissions (see Figure 1.3).

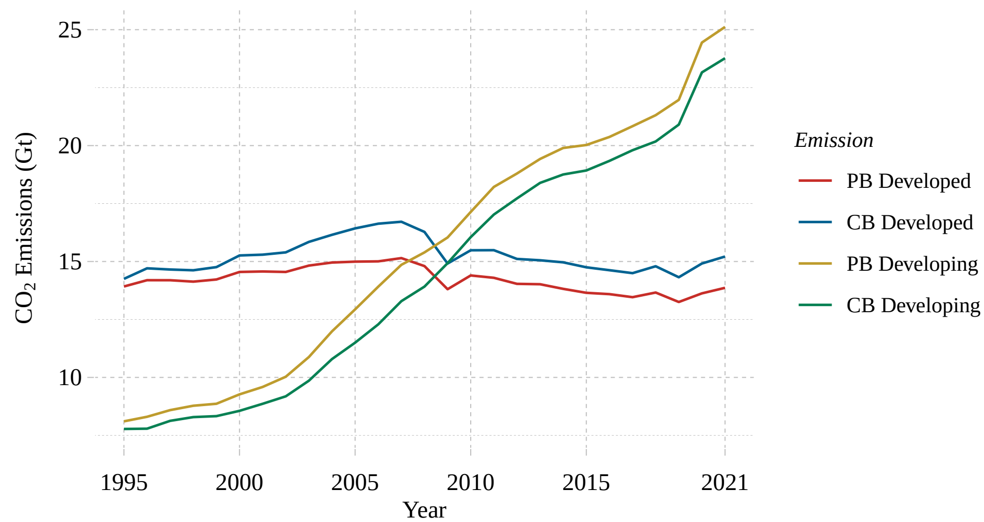


Figure 1.3: Production-based and consumption-based CO_2 emissions distinguished by developed and developing countries

Notes: The figure is generated based on the EXIOBASE 3.8.2 CO_2 emissions data (Stadler et al., 2021). PB stands for production-based and CB stands for consumption-based. PB emissions constitute the emissions generated within a country's territory for domestic and foreign consumption. CB emissions constitute the domestic and foreign emissions embodied in domestic consumption. The gap between PB and CB emissions implies the net transfer of emissions, or balance of emissions embodied in trade.

There exists a negative cross-country correlation between net emission transfers and per-capita income (Wu et al., 2022). Many advanced economies have managed to 'decouple' economic growth and emissions, meaning they have reduced their domestic production-based CO_2 emissions while maintaining an acceptable rate of economic growth (Aden, 2018). It is not clear to what extent these countries managed to decouple growth and consumption-based emissions.

What could be inferred from these empirical facts? The optimistic interpretation suggests that the 'decoupling' success in the developed economies to better technological progress and more stringent energy and climate policy. Technological advancement in renewable energies has relatively been better in most developed economies than in the developing world. Feed-in tariffs and other support schemes have served as a catalyst to promote the expansion of renewable energies including solar PV and wind energy. This had resulted in a decline of the cost of electricity generation from renewable energy sources

(Arndt et al., 2019). Emissions trading systems and carbon taxes have been implemented or are scheduled for implementation in the near future. In the developed economies, the economywide energy intensity is falling and power sectors are decarbonizing (IEA, 2018).

However, most developed countries also record increases in CO_2 emissions embodied in imports (Stadler et al., 2021). In general, most developed countries are *net-importers* of CO_2 emissions (Friedlingstein et al., 2022). This means that most developed countries generate more CO_2 emissions outside their territories where their imports are produced than the CO_2 emissions they generate inside their own territories to produce exports. Most developing countries, on the other hand, are *net-exporters* of CO_2 emissions, meaning most developing countries generate more CO_2 emissions to produce exports than the CO_2 emissions they generate in the rest of the world to produce their imports (Friedlingstein et al., 2022). Figure 1.3 documents the net transfers between developed and developing countries. Over the past 10-20 years, the modest declines in CO_2 emissions in the advanced economies were more than offset by the rapid growth of CO_2 emissions in China, India, and most developing countries (Quéré et al., 2019).

A skeptical interpretation suspects that the observed emission 'imbalance' between developed and developing countries might stem from the shift of (CO_2 intensive) production activities from the developed to the developing countries. International trade might thus have encouraged developed countries to 'outsource emissions' by means of production outsourcing to developing countries. The developed countries' participation in trade, therefore, might have allowed them to bring down the level of their territorial emissions while raising the level of CO_2 emissions in developing countries. As a result, the emission reductions in developed countries hardly translate into a reduction in global CO_2 emissions. The 'success' of developed countries to reduce domestic CO_2 emissions while maintaining a substantial rate of economic growth might have been a mere 'delusion' (Jiborn et al., 2018).

Jakob and Marschinski (2013) advise that we should refrain from drawing premature conclusions based only on the numbers revealed by the conventional emission accounts. They emphasize that the interpretation of international emission imbalances, and the derivation of climate policy implications, requires a better understanding of the underlying driving forces. The cross-country emission imbalances, they argue, are partially driven by other factors such as international technology differences, that is, cross-country differences in the carbon intensity of energy and the energy intensity of production. In a world with only two countries with different production technologies in existence, exchanging one unit of identical product between them at equal prices would result in one country generating higher emissions than the other (Jakob and Marschinski, 2013; Jakob et al., 2014). One of these countries would then end up as a net importer of emissions because its relatively 'cleaner' production technology produces relatively less emissions.

To assess the impact of a country's trade on domestic and foreign emissions, emission transfer analysis should consider cross-country technology differences. Kander et al. (2015) develop a technology-adjusted emissions accounting method by standardizing technology at the world average level. They use this method to develop an accounting principle that 'incentivizes' countries with cleaner-than-average production technologies and 'punishes' those with relatively dirtier production technologies. Jiborn et al. (2018), Baumert et al. (2019), and Jiborn et al. (2020) implement this standardization principle to evaluate the claim whether trade participation indeed has allowed the developed countries to 'systematically' outsource emissions to the developing countries, thereby increasing the domestic emissions in the developing countries. In the same spirit, Wu et al. (2022) look at the net impact of trade participation on domestic emissions to evaluate whether the decoupling of economic growth and carbon emissions in the advanced economies' is indeed 'genuine'.

This dissertation contributes to this literature and seeks to conceptually and empirically assess the claim whether the decreases in territorial CO_2 emissions reported by the developed countries have been associated with emission increases in the rest of the world, and have, as a result, translated into global emission increases. This dissertation builds on the extant literature, yet departs from this by presenting a novel approach to standardizing technology at the world average level and by offering a new interpretations for the revealed technology-adjusted emission concepts. For comparison and contrast, this dissertation documents the emissions accounts from the conventional emission measurements and compares these accounts with the proposed technology-adjusted emission concepts.

1.1.2 Regulating CO_2 Emissions by Carbon Taxation Policy

Given the need for an alternative emission accounting principle to appraise the dynamics of cross-border CO_2 emissions, there arises at the same time a need to explore specific regulation mechanisms that can address the issue of global CO_2 increases. Carbon taxation policy represents one of the mechanisms. Theoretically, a carbon tax is an economically-efficient policy for reducing carbon emissions as it holds polluters accountable for the emissions they generate from their economic activities and forces them to internalize the social cost of carbon in their production costs and prices (Pigou, 1924; Pearce, 1991; Cramton et al., 2017). By assigning a price on carbon emissions, a carbon tax creates a direct financial incentive for both producers and consumers to reduce the carbon footprints associated with their economic activities. In the long-run, a carbon tax creates room for behavioral changes: as the cost of emitting carbon increases, producers and consumers are stimulated to either substitute emission-intensive for less-polluting energy sources or to increase the energy efficiency of their activities. In Weitzman's (2007, p. 723) words: "the breathtakingly simple vision [is] that steady pressure from ... a high carbon price reflecting social costs ... would do more to unleash the decentralized power of capitalist ... inventive genius on the problem of researching, developing, and finally investing in economically efficient carbon-avoiding alternative technologies than all of the piece-meal command-and-control standards and patchwork subsidies making the round ... these days."

Carbon taxes also generate revenues which governments can use to help the decarbonization of their economies. Economic studies have shown that trillions of US dollars will be needed to finance investment in renewable energy technologies and low-carbon (energy and transportation) infrastructure. Songwe et al. (2022), for instance, find that the developing countries alone, excluding China, will need more than $2 trillion a year by 2030, to cut CO2 emissions and cope with the impact of extreme weather. Some 40 countries already use carbon pricing mechanisms, and many are planning to implement them in the future (World Bank, 2023). Together the carbon pricing schemes now in place cover about half the emissions of these 40 countries, which translates to about 23 percent of annual global GHG emissions (World Bank, 2023).

The greater challenge of implementing carbon tax might lie on public acceptance due to its short-run (distributionally-regressive) economic consequences (Baumol et al., 1988; Baranzini et al., 2000). In the short run, a carbon tax raises the prices of fossil fuels, leading to higher prices of other energy products and the associated commodities that are produced using these energies. These price increases disproportionately affect low-income households and places a heavier burden on them, which often results in public resistance. There have been various instances across the world where the public opposes the government's plan in removing fossil-fuel subsidies or enacting climate mitigation policies. This is because in many developing countries, people are highly reliant on the use of fossil fuel because of its affordability. Removing fossil-fuel subsidies or assigning a tax on emissions will consequentially increase the energy prices, which translates into economywide price hikes (Steckel et al., 2021). In Indonesia, the public has frequently demonstrated opposition to such policies, as shown by the mass protests that happened immediately after the government's decision to eliminate fossil fuel subsidies in 2008 (Mourougane, 2010; Renner et al., 2019) or in 2022 (Jones and Cardinale, 2023). The mass protests took place in Indonesia, notwithstanding the fact that in some instances the subsidy removals were followed by cash transfer initiatives to shield poor households from the (energy) price hikes. Studying the immediate distributional impacts of carbon tax is, therefore, essential in order to understand and next mitigate the potentially regressive impacts of carbon tax on low-income households.

In this dissertation, to study how the implementation of carbon taxation policy affects households across income levels, Indonesia is chosen as a case study for several reasons. As one of the world's largest CO_2 emitters, Indonesia has faced a persistent challenge of reducing CO_2 emissions while maintaining its development objectives. To halt its increasing reliance on fossil-based energy sources, Indonesia (which is a major oil producer and the world's ninth-largest CO_2 emitter) has planned to implement various climate-related policy measures. One such measure is a carbon pricing policy, including carbon taxation policy, which is regulated under the Presidential Regulation 98/2021 and the ESDM (Energy and Mineral Resources) Ministerial Regulation 16/2022. The carbon taxation policy is scheduled to be implemented in the near future for the electricity sectors, with additional plans to later extend it to cover all sectors in the economy. Indonesia is also chosen as a case study to showcase whether the carbon tax might become progressive (e.g., the negative impact on household spending increases as household income increases) if the policy is bundled with a countermeasure policy such as cash transfer for low-income households (intended to shield them from the inflation caused by carbon taxation). The previous cash transfer initiatives in Indonesia are said to have contributed to a dampening of the distributional effects when the government increased the price of rice and fuel in 2006 (Basri and Rahardja, 2010a), or in the event of the economic shock exerted by the 2008 Global Financial Crisis (Basri and Rahardja, 2010b). Understanding the extent to which the implementation of carbon taxation policy affects households in Indonesia is practically relevant for its potential regressive impact on low-income households – and to gauge the political acceptability of such a policy innovation.

1.2 Motivation for this dissertation

This dissertation has three primary objectives. First, it seeks to empirically evaluate the claim that the participation in international trade enables developed countries to outsource emissions to developing countries. In a more general framework, it seeks to understand the net effect of a country's participation in international trade on foreign emissions. In doing so, a novel method of 'technology-adjusted' accounting for emissions embodied in trade is proposed to carry out an ex-post analysis of emissions embodied in trade. In addition to the empirical analysis, the proposed 'technology-adjusted' emissions accounting contributes to the normative debate concerning the attribution of CO_2 emission responsibility, and could serve as an alternative – and superior – approach to global emission accounting. Secondly, this research aims to assess whether some countries have indeed achieved an actual decoupling between economic growth and CO_2 emissions, in that they have significantly reduced domestic emissions while maintaining meaningful economic growth. To this end, the net effect of a country's participation in international trade on domestic CO_2 emissions is scrutinized. Thirdly, the present study seeks to understand the potential implications arising from the implementation of climate-related policy (such as carbon taxation) on households' welfare across income levels. By considering both domestic and foreign emissions associated with domestic consumption, this dissertation investigates how the collective welfare of households belonging to different income groups would be affected by the implementation of a carbon taxation policy.

1.3 Research questions

Based on the aforementioned research motivation, this dissertation asks a following overarching question:

To what extent does a country's participation in international trade affect domestic and foreign CO_2 emissions, and how does the carbon taxation policy – as an instrument to stimulate carbon emissions reduction – affects the income of households in developing countries?

In order to answer this general research question, three sub-research questions are formulated:

1. How does a country's participation in international trade affect carbon emissions in the rest of the world?
2. How does the participation in international trade affect a country's domestic carbon emissions?
3. How are the households across income levels affected by the implementation of carbon taxation policy?

1.4 Overview of the main method used

To address these research questions, this dissertation employs a combination of theoretical thought experiments and multiple mathematical models. These tools are utilized to establish both *ex-post* emissions measurements and *ex-ante* projections of potential outcomes arising from the implementation of a certain policy. The mathematical models serve as a basis for calculating emissions, estimating the relationship between emissions and development parameters, and measuring how the implementation of a carbon pricing policy (e.g., carbon taxation) affects households across different income levels.

Three models are employed in this dissertation. The environmentally-extended Multi-Regional Input-Output (MRIO) model quantifies the carbon emissions embodied in final demand on both country and global levels. Ordinary least squares (OLS) linear regression is utilized to explore correlations between emission concepts, measurements, and development parameters (e.g., per-capita GDP), and to assess existing emissions-economy narratives. Microsimulation is combined with the MRIO model to construct a comparative static model for evaluating the consequences of regulating carbon emissions through a carbon pricing policy. The following section briefly describes these methods.

1.4.1 Multi-Regional Input-Output model

The MRIO model is an extended version of the traditional input-output (IO) analysis framework that considers multiple regions or economies in its analysis. The traditional IO model was initially developed by Leontief (1941) to examine the interdependencies between industries within a single country. The MRIO model, meanwhile, accounts for interconnected production processes (across global value chains) and consumption activities across multiple regions or economies, allowing for the measurement of intermediate product flows embedded in final products. The MRIO framework finds application in various contexts, one of which is the environmentally-extended MRIO (EE MRIO) model (Miller and Blair, 2009). The EE MRIO model integrates environmental pressure information (such as carbon emissions) into the MRIO analysis, making it possible to account for the environmental flows and impacts associated with the consumption of final products.

At the heart of the EE MRIO model is a global system of linear algebra equations connecting an environmental-stressor vector, an inverted technical coefficients (or 'production recipe') matrix called the Leontief inverse matrix (Leontief, 1970), and a matrix of countries' final demands. The environmental-stressor of interest is carbon dioxide emissions; hence, the global environmental-stressor vector contains the quantity of sectoral carbon emissions contained in one unit of monetary economic output produced in a given year. The global technical coefficients matrix[3] records the ratio of intermediate inputs per unit of output required to produce outputs. The final demand matrix is self-explanatory; it records the monetary value of consumption demand for final products for each region or economy in a particular year.

The EE MRIO model is used in this dissertation to measure the direct and indirect emissions associated with final demand. In Chapters 2 and 3, the EE MRIO model is used to measure the emissions embodied in exports and imports, as well as the domestic emissions

[3]technical coefficient matrix is sometimes recognized as the input-output coefficient matrix, or direct input coefficient matrix (Miller and Blair, 2009).

embodied in domestic consumption, which then serves as the building blocks for measuring various emission concepts. The technology adjustment in Chapter 2 is then carried out by adjusting the emission intensity and technical coefficients matrix in the MRIO system. In Chapter 4, the EE MRIO model is used to account for the (direct and indirect) emissions associated with households' consumption of final products in Indonesia. The results of this emission accounting is next combined with the household expenditure data for Indonesia.

1.4.2 Hybrid model: MRIO and microsimulation

The fourth Chapter in this dissertation evaluates the distributional implications of carbon tax and revenue recycling policies on households across different income levels in Indonesia. In doing so, the analysis combines the MRIO and a microsimulation approach to form a so-called hybrid model to evaluate the distributional implications of carbon pricing policy (e.g., carbon tax). In its basic form, the microsimulation approach is a static model capable of evaluating the short-run implications of carbon pricing on households (Cornwell and Creedy, 1996; Symons et al., 2000) on the basis of direct emissions generated by household's daily activities (for instance, the fuel consumption for private vehicle and cooking activities). However, most single-standing microsimulation models do not consider the indirect emissions embodied in other consumption items. The combination of the MRIO and a microsimulation approach makes it possible to assess the cost of carbon that households have to bear on the basis of the direct and indirect emissions associated with their consumption. The microsimulation model also allows us to measure the net effect of a carbon tax on the expenditure of individual households. The impact of a carbon tax on a household is measured in relative terms: the expenditure after the carbon tax and revenue recycling policy relative to its initial expenditure.

1.5 The outline of the dissertation

The remainder of this dissertation consists of three main chapters. Chapter 2 presents analyses based on a novel method to measure CO_2 emissions embodied in international trade; this chapter is based on the paper by Darwili and Schröder (2022), titled "On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade", published in Environmental and Resources Economics, 84(1), 65-98. Chapter 3 presents a new approach (and empirical application) to estimate the net onshoring of emissions. Chapter 4 deals with an input-output model based micro-simulation analysis of the distributional impacts of carbon taxation in Indonesia. Chapter 5 summarizes and concludes the findings. The structure, therefore, is as follows:

Chapter 2: On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade

The size and direction of international emission transfers might largely be determined by the international technology differences. In the presence of technology differences, exchanging identical products of similar monetary value would imply emission transfers. If this indeed holds true, the claim that the advanced-economy systematically outsources emissions falters. Existing studies have attempted to re-evaluate this claim using the technology-adjusted emissions accounting, yet the 'technology-adjustment' implemented thus far only standardizes emission intensity. In this chapter, we propose a novel method to standardize the production technology and interprets the technology-adjusted emission balance as net weak carbon leakage, defined as the difference between the foreign emissions avoided by exports and the foreign emissions generated by imports, which measures the effect of a country's trade on foreign emissions.

Chapter 3: Which Countries Have Offshored Carbon Dioxide Emissions in Net Terms?

There has been a widely-known negative cross-country correlation between net emission transfers and per-capita income. This fact is seen either as an indication that the developed economies have successfully reduced domestic emissions while maintaining economic growth, or as an indication that the trade participation itself enables the developed economies to reduce domestic emissions by relocating production to developing economies. In this chapter, we seek to evaluate the claim whether trade participation allows the developed economies to supress domestic emissions by relocating production to other countries. The impact of trade on domestic emissions, in our verdict, needs to be evaluated by the concept of net onshoring of emissions, defined as the net effect of trade participation on domestic emissions, calculated by the gap between domestic emissions generated to produce exports and domestic emissions avoided by imports.

Chapter 4: Distributional Implications of Carbon Tax Policy in Indonesia

Carbon taxation is considered as a climate-mitigation policy for its ability to generate revenue for government and to create an incentive for both producers and consumers to reduce carbon footprints of their economic activities. However, in the short run, a carbon tax raises the prices of fossil fuels, leading to higher prices of other commodities. This might disproportionally place a heavier burden on poor households, often resulting in public resistance to the carbon tax policy. Understanding the short-run impacts of carbon tax is instrumental to protect poor households from the potentially regressive impacts of carbon tax. This chapter studies the short-run distributional implications of carbon tax policy in

Indonesia. To determine who would be affected in what way by carbon tax policy, we construct a static model by combining the EE MRIO model with a microsimulation model. We test this model for Indonesia, one of the world largest carbon emitters which is planning to implement various environmental policy designs to lower carbon emissions in the near future.

Chapter 5: Conclusions

This chapter summarises the relevant findings of the dissertation. This is done by first answering the research sub- and main-questions and then by outlining the limitations concerning each of the three main studies. This chapter is closed by providing recommendations for future research and highlighting the real-world policy relevance of this dissertation.

Chapter 2

On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade

We propose a new method for standardizing the production technology at the world average level and derive interpretations for the resulting carbon emission concepts. The technology-adjusted emission balance measures net weak carbon leakage defined as the difference between the foreign emissions avoided by exports and the foreign emissions generated by imports. We use global multi-regional input-output tables to document the variable's spatio-temporal variation for 49 economies between 1995–2015. There is a positive cross-country correlation between net leakage and per-capita income. Changes in net leakage are generally small and do not account for country-specific emission trends, that is, domestic emission decreases were not offset by foreign emission increases.

This chapter was originally published as Darwili, A., & Schröder, E. (2023). On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade. *Environmental and Resource Economics*, 84(1), 65-98.

2.1 Introduction

International emission transfers are measured by the balance of emissions embodied in trade (BEET), meaning the difference between the emissions embodied in exports (EEX) and the emissions embodied in imports (EEM), which equals the difference between production-based emissions (PBE) and consumption-based emissions (CBE). The analysis of global multi-regional input-output tables has revealed how international emission transfers vary over time, across countries, and by income level (e.g. Peters and Hertwich, 2008a; Hertwich and Peters, 2009; Davis and Caldeira, 2010). Between 1990–2011, the Kyoto-relevant territorial emissions decreased in the developed (Annex-B) countries while the CBE increased (Kanemoto et al., 2014). In 2008, the Annex-B countries transferred 1.6 GtCO2 to non-Annex-B countries; this amount exceeds the reductions achieved in the Kyoto protocol period until then (Peters et al., 2011). In general, the developed countries are "net importing" emissions (PBE < CBE) while the developing countries are "net exporting" emissions (PBE > CBE).

How to interpret these facts? Economic activity and the associated emissions may simply have migrated from the developed to the developing world. Trade liberalization might have encouraged the developing countries to specialize in the production and export of emission intensive products. "Emission outsourcing" might explain the advanced-economy decoupling success. National emission decreases apparently did not translate into corresponding global emission decreases. Jakob and Marschinski (2013) caution against premature conclusions and emphasize that the interpretation of international emission transfer patterns, and the derivation of climate policy implications, requires better understanding of the underlying driving forces. The size and direction of international emission transfers are determined to a large extent by international technology differences, that is, cross-country differences in the carbon intensity of energy and the energy intensity of production. In the presence of technology differences, exchanging identical products at equal prices would imply emission transfers (Jakob and Marschinski, 2013; Jakob et al., 2014). Kander et al. (2015) propose a new scheme to account for the emissions embodied in trade – technology-adjusted accounting – which standardizes the emission intensity at the world average level. Jiborn et al. (2018), Baumert et al. (2019), and Jiborn et al. (2020) implement the technology adjustment in order to appraise competing narratives about the advanced-economy decoupling. These studies seek to evaluate the claim that the developed countries are "systematically outsourcing emissions" to the developing countries, and to assess the extent to which developed-country PBE trends are driven by international trade. The scale of emission outsourcing, it turns out, is much smaller than previously suggested, and the clear divide between the developed world and the developing world disappears. Many developed countries, especially in Europe, are "insourcing" emissions and not "outsourcing" them (Baumert et al., 2019).

How to interpret the new facts revealed by technology-adjusted accounting? We propose a new method for technology-adjusted accounting and develop interpretations for the resulting emission concepts. We interpret the technology-adjusted emission balance as a measure of *net weak carbon leakage*, document how the variable varies across space and over time, analyze its cross-country relationship with per-capita income, and discuss what technology-adjusted accounting implies with respect to the decoupling of emissions and economic growth.

The "technology adjustment" implemented thus far really is an *emission intensity adjustment*: the direct emission intensities (the ratios of emissions to gross outputs) are standardized but not the input intensities (the ratios of intermediate inputs to gross outputs). In input-output analysis (Leontief, 1986), the ratios of inputs to outputs are said to represent the production technology (the "production recipes"). This point is not merely a semantic quibble but matters in practice. The observed cross-country differences in the input intensity are non-negligible, e.g. China's cement, lime, and plaster production requires 0.82 euros worth of inputs per unit worth of output while the same sector in Germany requires just 0.64 euros. On average, Chinese producers require 0.61 euros worth of inputs per euro worth of gross output while German producers require only 0.48 euros.[1] The same demand will generate greater environmental impacts, ceteris paribus, if more inputs are required per unit of output. A comparative standard intended to represent the world average production technology should also eliminate international differences in the input intensity. In this article we build on the decomposition proposed by Xu and Dietzenbacher (2014) in order to standardize the input intensities across countries. We implement the technology adjustment using EXIOBASE3 (Stadler et al., 2018), which offers finer sector detail than the MRIO tables used by our antecedents.

The emission intensity adjustment has a curious feature: it tends to be inconsequential when the analysis draws on highly dis-aggregated data, i.e. input-output tables with fine sector detail. The intensity adjustment is inconsequential, in particular, when the electricity sector is broken down by green and brown energy sources. The energy mix of the domestic electricity sector is a key driver of embodied emissions. As a rough approximation, the emission intensity of Sweden's aggregate electricity sector is low because Sweden uses hydro power rather than coal, and not because Sweden's hydro electricity production is exceptionally clean. In general, the emission intensity of the aggregate electricity sector

[1] These are value added-weighted national means based on EXIOBASE3 (Stadler et al., 2018) calculated as follows: for each sector, sum all intermediate input purchases from all sectors and countries and divide the sum by gross output, then form the weighted mean of these ratios using sector values added as weights.

varies a lot more across countries than the emission intensities of electricity sub-sectors vary across countries. Therefore, with fine sector detail, standardizing only the emission intensity – substituting a sector's world average value for the sector's country-specific emission intensity – will be relatively inconsequential. Our proposed technology adjustment behaves differently, because the technology adjustment standardizes the direct emission intensities *and* the intermediate input requirements. Standardizing the input requirements implies, for example, that the aluminum sectors of Sweden and China require the same amount of hydro electricity input per unit of output. As a result, the technology adjustment is consequential even when based on highly dis-aggregated data (EXIOBASE3 provides global MRIO tables with 163 sectors per country).

2.2 Related Literature and Key Concepts

Kander et al. (2015) first proposed the emission intensity adjustment to address concerns over the incentives implicit in PB and CB accounting. PB accounting does not hold countries responsible for the emissions associated with the production of imported products, while CB accounting does not hold countries responsible for the emissions associated with the production of exported products. In either case, there are no incentives for taking mitigation action with respect to certain emissions attributed to trading partners. The emission-intensity adjustment was designed to serve the principle that national "actions that contribute to reduced global emissions should be credited, and actions that increase them should be penalized" (Kander et al., 2015, p. 431). Kander et al. (2015) propose to hold countries responsible for the emission intensity-adjusted consumption-based emissions (EICBE), calculated as EICBE = PBE − EIEEX + EEM, where EIEEX are the emission intensity-adjusted emissions embodied in exports. Compared to regular CB accounting, this scheme introduces a new mitigation incentive by rewarding countries for cleaning up their export production. As such it contributes to the normative debate about the merit of alternative carbon accounting schemes, which discusses how emission responsibility should be attributed in order to support mitigation incentives, equity and fairness, and other principles (Rodrigues et al., 2010; Afionis et al., 2017; Zhang, 2018; Dietzenbacher et al., 2020; Jakob et al., 2021).

The existing empirical implementations of the emission intensity adjustment do not discuss implicit incentive structures and normative principles, but interpret the results of positive ex-post empirical analyses of trade and emission flows. Jiborn et al. (2018) use data for Sweden and the UK to investigate if the decoupling of national emissions and production is a delusion. The decoupling would be a delusion if the emission decreases observed in Sweden and the UK were in fact offset by emission increases in the ROW. The underlying issue, at a general level, is how and to what extent "trade-driven" emission changes in individual countries *are related* to emission changes in the ROW. Baumert et al. (2019) extend the analysis to the global economy and implement the emission intensity adjustment for 40 countries and 35 sectors between 1995–2009, drawing on data from the World Input-Output Database, 2013 Release (Timmer et al., 2015). Jiborn et al. (2020) implement the emission intensity adjustment for 43 countries and 56 sectors between 2000–2014, drawing on the World Input-Output Database, 2016 Release. These studies ask if the emission trends in the developed countries are in fact driven by trade, and they seek to evaluate the claim that the developed countries are "systematically outsourcing" emissions to the developing countries.

It is important to be clear about the meaning of "emission outsourcing", and about what is being measured for which region when embodied emission flows are adjusted for intensity differences. "Emission displacement means that a country's foreign trade contributes to i) reduced domestic emissions and ii) increased emissions abroad compared to a no-trade scenario with the same domestic and foreign consumption" (Jiborn et al., 2018, p. 27). Note that the authors use the terms displacement, outsourcing, and weak leakage interchangeably. As explained below, the intensity-adjusted emission balance does not actually say something about the contribution of trade to *domestic* emissions – it represents the contribution of trade to *foreign* emissions – and therefore we settle on the term (net weak) leakage. Strong carbon leakage refers to policy-driven emission increases in the ROW, the idea being that e.g. more ambitious European climate policy will lead to increased production and emissions in China.[2] Weak carbon leakage refers to "demand-driven" emission increases in the ROW, the idea being that e.g. higher European import demand will lead to increased production and emissions in China (Peters, 2008a, 2010). The original definitions refer to the relation between Kyoto-constrained Annex-B countries and unconstrained non-Annex B countries, but many later studies simply analyze the relation between a focus country and the ROW. In either case, leakage refers to emission changes outside a focus country. The accounting for emissions embodied in trade was developed largely in response to concerns over weak leakage. Peters (2008a) proposed to measure weak leakage by the emissions embodied in imports.

Jakob and Marschinski (2013) suggest that assessing a *net impact of trade on emissions* requires answering a but-for question: what would emissions be without trade? In

[2]The evidence for strong leakage effects was always weak to non-existent, and still is. The careful econometric analysis of micro-data can uncover effects of environmental policy on trade and investment flows for certain narrowly defined energy- and pollution-intensive economic activities, but in general international environmental policy differences hardly influence the global production and investment decisions of firms (Cherniwchan et al., 2017; Dechezleprêtre and Sato, 2017; Dechezleprêtre et al., 2019).

this spirit Kander et al. (2015) imagine a counterfactual no-trade scenario that considers "what would be the case if a certain commodity were not to be exported from the country in question" (Kander et al., 2015, p. 432). The counterfactual scenario takes domestic and foreign demand as given, meaning a foreign producer using foreign technology will have to produce the focus country's exports instead. Without further knowledge about the counterfactual producer, "the most plausible, and least demanding, assumption is that a similar good would have been produced at the average emissions intensity on the world market for the relevant sector" (Kander et al., 2015, p. 432). Thus, when the emission intensity adjustment is applied to the emissions embodied in exports, the resulting variable (EIEEX) has to be interpreted as a measure of the *foreign emissions avoided by exports* (i.e. the PBE avoided in the ROW by the focus country's exports).

Kander et al. (2015) and Jiborn et al. (2020) define the intensity-adjusted emission balance as EIBEET = EIEEX − EEM. If applied only to the export side, the intensity adjustment violates scale invariance (Domingos et al., 2016). Scale invariance is a desirable property of carbon accounting schemes (the emission responsibility attributed to an aggregate region must equal the sum of the emission responsibility attributed to its sub-regions). To preserve it, Jiborn et al. (2018) and Baumert et al. (2019) also adjust the emissions embodied in imports. But what the resulting variable measures is not so clear. The emission-intensity adjusted emissions embodied in imports (EIEEM) has no obvious interpretation. There is a conflict between methodological choices that serve the attribution of emission responsibility and methodological choices that serve the ex-post analysis of trade and emission flows. We are performing the latter, we like to preserve clean interpretations of the technology-adjusted emission concepts, and therefore we adjust only the export side.

The intensity-adjusted emission balance (EIBEET = EIEEX − EEM) compares the foreign emissions avoided by exports to the foreign emissions generated by imports; with reversed sign, it can be interpreted as a measure of *net weak carbon leakage*. A positive EIBEET indicates that a country's trade is net avoiding emissions in the ROW, or net avoiding foreign emissions for short. The contribution of trade to domestic emissions would be given by the difference between the observed emissions embodied in exports and the counterfactual emissions avoided by imports, and is typically measured by the *balance of avoided emissions*.[3]

[3]The balance of avoided emissions is given by the difference between the domestic emissions embodied in gross exports and the domestic emissions avoided by gross imports. Both magnitudes are routinely calculated calculated based on the domestic technology assumption and the *emissions embodied in bilateral trade approach* (e.g. Dietzenbacher and Mukhopadhyay, 2007; Zhang, 2012; López et al., 2013; Zhang et al., 2017).

2.3 Methods

2.3.1 Emissions Embodied in Trade and the Emission Intensity Adjustment

We use the environmentally-extended MRIO model to calculate carbon dioxide emissions embodied in trade (Leontief, 1970; Miller and Blair, 2009). For ease of exposition we simplify to the two-country setting and follow the notation of Jiborn et al. (2020) to write the MRIO model in compact form:

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{2.1}$$

Here the global emission matrix E, the global direct emissions intensity vector q (the hat denotes a diagonal matrix formed by the vector), the global Leontief inverse L, and the global final demand matrix Y are partitioned into sub-matrices and sub-vectors for countries 1 and 2. Country 1 can be considered as the focus country and country 2 as the ROW. e^{11} and e^{22} each represent the "domestic-domestic" emissions (DDE^1 and DDE^2), meaning domestic emissions embodied in domestic final demand. From the perspective of country 1, $e^{12} = \hat{q}^1 L^{11} y^{12} + \hat{q}^1 L^{12} y^{22}$ represents the emissions embodied in exports (EEX^1), meaning the domestic emissions embodied in foreign final demand. $e^{21} = \hat{q}^2 L^{21} y^{11} + \hat{q}^2 L^{22} y^{21}$ represents the emissions embodied in imports (EEM^1), meaning the foreign emissions embodied in domestic final demand. Country 1's production-based emissions (PBE^1) are the sum of DDE^1 and EEX^1. Its consumption-based emissions (CBE^1) are the sum of DDE^1 and EEM^1. Country 1's balance of emissions embodied in trade ($BEET^1$), the net emissions transfer, is given by $BEET^1 = EEX^1 - EEM^1 = PBE^1 - CBE^1$. A positive BEET ($EEX^1 > EEM^1$) indicates that country 1 is net transferring, or net exporting, emissions to the ROW.[4]

The emission intensity adjustment replaces country-specific values of the each sector's emission intensity by the respective sector's world average value. We use a gross output-

[4] The equation system 3.1 does not capture direct household emissions. In the empirical analysis we will always add household emissions to the domestic-domestic emissions, and therefore treat them as part of PBE and CBE.

weighted average:[5]

$$\dot{q}_i = \sum_s \frac{x_i^s}{x_i} \cdot q_i^s \tag{2.2}$$

$\dot{q}_i$ denotes sector i's standardized emission intensity, q_i^s the direct emission intensity of sector i in country s, x_i^s the gross output of sector i in country s, $x_i = \sum_s x_i^s$ sector i's global gross output, and i and s sector and country indices.

The calculation would more accurately capture the target concept (the emissions avoided in the ROW by the focus country's export production) if the world average intensity was calculated excluding the focus country. This calculation would yield country-specific ROW emission intensities, rather than a single global average for each sector. For most countries it will not matter much, but even China and the USA make up only 15% of global GDP each (a rough indication of the average industry weight for these countries). In our view, this is acceptable, especially because there are also benefits to using a single global average: i) the results are comparable to previous studies and ii) the comparison of each country to the same global comparative standard has intuitive appeal.

Using the standardized emission intensities, the MRIO system is:

$$\begin{bmatrix} \dot{e}^{11} & \dot{e}^{12} \\ \dot{e}^{21} & \dot{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{\dot{q}}^1 & 0 \\ 0 & \hat{\dot{q}}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{2.3}$$

The domestic-domestic emissions should be ignored, only the emissions embodied in trade are relevant in what follows. From the perspective of country 1, $\dot{e}^{12} = \hat{\dot{q}}^1 L^{11} y^{12} + \hat{\dot{q}}^1 L^{12} y^{22}$ represents the emission intensity-adjusted emissions embodied in exports ($EIEEX^1$), and $\dot{e}^{21} = \hat{\dot{q}}^2 L^{21} y^{11} + \hat{\dot{q}}^2 L^{22} y^{21}$ the emission intensity-adjusted emissions embodied in imports ($EIEEM^1$). The no-trade scenario assumes foreign sectors produce country 1's exports using the world average emission intensity, so the EIEEX measure the foreign emissions avoided by country 1's exports. We follow Kander et al. (2015) and Jiborn et al. (2020) and define country 1's emission intensity-adjusted balance of emissions embodied in trade as $EIBEET^1 = EIEEX^1 - EEM^1$. Only the exports are adjusted. The EIBEET therefore compares the hypothetical foreign emissions avoided by exports to the observed foreign emissions generated by imports. A positive EIBEET implies a net decrease in foreign emissions.

[5] Jiborn et al. (2020) use gross outputs as weights while Kander et al. (2015) and Baumert et al. (2019) use trade flows as weights. In either case, large economies like the USA and China heavily influence the world average.

2.3.2 The Technology Adjustment

We propose to adjust not only the direct emission intensity but also the intermediate input intensity, the quantity of inputs per unit of output. The technology-adjusted MRIO system is:

$$\begin{bmatrix} \ddot{e}^{11} & \ddot{e}^{12} \\ \ddot{e}^{21} & \ddot{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^{1} & 0 \\ 0 & \hat{q}^{2} \end{bmatrix} \begin{bmatrix} \dot{L}^{11} & \dot{L}^{12} \\ \dot{L}^{21} & \dot{L}^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{2.4}$$

The equations for embodied emissions are the same as before: from the perspective of country 1, $\ddot{e}^{12} = \hat{q}^1 \dot{L}^{11} y^{12} + \hat{q}^1 \dot{L}^{12} y^{22}$ represents the technology-adjusted emissions embodied in exports ($TEEX^1$), and $\ddot{e}^{21} = \hat{q}^2 \dot{L}^{21} y^{11} + \hat{q}^2 \dot{L}^{22} y^{21}$ represents the technology-adjusted emissions embodied in imports ($TEEM^1$). The only difference to system 2.3 is the appearance of the technology-adjusted Leontief inverse $\dot{L}$, which is derived from adjusted technical coefficients. The adjustment is inspired by Xu and Dietzenbacher (2014) and explained in the remainder of this section.

Consider the aluminum sector in Sweden and its intermediate input purchases of nuclear electricity. We so adjust the technical coefficients that Sweden's aluminum sector directly requires as much nuclear electricity per unit of output as the world average aluminum sector. To this end we calculate the *technological* coefficients, which represent direct sector-by-sector intermediate input requirements regardless which country supplies the inputs. Let a^{sr}_{ij} be an element of the global technical coefficient matrix A representing country-sector pair rj's intermediate input purchases from the country-sector pair si. Summing over all supplying countries s gives the technological coefficient:[6]

$$h^r_{ij} = \sum_{s=1}^{m} a^{sr}_{ij} \tag{2.5}$$

Country r's technological coefficient matrix H^r (size $n \times n$) collects these coefficients:

$$H^r = \sum_{s=1}^{m} A^{sr} \tag{2.6}$$

where A^{sr} is a $n \times n$ sub-matrix of the global technical coefficient matrix A.

The *trade structure matrix* T reflects the origin (geographical composition) of the

[6]The term *technological* coefficient is from Xu and Dietzenbacher (2014). It needs to be distinguished from the *technical* coefficients in A, which are common to any input-output analysis.

intermediate inputs:

$$T = \begin{bmatrix} T^{11} & \cdots & T^{1m} \\ \vdots & \ddots & \vdots \\ T^{m1} & \cdots & T^{mm} \end{bmatrix} \tag{2.7}$$

Its elements represent the share of all inputs i (required per unit of output by sector j in country r) that originates in country s, calculated as:

$$t_{ij}^{sr} = a_{ij}^{sr} / h_{ij}^{r} \tag{2.8}$$

The sum over all countries s necessarily adds up to one: $\sum_{s=1}^{m} t_{ij}^{sr} = 1$.

We have introduced all the objects needed to decompose the global technical coefficients matrix:

$$A = \begin{bmatrix} T^{11} \otimes H^{1} & \cdots & T^{1m} \otimes H^{m} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes H^{1} & \cdots & T^{mm} \otimes H^{m} \end{bmatrix} \tag{2.9}$$

where $\otimes$ represents the Hadamard product (element-wise multiplication). The technology adjustment replaces country-specific values of the technological coefficients by world average values. The standardized coefficients are calculated as gross output-weighted averages:

$$\dot{h}_{ij} = \sum_{s} \frac{x_i^s}{x_i} \cdot h_{ij}^{s} \tag{2.10}$$

where $x_i = \sum_s x_i^s$ is sector i's global gross output. Using the same technological coefficients for all countries, $\dot{H} = H^1 = H^2 = \ldots$, the new technical coefficients matrix is:

$$\dot{A} = \begin{bmatrix} T^{11} \otimes \dot{H} & \cdots & T^{1m} \otimes \dot{H} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes \dot{H} & \cdots & T^{mm} \otimes \dot{H} \end{bmatrix} \tag{2.11}$$

$\dot{A}$ defines the technology-adjusted Leontief inverse, $\dot{L} = (I - \dot{A})^{-1}$, which is used to calculate the technology-adjusted emissions embodied in trade per system 2.4.

The regular emission balance is defined as BEET = EEX − EEM and the technology-adjusted balance as TBEET = TEEX − EEM. The BEET compares *domestic* emissions generated by foreign demand and *foreign* emissions generated by domestic demand. The BEET measures international emission transfers; when it is positive, we say the country is net exporting emissions or net transferring emissions to the ROW. The TBEET focuses on *foreign* emissions only, comparing hypothetical foreign emissions avoided by exports and observed foreign emissions generated by imports. The TBEET measures net weak carbon leakage; when it is positive, we say the country is net avoiding emissions in the ROW or simply net avoiding foreign emissions. When the TBEET is negative, we say the country is net generating foreign emissions or net leaking emissions.

2.4 Data

Our source for the annual MRIO tables are the monetary industry-by-industry tables from EXIOBASE3 (Stadler et al., 2018). The main inputs to EXIOBASE3 are macroeconomic data from the UN National Accounts Main Aggregates Database, goods trade data from BACI (Gaulier and Zignago, 2010), services trade data from the UN Service Trade Database, product and industry output data from the Detailed Tables of the UN National Accounts Statistics and national statistical offices, as well as supply- and use tables from national statistical offices. Stadler et al. (2018) describe the principles guiding the relations between different classification systems, the filling of gaps, and the reconciliation and balancing needed for the MRIO table construction. The resulting MRIO tables, covering 44 countries and five ROW aggregate regions between 1995–2015, stand out for their detailed sector classification dividing economic activity into 163 sectors per country. Notably, electricity production is not merely part of some larger utilities sector but is dis-aggregated by energy source (in total there are 12 different electricity sectors: coal, nuclear, hydro, etc.).

EXIOBASE3 includes environmental satellite accounts matching the sector classification of the MRIO tables. We select total CO2 emissions (kg) as the environmental stressor variable. Only up to 2015 does EXIOBASE3 use detailed emissions data as input to the values of the environmental stressor; we prioritize data quality and restrict our analysis to the period 1995–2015.

EXIOBASE3 covers mostly developed countries with the exceptions of Brazil, China, Indonesia, India, Mexico, and South Africa. The five ROW aggregates are largely composed of developing countries, though the average per-capita income of the Middle East ROW aggregate is at the same level as Greece and Hungary. EXIOBASE3 fills input data gaps for single countries and the ROW regions, so that the final database is exhaustive in that it covers the global economy. Values in the economic transactions tables are estimated in a way that global totals from the UN National Accounts Main Aggregates Database are preserved. The construction of exhaustive environmental satellite accounts involves the estimation of emission factors for the ROW regions (using weighted averages of all available countries) (Stadler et al., 2018, Supporting Information S3). The appendix lists all countries and sectors (Tables 2.B.8 and 2.B.9).

We supplement the environmentally-extended IO tables with country-level population and national accounts data from the Penn World Table Version 10 (PWT10, Feenstra et al., 2015). As an indicator of income per capita, we use output-side real GDP at chained PPPs in 2017US$ divided by population.

2.5 Results and Discussion

2.5.1 The Technology-Adjusted Balance of Emissions in Trade

We plot the technology-adjusted balance of emissions embodied in trade (TBEET) for two big developed countries with trade deficits and relatively large service sectors (the USA and the UK), two big developed countries with export orientation and relatively large manufacturing sectors (Germany and Japan), and the two biggest developing countries (China and India, Figure 2.1). For comparison and contrast we also plot the regular emission balance (BEET) and the emission intensity-adjusted emission balance (EIBEET). The USA records a negative TBEET, meaning the USA avoids less emissions in the ROW than it generates in the ROW, in other words, the USA net generates foreign emissions (or is net leaking emissions). No region in the whole sample net generates more foreign emissions than the USA (0.5 GtCO2 in 2015).[7] China net avoids foreign emissions, that is, China's participation in global value chains helps countries in the ROW to reach their climate targets – the "Factory of the World" provides a mitigation service to its trading partners. The amount of foreign emissions net avoided is modest and smaller, by a factor of four, than the amount of emissions transferred (China's TBEET in 2015 is 0.3 GtCO2 and its BEET is 1.2 GtCO2). For the USA, the difference between the TBEET and the BEET is less pronounced (the TBEET is −0.5 GtCO2 and the BEET is −0.8 GtCO2).

For India, Japan, and the UK, the size of the TBEET is relatively modest. These countries do not contribute very much to emissions in the ROW, neither in absolute terms nor relative to national PBE. No single country in the whole sample net avoids more foreign emissions than Germany (0.5 GtCO2 in 2015). Germany, China and other trade-surplus countries are producing more than they are consuming, which helps the ROW to avoid emissions.

There is a well-known negative cross-country relationship between the regular BEET and per-capita income. There is no analogous relationship between the TBEET and per-capita income – in fact there is a positive correlation between the two variables (Figure 2.2).

[7]The appendix contains the full set of results for all countries and ROW aggregates. Table 2.B.1 to Table 2.B.6 report emission balances, consumption-based emissions, and the emissions embodied in exports in GtCO2 and also in % of PBE. Figure 2.B.1 to Figure 2.B.3 show the same variables in line plots by country.

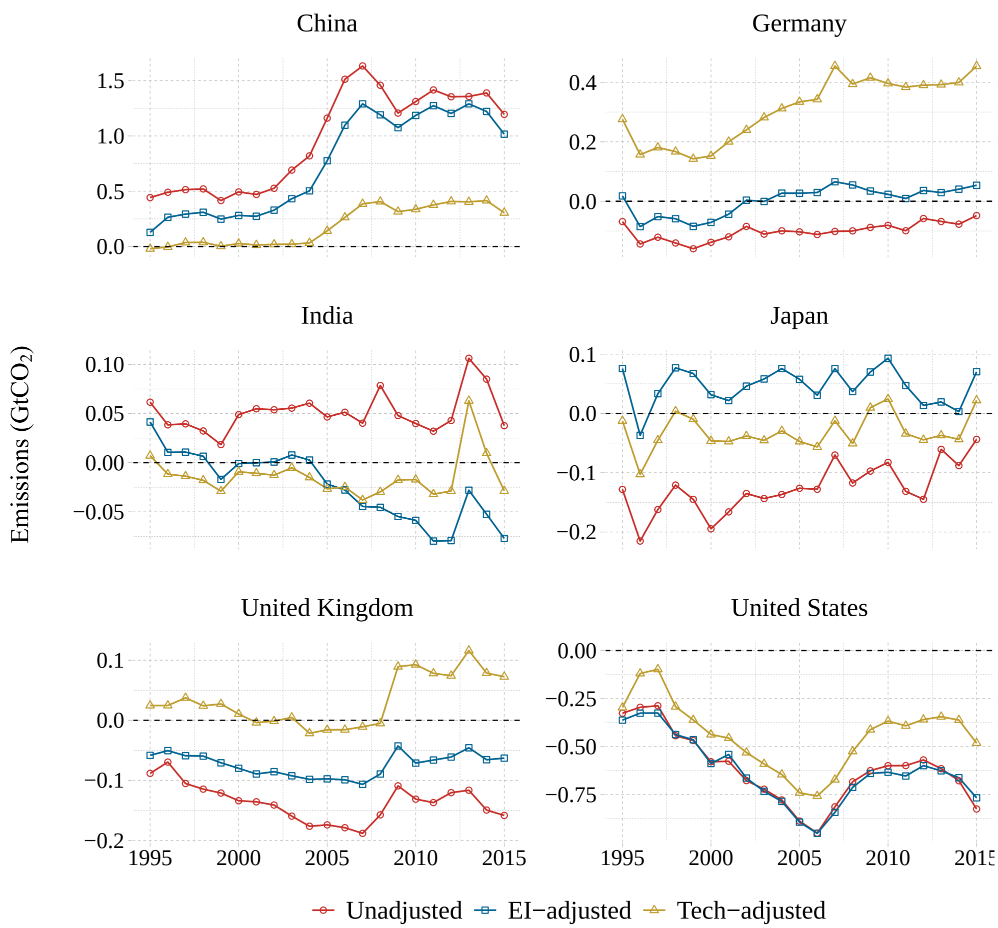
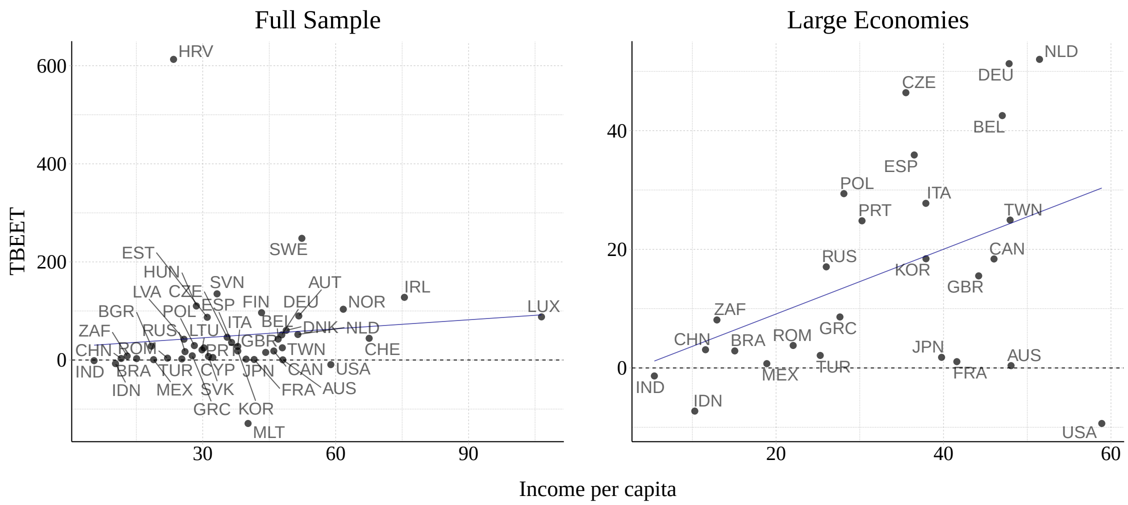


Figure 2.1: Balance of Emissions Embodied in Trade, GtCO2



Notes: Own calculations based on EXIOBASE3 and PWT10 using data from 2015. The TBEET is measured in % of PBE, income per capita in thousand PPP-adjusted US$. The right panel excludes economies whose 2015 population is lower than 10 million. The lines represent the best linear fit from simple OLS cross-country regressions (see section 2.A).

Figure 2.2: TBEET vs. Income per Capita, 2015 Snapshot

Germany, the Netherlands, and many other developed countries are net avoiding foreign emissions while India and Indonesia are net generating foreign emissions. But the strength of the TBEET-income relationship should not be overestimated (see the regression analysis in section 2.A). The rich USA is net generating foreign emissions while China and South Africa are net avoiding foreign emissions.

The negative cross-country BEET-income relationship is driven to a large extent by international technology differences, as producers tend to generate less emissions per unit of output in developed countries than in developing countries (Jakob and Marschinski, 2013; Baumert et al., 2019). The EEX depend on the focus country's production technology, but the technology adjustment replaces the country-specific technology by a common global standard, eliminating a key source of variation in EEX. The EEM calculation is based on a mix of production technologies. The more geographically diversified are the import partners, the more will the average import partner technology resemble the world average technology. The role of international technology differences thus dampened, the TBEET will significantly depend on the trade balance, i.e. the scale of exports and imports, and the composition of exports and imports.

Structural decomposition methods could shed light on the TBEET's proximate drivers, and quantify how much certain drivers contribute to the differences between the TBEET and the BEET. That type of analysis is beyond the scope of this study, but some patterns can be inferred from the reported results. First, the monetary trade balance is an important driver of the TBEET. This is evident from the TBEET's variation over time and across countries. For China, Germany, and the USA, the TBEET roughly tracks the trade balance. Prominent surplus countries (China, Germany, and the Netherlands) record positive TBEETs, while the most prominent deficit country (USA) records negative TBEETs (Appendix, Table 2.B.2). Second, the trade composition might explain why resource-abundant countries exporting mined raw materials tend to record positive TBEETs. Examples are Canada, Norway, Russia, and the Middle East ROW aggregate (Appendix, Table 2.B.2). Trade surpluses may partly explain the pattern, but the trade composition probably plays a role as well, as the cleaning and processing of resources can be quite emission intensive. Composition effects should be most visible in commodity-exporting countries, due to the export concentration. The exports of China, Germany, and the USA are more diversified, thus the trade composition plays a smaller role and trade balance effects are brought to light. Third, the regular BEET depends heavily on international differences in the input intensity. This can be inferred from the difference between the TEEX and the EEX: for most countries this difference is large and larger than the difference between the EIEEX and the EEX (Appendix, Table 2.B.6). Standardizing technology is more consequential than standardizing only the direct emission intensity.[8]

The Chinese production technology is browner than the world average, and the technology adjustment roughly halves China's EEX. The American production technology is greener than the world average, and the technology adjustment roughly doubles the USA's EEX (Appendix, Table 2.B.5). The technology adjustment triples Germany's EEX, and it is even more consequential for small countries like Austria, Croatia, Finland, Hungary, Slovenia, Sweden, and Switzerland, where the ratios of TEEX to EEX exceed four (Appendix, Table 2.B.5). Austria, Germany, and Hungary do not house exceptionally clean electricity sectors, so the energy mix is only part of the story, and the adjustment to the intermediate input intensities of the producing sectors matters as well.

2.5.2 Technology-Adjusted Consumption-Based Emissions

This section evaluates the national emission trends in the six focus countries. Our main interest rests with the PBE and the TCBE, but we also plot the CBE and EICBE for comparison and contrast (Figure 2.3). The TCBE represent the production-based emissions plus

[8]We report the emission-intensity adjusted variables for completeness, but the emission intensity adjustment should be implemented with input-output tables that come at a higher level of aggregation. The dis-aggregated electricity sector in EXIOBASE3 dampens the effects the intensity adjustment would otherwise have.

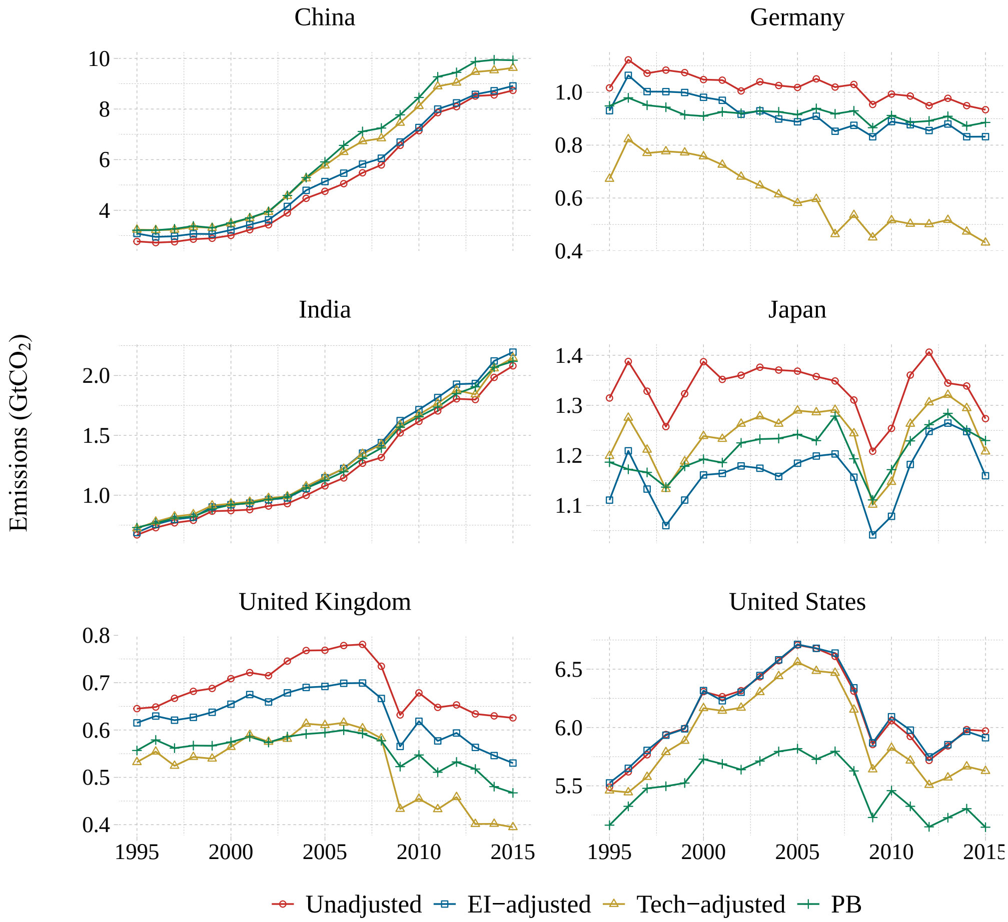


Figure 2.3: Consumption-based Emissions, GtCO2

the emissions net generated in the ROW. Assuming the economy is growing, decreasing PBE indicates successful decoupling. The decoupling would be a delusion, following Jiborn et al. (2018), if the TCBE increased over the same period, for then the increase in the net generation of foreign emissions was larger than the PBE decrease.

The overall picture is that emissions are increasing in the two big developing countries, are decreasing in Germany, show ups and downs while remaining overall roughly constant in Japan, and are increasing first and then decreasing in the UK and the USA. This picture emerges regardless of which emission concept is being considered. For each country, there are level differences between the PBE and TCBE, but the two variables tend to change in the same direction, following country-specific trends. Changes in the net generation of foreign emissions, as a rule, are too small to cause qualitative divergence between the existing emission concepts.

In much of the developed world, economic growth has decoupled from any of the existing emission concepts. Europe's CBE peaked in 2006 (Karstensen et al., 2018; Wood et al., 2019). Both PBE and CBE decreased in 18 developed countries between 2005–2015 (Quéré et al., 2019). Jiborn et al. (2020) analyze the period 2000–2014 and report that 21 countries record decreases in PBE, CBE, and the emission intensity-adjusted CBE. Our sample covers the period 1995–2015 and shows that PBE are decreasing in 24 countries (out of 44), the technology-adjusted CBE are decreasing in 29 countries, and both variables are decreasing in 19 countries (Appendix, Table 2.B.3 and Table 2.B.7). That said, the absolute decoupling of emissions and economic growth in the developed countries is insufficient – reaching climate targets requires far greater mitigation rates (e.g. Quéré et al., 2019).

While most developed countries record decreasing emissions, all the developing countries in our sample record increasing emissions. The proximate drivers are relatively clear. Production-side decompositions based on the Kaya identity show that energy intensity improvements (more than decarbonization) account for the bulk of the emission decreases in the developed countries. Meanwhile in the developing world, income and population growth are pushing emissions up more than decarbonization efforts and energy intensity improvements are pulling them down (Quéré et al., 2019; Xia et al., 2020). The importance of changes in the scale of economic activity is also visible from demand-side decompositions based on the input-output model. Rising domestic demand – more than the increased participation in global supply chains – has driven the emission increases in the developing countries (de Vries and Ferrarini, 2017). Alone the increased *domestic production serving domestic final demand in China* accounts for nearly 50% of the increase in *global* emissions between 2000–2014 (Jiborn et al., 2020).

Net weak carbon leakage as measured by the technology-adjusted emission balance cannot be regarded as an important driver of national emission trends. To avoid misunderstanding, this does not mean that international trade hardly influences national or global emissions. It may be true that the key proximate determinants of China's rapid emission growth are the (coal-fueled) buildup of the domestic capital stock and the rising consumption demand from the growing middle class, rather than observed trade flows. But this economic development is hard to imagine without the export-oriented growth strategy China was able to pursue in the increasingly integrated world economy. Without technology diffusion and learning spurred by foreign investment, without the foreign demand for manufactured products, China's domestic demand would never have increased as much. The input-output model rules out mechanisms through which trade influences technology and demand.[9] Net

[9] Standard models in the tradition of the pure theory of trade predict scale, composition, and technique effects of trade on emissions. Econometric methods can quantify these effects (e.g. Antweiler et al., 2001). In decomposition studies, the effects of the proximate drivers often bear the same names, but these "empirical" effects need to be distinguished from the causal effects of trade implied by economic models.

weak carbon leakage represents the contribution of a country's trade to foreign emissions, where this contribution is calculated for given technologies and demands. The interpretation is analogous to the balance of avoided emissions, also an input-output based concept that takes technology and demand as given, which represents the contribution of a country's trade to domestic emissions (e.g. Dietzenbacher and Mukhopadhyay, 2007; Zhang et al., 2017).

2.6 Summary and Concluding Remarks

We proposed and implemented a new method for the technology-adjusted accounting for emissions embodied in trade. Following the logic of emission intensity-adjusted accounting (Kander et al., 2015), the standardization should be extended to the production recipes.

Technology-adjusted accounting can be viewed as a contribution to the normative debate about the attribution of emission responsibility, which considers the design of incentive-compatible accounting schemes that would credit countries only for those national mitigation actions that lead to global emission reductions (Kander et al., 2015; Dietzenbacher et al., 2020; Jakob et al., 2021). Such schemes should not ignore international differences in the input intensity. Exploring the merits of alternative accounting schemes, irrespective of political and practical constraints, is a worthwhile enterprise. At the same time, there is little political momentum for adopting an alternative to territorial or PB accounting, and any scheme that depends on accurate input-output tables for all countries faces severe practical challenges (e.g. Liu, 2015; Afionis et al., 2017).

The technology adjustment can also be viewed as a tool for the positive analysis of emissions embodied in trade. After examining what the resulting emission concepts measure, we interpreted the technology-adjusted emission balance (with reversed sign) as a measure of net weak carbon leakage. A country's imports generate emissions in the ROW, while its exports avoid emissions in the ROW. The technology-adjusted EEX represent a measure of the foreign emissions avoided by exports, and the technology-adjusted BEET represents a measure of the foreign emissions net avoided by trade. The technology-adjusted CBE represent production-based emissions plus emissions net avoided in the ROW.

International emission transfers and net weak carbon leakage show different patterns. In contrast to the regular BEET, the TBEET exhibits a *positive* cross-country correlation with per-capita income. Most developed economies are net avoiding foreign emissions. China helps its trading partners to avoid emissions, though the amounts are modest and much smaller than China's net emission exports. Emissions are decreasing in many developed countries while they are increasing in the developing countries, regardless of the emission concept. The modest decoupling success in the developed countries would be tainted if the

PBE decreases had been accompanied by trade-driven emission increases in the ROW. This is not the case, changes in net weak leakage do not account for the decreases.

Appendix

2.A Cross-Country Regressions

To assess the strength of the positive cross-country correlation between the TBEET and per-capita income, we regress the TBEET in % of PBE on per-capita GDP in thousand PPP-adjusted US$ (Table 2.A.1). The columns 1 and 2 report the results of the simple OLS regressions with heteroskedasticity-consistent standard errors based on the 2015 cross section (Figure 2.2 shows the regression lines). The columns 3 and 4 report pooled OLS regressions with country-cluster-robust standard errors based on panel data from 1995–2015. The pooled OLS estimator is consistent for the parameters $\boldsymbol{\beta}$ of the model:

$$y_{it} = \boldsymbol{x}_{it}\boldsymbol{\beta} + v_{it} \tag{2.12}$$

where the regressor vector $\boldsymbol{x}_{it}$, which includes per-capita income and year dummies, does not correlate with the composite error (the unobserved country effect plus the idiosyncratic error $v_{it} = c_i + u_{it}$), i.e. $E(\boldsymbol{x}_{it}v_{it}) = \mathbf{0}$. The regressions yield coefficients that measure statistical association and should be viewed as a tool of descriptive analysis. A causal analysis would at the very least address the potential correlation between per-capita income and the unobserved effects (i.e. use the fixed effects estimator), and possibly deal with reverse causality as well. Our goal is merely to show how net weak carbon leakage and per-capita income are related in the cross-section.

The slope coefficient, statistically significant (5%) in one regression (Column 3), is always greater than zero and varies between 0.44 and 0.95. A coefficient of one would indicate that one thousand dollar higher income is associated with one percentage point higher TBEET. The R squares are low, the variation around the best linear fit is large, many factors other than income explain the TBEET.

Table 2.A.1: TBEET vs. Income per Capita: Cross-Country Regressions

	(1) 2015, all	(2) 2015, pop>10m	(3) Pooled, all	(4) Pooled, pop>10m
Income	0.612	0.546	0.947**	0.441
	(0.639)	(0.266)	(0.303)	(0.227)
Constant	26.91	-1.822	14.32	1.626
	(36.02)	(6.722)	(21.07)	(5.800)
Year effects	No	No	Yes	Yes
N	44	26	924	559
R squared	0.012	0.192	0.151	0.182

Notes: Own calculations based on EXIOBASE3 and PWT10. *p<0.1; **p<0.05; ***p<0.01. Regressions of the TBEET in % of PBE on per-capita income in thousand PPP-adjusted US$. Column 1 reports a simple OLS regression with heteroskedasticity-consistent standard errors based on the 2015 cross-section. Column 2 repeats the OLS regression but excludes countries whose 2015 population is lower than 10 million. Column 3 reports a pooled OLS regression with year fixed effects and cluster-robust standard errors based on the 1995–2015 panel. The regression constant represents the intercept for the year 2015. Column 4 repeats the pooled OLS regression but excludes countries whose 2015 population is lower than 10 million.

2.B Other Results and Supplementary Information

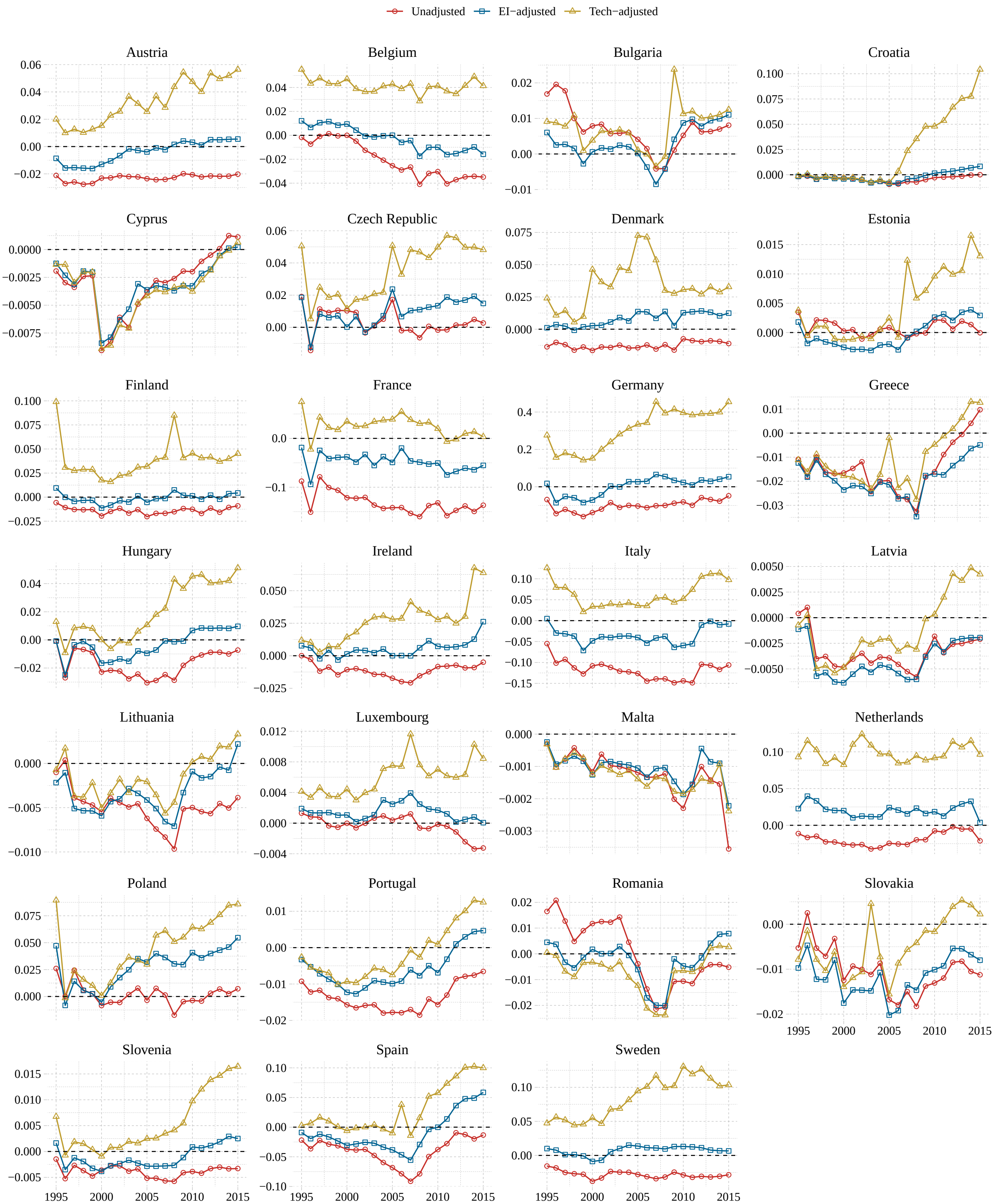


Figure 2.B.1: Balance of emissions embodied in trade 1995–2015, line plots by country

Figure 2.B.1: Balance of emissions embodied in trade 1995–2015, line plots by country *(continued)*

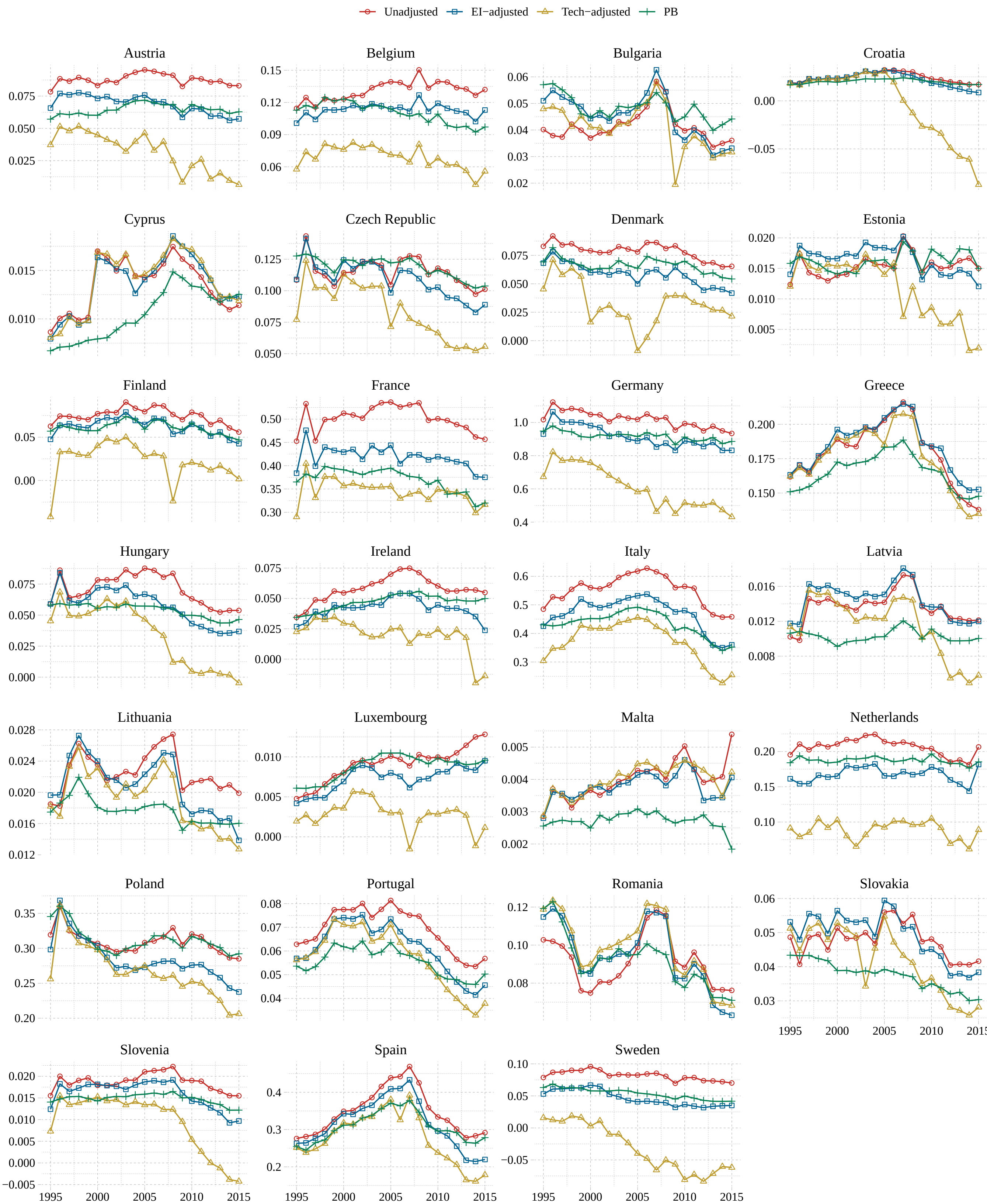


Figure 2.B.2: Consumption-based and production-based emissions 1995–2015, line plots by country

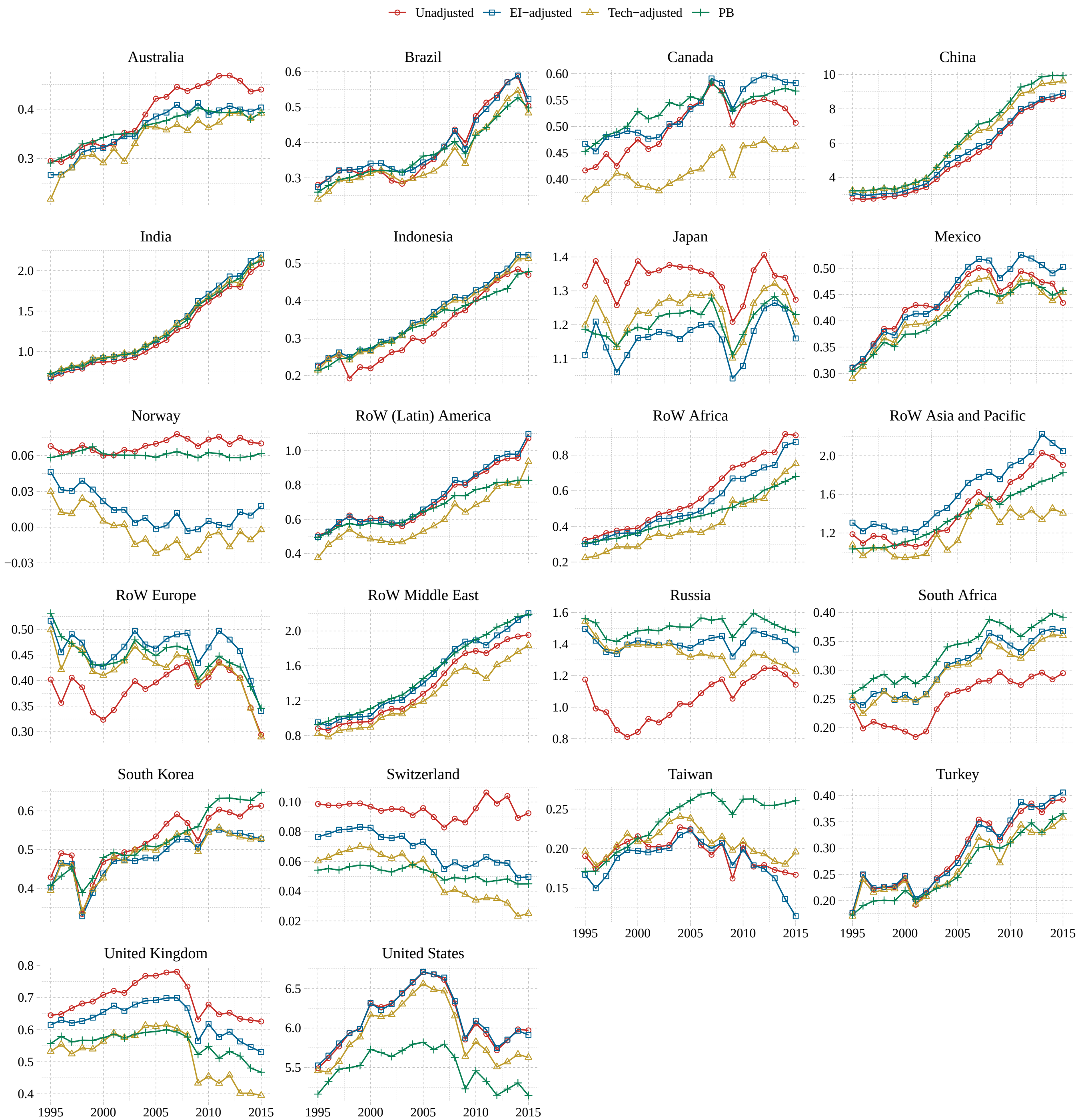


Figure 2.B.2: Consumption-based and production-based emissions 1995–2015, line plots by country *(continued)*

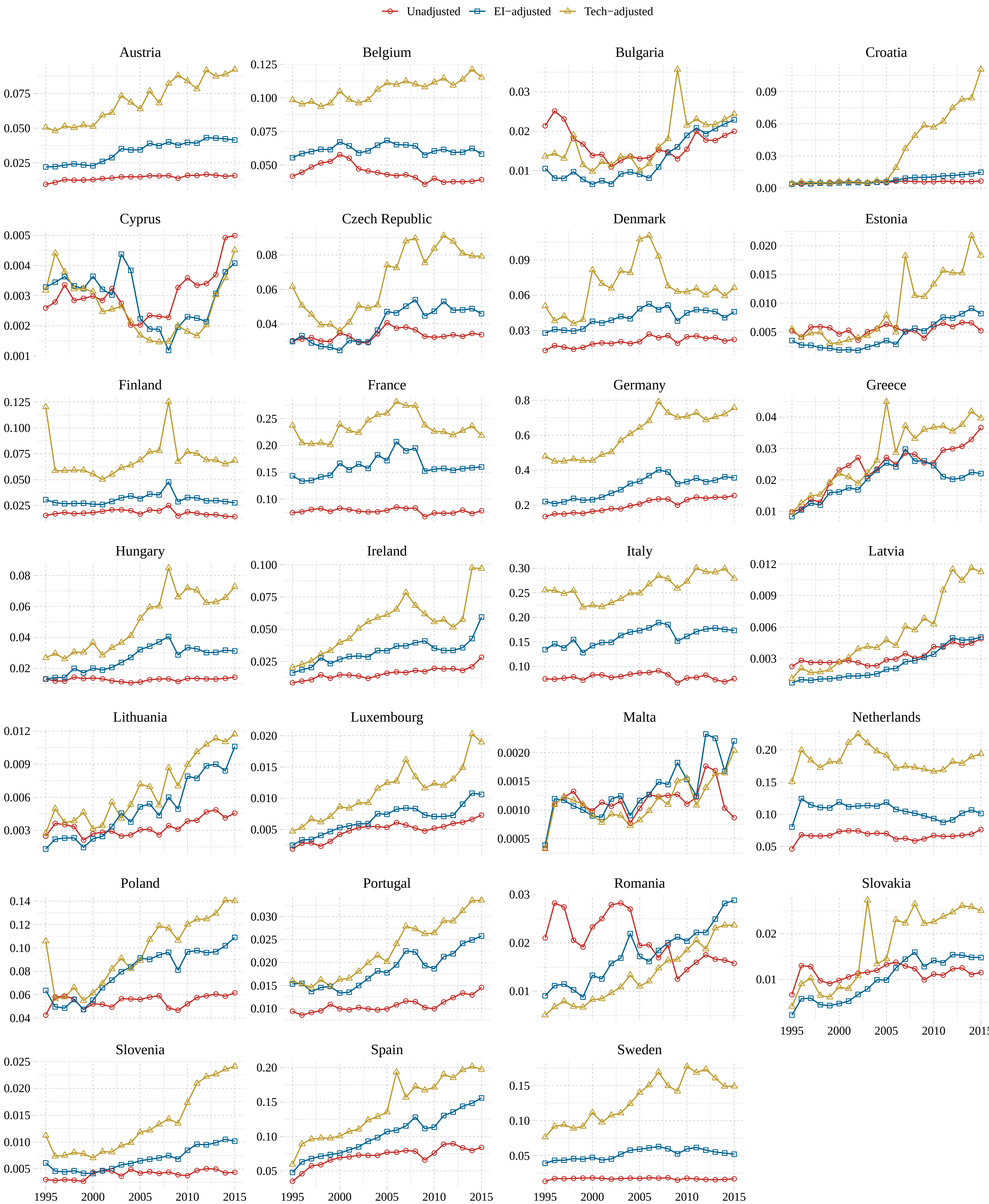


Figure 2.B.3: Emissions embodied in exports 1995–2015, line plots by country

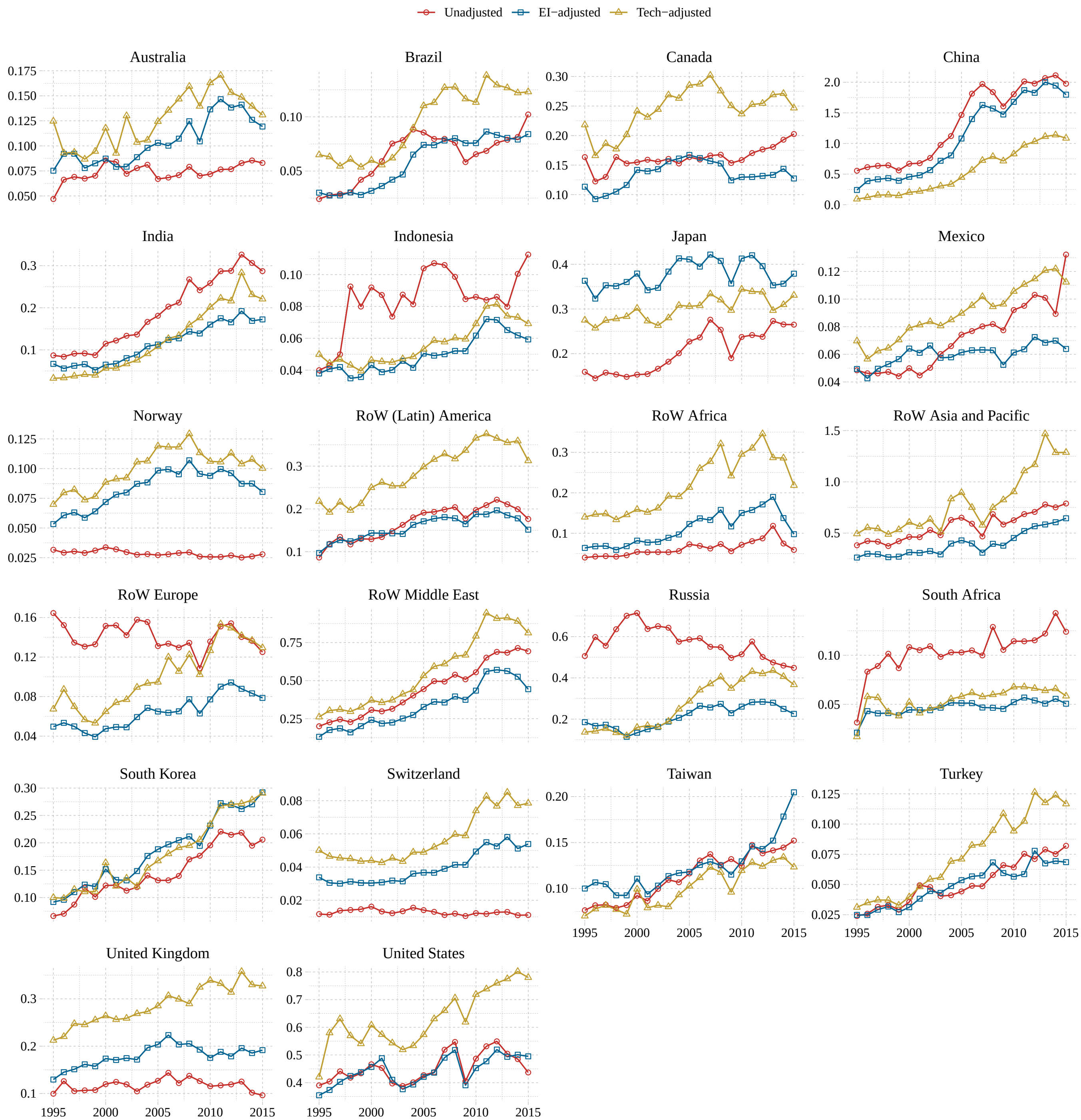


Figure 2.B.3: Emissions embodied in exports 1995–2015, line plots by country *(continued)*

Table 2.B.1: Balance of Emissions Embodied in Trade, GtCO2

	1995			2005			2015		
Country	BEET	EIBEET	TBEET	BEET	EIBEET	TBEET	BEET	EIBEET	TBEET
Australia	-0.005	0.024	0.073	-0.049	-0.013	0.008	-0.046	-0.010	0.002
Austria	-0.021	-0.009	0.020	-0.024	-0.004	0.026	-0.020	0.005	0.056
Belgium	-0.002	0.012	0.055	-0.025	0.000	0.043	-0.035	-0.016	0.041
Brazil	-0.021	-0.015	0.020	0.030	0.018	0.054	-0.007	-0.025	0.014
Bulgaria	0.017	0.006	0.009	0.004	0.000	0.001	0.008	0.011	0.012
Canada	0.036	-0.014	0.091	0.019	0.023	0.141	0.060	-0.015	0.104
China	0.442	0.128	-0.020	1.161	0.776	0.141	1.195	1.016	0.305
Croatia	-0.002	-0.002	-0.001	-0.009	-0.009	-0.008	0.000	0.008	0.104
Cyprus	-0.002	-0.001	-0.001	-0.004	-0.004	-0.004	0.001	0.000	0.001
Czech Republic	0.019	0.019	0.050	0.017	0.024	0.051	0.003	0.015	0.048
Denmark	-0.014	0.001	0.024	-0.014	0.014	0.073	-0.011	0.012	0.033
Estonia	0.003	0.002	0.004	0.001	-0.002	0.002	0.000	0.003	0.013
Finland	-0.006	0.009	0.099	-0.020	-0.005	0.032	-0.009	0.004	0.045
France	-0.087	-0.019	0.075	-0.142	-0.049	0.039	-0.137	-0.055	0.003
Germany	-0.068	0.018	0.276	-0.103	0.027	0.334	-0.048	0.054	0.454
Greece	-0.011	-0.012	-0.011	-0.020	-0.021	-0.002	0.010	-0.005	0.013
Hungary	-0.001	-0.001	0.013	-0.031	-0.010	0.011	-0.007	0.010	0.051
India	0.062	0.041	0.007	0.047	-0.022	-0.027	0.038	-0.077	-0.029
Indonesia	-0.012	-0.014	-0.002	0.042	-0.012	-0.009	0.009	-0.045	-0.035
Ireland	0.000	0.008	0.012	-0.017	0.000	0.028	-0.005	0.026	0.064
Italy	-0.055	0.005	0.126	-0.126	-0.040	0.036	-0.106	-0.008	0.098
Japan	-0.128	0.076	-0.012	-0.126	0.058	-0.047	-0.044	0.070	0.022
Latvia	0.000	-0.001	-0.001	-0.004	-0.005	-0.002	-0.002	-0.002	0.004
Lithuania	-0.001	-0.002	-0.001	-0.006	-0.004	-0.002	-0.004	0.002	0.003
Luxembourg	0.001	0.002	0.004	0.000	0.002	0.008	-0.003	0.000	0.008
Malta	0.000	0.000	0.000	-0.001	-0.001	-0.001	-0.004	-0.002	-0.002
Mexico	-0.007	-0.006	0.014	-0.034	-0.047	-0.019	0.023	-0.045	0.003
Netherlands	-0.011	0.023	0.093	-0.024	0.024	0.097	-0.021	0.004	0.096
Norway	-0.010	0.012	0.029	-0.011	0.060	0.081	-0.008	0.044	0.064
Poland	0.026	0.047	0.089	-0.003	0.032	0.030	0.007	0.055	0.086
Portugal	-0.009	-0.003	-0.003	-0.018	-0.010	-0.008	-0.007	0.005	0.012
Romania	0.016	0.004	0.000	-0.004	-0.006	-0.012	-0.005	0.008	0.003
RoW (Latin) America	-0.013	-0.003	0.118	0.008	-0.012	0.115	-0.245	-0.270	-0.109
RoW Africa	-0.019	0.004	0.081	-0.069	-0.018	0.072	-0.231	-0.192	-0.071
RoW Asia and Pacific	-0.152	-0.272	-0.040	0.010	-0.212	0.255	-0.080	-0.224	0.419
RoW Europe	0.130	0.015	0.032	0.052	-0.014	0.016	0.052	0.005	0.056
RoW Middle East	0.045	-0.024	0.107	0.174	0.057	0.262	0.235	-0.014	0.355
Russia	0.386	0.065	0.017	0.489	0.133	0.191	0.333	0.110	0.251
Slovakia	-0.005	-0.010	-0.008	-0.017	-0.020	-0.016	-0.011	-0.008	0.002
Slovenia	-0.001	0.002	0.007	-0.005	-0.003	0.002	-0.003	0.003	0.016
South Africa	0.021	0.011	0.007	0.081	0.030	0.037	0.097	0.024	0.032
South Korea	-0.021	0.005	0.013	-0.027	0.030	0.009	0.034	0.121	0.119
Spain	-0.022	-0.009	0.003	-0.068	-0.038	-0.010	-0.013	0.059	0.100
Sweden	-0.016	0.010	0.047	-0.028	0.014	0.095	-0.028	0.007	0.103
Switzerland	-0.045	-0.022	-0.006	-0.041	-0.019	-0.007	-0.048	-0.005	0.020
Taiwan	-0.019	0.004	-0.026	0.036	0.038	0.023	0.094	0.146	0.065
Turkey	-0.005	-0.004	0.002	-0.037	-0.027	-0.010	-0.027	-0.040	0.008
United Kingdom	-0.088	-0.058	0.025	-0.174	-0.098	-0.016	-0.158	-0.063	0.073
United States	-0.326	-0.362	-0.296	-0.888	-0.894	-0.741	-0.825	-0.767	-0.482

Table 2.B.2: Balance of Emissions Embodied in Trade, % of PBE

	1995			2005			2015		
Country	BEET	EIBEET	TBEET	BEET	EIBEET	TBEET	BEET	EIBEET	TBEET
Australia	-1.549	8.196	25.192	-13.312	-3.608	2.128	-11.798	-2.548	0.385
Austria	-37.035	-15.073	34.899	-32.752	-5.503	35.529	-32.144	8.730	89.846
Belgium	-1.527	10.741	48.814	-22.278	0.014	37.521	-35.907	-16.275	42.547
Brazil	-7.977	-5.706	7.736	8.160	5.013	15.019	-1.335	-4.971	2.872
Bulgaria	29.588	10.587	15.984	8.345	0.311	2.206	18.330	24.950	28.292
Canada	7.946	-3.126	19.982	3.446	4.081	25.315	10.602	-2.671	18.374
China	13.777	3.987	-0.631	19.641	13.127	2.393	12.037	10.232	3.071
Croatia	-10.560	-9.453	-6.795	-41.247	-37.273	-33.803	0.438	48.953	613.024
Cyprus	-28.761	-18.447	-20.114	-36.716	-34.717	-39.990	8.975	1.689	5.141
Czech Republic	14.997	14.564	39.576	14.163	19.414	41.522	2.594	14.322	46.411
Denmark	-19.746	1.620	34.638	-22.546	21.453	113.919	-20.475	22.943	60.411
Estonia	21.929	11.331	23.895	5.176	-12.018	14.835	-0.252	19.519	87.133
Finland	-10.061	16.625	173.955	-34.226	-9.131	53.885	-19.381	9.220	96.540
France	-23.958	-5.147	20.535	-35.943	-12.456	9.900	-42.785	-17.274	1.059
Germany	-7.221	1.891	29.084	-11.247	2.948	36.516	-5.441	6.065	51.301
Greece	-7.191	-8.208	-7.386	-10.736	-11.692	-1.068	6.571	-3.332	8.595
Hungary	-1.339	-1.424	22.273	-53.282	-16.663	18.635	-15.671	20.765	110.144
India	8.430	5.670	0.975	4.136	-1.936	-2.364	1.776	-3.636	-1.353
Indonesia	-5.456	-6.416	-0.795	12.492	-3.498	-2.678	1.814	-9.350	-7.279
Ireland	0.175	22.368	34.604	-32.843	0.088	53.129	-9.970	52.471	127.775
Italy	-12.732	1.130	29.311	-25.716	-8.202	7.307	-30.094	-2.226	27.753
Japan	-10.794	6.383	-1.045	-10.159	4.638	-3.814	-3.555	5.718	1.785
Latvia	3.859	-10.623	-6.868	-38.457	-47.298	-19.906	-20.899	-19.407	42.325
Lithuania	-5.835	-12.401	-4.218	-34.132	-22.747	-11.421	-24.061	13.644	20.647
Luxembourg	21.420	31.206	68.045	3.705	23.638	71.752	-33.866	0.670	88.002
Malta	-11.644	-9.499	-12.207	-38.578	-34.130	-45.108	-192.948	-120.416	-129.373
Mexico	-2.439	-2.132	4.556	-7.969	-10.959	-4.377	5.087	-9.853	0.724
Netherlands	-6.111	12.342	50.458	-12.909	12.693	51.247	-11.419	2.057	52.028
Norway	-16.511	20.541	48.927	-19.166	102.293	137.562	-13.470	71.403	103.512
Poland	7.548	13.660	25.886	-1.144	10.482	9.796	2.471	18.692	29.386
Portugal	-17.252	-6.118	-4.860	-27.988	-15.584	-11.814	-13.016	9.323	24.807
Romania	13.814	3.756	0.401	-4.022	-6.410	-12.923	-7.326	11.073	3.787
RoW (Latin) America	-2.679	-0.531	23.907	1.215	-1.930	17.816	-29.613	-32.632	-13.156
RoW Africa	-6.342	1.440	26.428	-15.342	-4.118	16.100	-33.898	-28.189	-10.496
RoW Asia and Pacific	-14.730	-26.307	-3.908	0.695	-15.439	18.541	-4.369	-12.286	22.970
RoW Europe	24.377	2.763	6.099	11.625	-3.137	3.488	14.969	1.571	16.241
RoW Middle East	4.885	-2.550	11.478	11.964	3.906	18.022	10.728	-0.656	16.222
Russia	24.710	4.188	1.082	32.456	8.846	12.643	22.581	7.466	17.047
Slovakia	-12.165	-22.456	-18.084	-42.850	-51.605	-39.731	-37.071	-26.328	7.394
Slovenia	-10.430	11.678	48.022	-32.519	-17.909	15.673	-27.107	20.569	134.953
South Africa	8.262	4.267	2.646	23.586	8.640	10.602	24.790	6.102	8.092
South Korea	-5.149	1.147	3.163	-5.290	5.913	1.747	5.312	18.662	18.408
Spain	-8.597	-3.539	1.058	-18.407	-10.353	-2.698	-4.757	21.062	35.906
Sweden	-24.774	15.924	75.051	-51.281	25.058	173.317	-68.231	15.846	248.125
Switzerland	-82.153	-41.385	-11.382	-75.956	-34.436	-12.031	-105.714	-10.511	44.239
Taiwan	-11.270	2.532	-14.941	13.939	14.592	8.676	35.969	56.123	24.933
Turkey	-2.770	-2.235	1.422	-14.997	-11.207	-4.057	-7.379	-11.072	2.104
United Kingdom	-15.879	-10.484	4.421	-29.291	-16.405	-2.657	-33.903	-13.478	15.521
United States	-6.322	-7.016	-5.742	-15.255	-15.356	-12.736	-16.032	-14.900	-9.364

Table 2.B.3: Consumption-Based Emissions, GtCO2

	1995			2005			2015		
Country	CBA	EICBA	TCBA	CBA	EICBA	TCBA	CBA	EICBA	TCBA
Australia	0.295	0.267	0.218	0.421	0.385	0.364	0.440	0.403	0.392
Austria	0.078	0.066	0.037	0.095	0.076	0.046	0.083	0.057	0.006
Belgium	0.115	0.101	0.058	0.139	0.114	0.071	0.132	0.113	0.056
Brazil	0.280	0.275	0.240	0.332	0.344	0.307	0.504	0.522	0.483
Bulgaria	0.040	0.051	0.048	0.045	0.049	0.048	0.036	0.033	0.032
Canada	0.417	0.467	0.362	0.537	0.533	0.415	0.507	0.582	0.463
China	2.768	3.083	3.231	4.750	5.135	5.769	8.734	8.914	9.625
Croatia	0.019	0.019	0.018	0.032	0.031	0.031	0.017	0.009	-0.087
Cyprus	0.009	0.008	0.008	0.014	0.014	0.015	0.011	0.012	0.012
Czech Republic	0.108	0.109	0.077	0.105	0.098	0.071	0.101	0.089	0.056
Denmark	0.083	0.068	0.045	0.078	0.050	-0.009	0.065	0.042	0.021
Estonia	0.012	0.014	0.012	0.016	0.018	0.014	0.015	0.012	0.002
Finland	0.063	0.047	-0.042	0.079	0.065	0.027	0.056	0.042	0.002
France	0.453	0.384	0.290	0.537	0.444	0.356	0.457	0.375	0.316
Germany	1.017	0.930	0.672	1.018	0.888	0.581	0.934	0.832	0.431
Greece	0.162	0.163	0.162	0.203	0.205	0.185	0.138	0.153	0.135
Hungary	0.059	0.059	0.045	0.088	0.067	0.047	0.054	0.037	-0.005
India	0.669	0.689	0.723	1.078	1.146	1.151	2.081	2.195	2.147
Indonesia	0.225	0.227	0.215	0.293	0.346	0.344	0.469	0.522	0.512
Ireland	0.034	0.027	0.023	0.070	0.053	0.025	0.055	0.024	-0.014
Italy	0.485	0.425	0.304	0.618	0.532	0.456	0.458	0.360	0.255
Japan	1.315	1.111	1.199	1.368	1.185	1.290	1.274	1.159	1.208
Latvia	0.010	0.012	0.011	0.014	0.015	0.012	0.012	0.012	0.006
Lithuania	0.018	0.020	0.018	0.024	0.022	0.020	0.020	0.014	0.013
Luxembourg	0.005	0.004	0.002	0.010	0.008	0.003	0.013	0.010	0.001
Malta	0.003	0.003	0.003	0.004	0.004	0.004	0.005	0.004	0.004
Mexico	0.312	0.311	0.290	0.465	0.478	0.449	0.434	0.502	0.454
Netherlands	0.195	0.161	0.091	0.214	0.166	0.092	0.207	0.182	0.089
Norway	0.068	0.046	0.030	0.070	-0.001	-0.022	0.070	0.018	-0.002
Poland	0.319	0.298	0.256	0.308	0.273	0.275	0.285	0.238	0.206
Portugal	0.063	0.057	0.056	0.081	0.073	0.071	0.057	0.046	0.038
Romania	0.103	0.115	0.119	0.099	0.101	0.107	0.076	0.063	0.068
RoW (Latin) America	0.507	0.496	0.376	0.636	0.657	0.529	1.072	1.097	0.936
RoW Africa	0.324	0.301	0.224	0.516	0.466	0.375	0.911	0.872	0.752
RoW Asia and Pacific	1.188	1.307	1.076	1.364	1.585	1.119	1.904	2.048	1.405
RoW Europe	0.402	0.517	0.499	0.396	0.463	0.433	0.294	0.340	0.290
RoW Middle East	0.884	0.953	0.822	1.281	1.398	1.192	1.954	2.203	1.834
Russia	1.175	1.495	1.544	1.018	1.374	1.317	1.142	1.365	1.224
Slovakia	0.049	0.053	0.051	0.056	0.059	0.055	0.042	0.038	0.028
Slovenia	0.016	0.012	0.007	0.021	0.019	0.013	0.015	0.010	-0.004
South Africa	0.237	0.248	0.252	0.264	0.315	0.309	0.295	0.368	0.360
South Korea	0.428	0.402	0.394	0.534	0.477	0.498	0.613	0.527	0.528
Spain	0.276	0.263	0.252	0.439	0.409	0.381	0.292	0.220	0.178
Sweden	0.079	0.053	0.016	0.083	0.041	-0.040	0.070	0.035	-0.062
Switzerland	0.099	0.077	0.060	0.096	0.073	0.061	0.092	0.050	0.025
Taiwan	0.190	0.167	0.197	0.225	0.223	0.238	0.167	0.114	0.196
Turkey	0.177	0.176	0.170	0.281	0.272	0.254	0.393	0.406	0.358
United Kingdom	0.645	0.615	0.532	0.769	0.692	0.610	0.626	0.530	0.395
United States	5.489	5.525	5.459	6.706	6.712	6.560	5.970	5.912	5.627

Table 2.B.4: Consumption-Based Emissions, % of PBE

	1995			2005			2015		
Country	CBA	EICBA	TCBA	CBA	EICBA	TCBA	CBA	EICBA	TCBA
Australia	101.55	91.80	74.81	113.31	103.61	97.87	111.80	102.55	99.61
Austria	137.03	115.07	65.10	132.75	105.50	64.47	132.14	91.27	10.15
Belgium	101.53	89.26	51.19	122.28	99.99	62.48	135.91	116.28	57.45
Brazil	107.98	105.71	92.26	91.84	94.99	84.98	101.33	104.97	97.13
Bulgaria	70.41	89.41	84.02	91.65	99.69	97.79	81.67	75.05	71.71
Canada	92.05	103.13	80.02	96.55	95.92	74.68	89.40	102.67	81.63
China	86.22	96.01	100.63	80.36	86.87	97.61	87.96	89.77	96.93
Croatia	110.56	109.45	106.79	141.25	137.27	133.80	99.56	51.05	-513.02
Cyprus	128.76	118.45	120.11	136.72	134.72	139.99	91.03	98.31	94.86
Czech Republic	85.00	85.44	60.42	85.84	80.59	58.48	97.41	85.68	53.59
Denmark	119.75	98.38	65.36	122.55	78.55	-13.92	120.48	77.06	39.59
Estonia	78.07	88.67	76.11	94.82	112.02	85.17	100.25	80.48	12.87
Finland	110.06	83.37	-73.95	134.23	109.13	46.12	119.38	90.78	3.46
France	123.96	105.15	79.47	135.94	112.46	90.10	142.78	117.27	98.94
Germany	107.22	98.11	70.92	111.25	97.05	63.48	105.44	93.93	48.70
Greece	107.19	108.21	107.39	110.74	111.69	101.07	93.43	103.33	91.41
Hungary	101.34	101.42	77.73	153.28	116.66	81.36	115.67	79.23	-10.14
India	91.57	94.33	99.03	95.86	101.94	102.36	98.22	103.64	101.35
Indonesia	105.46	106.42	100.79	87.51	103.50	102.68	98.19	109.35	107.28
Ireland	99.82	77.63	65.40	132.84	99.91	46.87	109.97	47.53	-27.78
Italy	112.73	98.87	70.69	125.72	108.20	92.69	130.09	102.23	72.25
Japan	110.79	93.62	101.05	110.16	95.36	103.81	103.55	94.28	98.22
Latvia	96.14	110.62	106.87	138.46	147.30	119.91	120.90	119.41	57.68
Lithuania	105.83	112.40	104.22	134.13	122.75	111.42	124.06	86.36	79.35
Luxembourg	78.58	68.79	31.96	96.29	76.36	28.25	133.87	99.33	12.00
Malta	111.64	109.50	112.21	138.58	134.13	145.11	292.95	220.42	229.37
Mexico	102.44	102.13	95.44	107.97	110.96	104.38	94.91	109.85	99.28
Netherlands	106.11	87.66	49.54	112.91	87.31	48.75	111.42	97.94	47.97
Norway	116.51	79.46	51.07	119.17	-2.29	-37.56	113.47	28.60	-3.51
Poland	92.45	86.34	74.11	101.14	89.52	90.20	97.53	81.31	70.61
Portugal	117.25	106.12	104.86	127.99	115.58	111.81	113.02	90.68	75.19
Romania	86.19	96.24	99.60	104.02	106.41	112.92	107.33	88.93	96.21
RoW (Latin) America	102.68	100.53	76.09	98.79	101.93	82.18	129.61	132.63	113.16
RoW Africa	106.34	98.56	73.57	115.34	104.12	83.90	133.90	128.19	110.50
RoW Asia and Pacific	114.73	126.31	103.91	99.30	115.44	81.46	104.37	112.29	77.03
RoW Europe	75.62	97.24	93.90	88.38	103.14	96.51	85.03	98.43	83.76
RoW Middle East	95.11	102.55	88.52	88.04	96.09	81.98	89.27	100.66	83.78
Russia	75.29	95.81	98.92	67.54	91.15	87.36	77.42	92.53	82.95
Slovakia	112.16	122.46	118.08	142.85	151.60	139.73	137.07	126.33	92.61
Slovenia	110.43	88.32	51.98	132.52	117.91	84.33	127.11	79.43	-34.95
South Africa	91.74	95.73	97.35	76.41	91.36	89.40	75.21	93.90	91.91
South Korea	105.15	98.85	96.84	105.29	94.09	98.25	94.69	81.34	81.59
Spain	108.60	103.54	98.94	118.41	110.35	102.70	104.76	78.94	64.09
Sweden	124.77	84.08	24.95	151.28	74.94	-73.32	168.23	84.15	-148.13
Switzerland	182.15	141.39	111.38	175.96	134.44	112.03	205.71	110.51	55.76
Taiwan	111.27	97.47	114.94	86.06	85.41	91.32	64.03	43.88	75.07
Turkey	102.77	102.23	98.58	115.00	111.21	104.06	107.38	111.07	97.90
United Kingdom	115.88	110.48	95.58	129.29	116.40	102.66	133.90	113.48	84.48
United States	106.32	107.02	105.74	115.26	115.36	112.74	116.03	114.90	109.36

Table 2.B.5: Emissions Embodied in Exports, GtCO2

	1995			2005			2015		
Country	EEX	EIEEX	TEEX	EEX	EIEEX	TEEX	EEX	EIEEX	TEEX
Australia	0.047	0.075	0.125	0.067	0.103	0.124	0.083	0.119	0.131
Austria	0.009	0.022	0.051	0.015	0.034	0.064	0.016	0.041	0.092
Belgium	0.042	0.055	0.098	0.043	0.068	0.111	0.039	0.058	0.115
Brazil	0.024	0.030	0.065	0.086	0.074	0.110	0.102	0.084	0.123
Bulgaria	0.021	0.011	0.014	0.013	0.009	0.010	0.020	0.023	0.024
Canada	0.164	0.113	0.218	0.164	0.167	0.285	0.203	0.127	0.247
China	0.555	0.241	0.093	1.466	1.081	0.447	1.976	1.797	1.086
Croatia	0.004	0.004	0.004	0.005	0.006	0.007	0.007	0.015	0.111
Cyprus	0.003	0.003	0.003	0.002	0.002	0.002	0.005	0.004	0.005
Czech Republic	0.030	0.030	0.062	0.041	0.047	0.074	0.034	0.046	0.079
Denmark	0.013	0.028	0.051	0.021	0.049	0.107	0.022	0.046	0.066
Estonia	0.005	0.004	0.006	0.006	0.004	0.008	0.005	0.008	0.018
Finland	0.016	0.031	0.120	0.017	0.032	0.069	0.014	0.028	0.069
France	0.075	0.143	0.237	0.079	0.172	0.260	0.078	0.160	0.218
Germany	0.134	0.220	0.478	0.206	0.336	0.643	0.254	0.356	0.757
Greece	0.010	0.008	0.010	0.027	0.025	0.045	0.037	0.022	0.040
Hungary	0.013	0.013	0.027	0.011	0.032	0.052	0.014	0.031	0.073
India	0.087	0.067	0.033	0.181	0.113	0.108	0.287	0.172	0.221
Indonesia	0.040	0.038	0.050	0.104	0.050	0.053	0.113	0.059	0.069
Ireland	0.008	0.016	0.020	0.016	0.033	0.061	0.028	0.059	0.097
Italy	0.075	0.134	0.256	0.087	0.173	0.249	0.075	0.173	0.279
Japan	0.159	0.363	0.275	0.227	0.411	0.306	0.265	0.379	0.331
Latvia	0.002	0.001	0.001	0.003	0.002	0.005	0.005	0.005	0.011
Lithuania	0.002	0.001	0.003	0.003	0.005	0.007	0.005	0.011	0.012
Luxembourg	0.002	0.002	0.005	0.005	0.007	0.012	0.007	0.011	0.019
Malta	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.002	0.002
Mexico	0.048	0.049	0.070	0.074	0.061	0.090	0.132	0.064	0.112
Netherlands	0.046	0.080	0.150	0.070	0.119	0.192	0.076	0.101	0.194
Norway	0.032	0.053	0.070	0.027	0.098	0.119	0.028	0.080	0.100
Poland	0.043	0.064	0.106	0.056	0.091	0.089	0.062	0.109	0.140
Portugal	0.009	0.015	0.016	0.010	0.018	0.020	0.015	0.026	0.034
Romania	0.021	0.009	0.005	0.019	0.017	0.011	0.016	0.029	0.024
RoW (Latin) America	0.086	0.097	0.218	0.191	0.171	0.298	0.176	0.152	0.313
RoW Africa	0.040	0.064	0.140	0.073	0.123	0.213	0.059	0.098	0.218
RoW Asia and Pacific	0.381	0.261	0.493	0.650	0.429	0.895	0.789	0.644	1.288
RoW Europe	0.164	0.050	0.067	0.131	0.065	0.095	0.125	0.079	0.129
RoW Middle East	0.200	0.131	0.262	0.444	0.327	0.533	0.693	0.444	0.813
Russia	0.506	0.185	0.137	0.586	0.230	0.287	0.449	0.226	0.367
Slovakia	0.007	0.002	0.004	0.013	0.010	0.015	0.012	0.015	0.025
Slovenia	0.003	0.006	0.011	0.004	0.007	0.012	0.004	0.010	0.024
South Africa	0.031	0.021	0.017	0.103	0.051	0.058	0.124	0.051	0.058
South Korea	0.066	0.092	0.100	0.131	0.188	0.167	0.206	0.292	0.291
Spain	0.035	0.048	0.059	0.077	0.107	0.135	0.084	0.156	0.197
Sweden	0.013	0.039	0.076	0.018	0.059	0.140	0.017	0.052	0.149
Switzerland	0.012	0.034	0.050	0.014	0.037	0.049	0.011	0.054	0.079
Taiwan	0.076	0.100	0.070	0.116	0.118	0.103	0.152	0.205	0.123
Turkey	0.024	0.025	0.031	0.044	0.054	0.071	0.082	0.068	0.117
United Kingdom	0.099	0.129	0.212	0.127	0.203	0.285	0.096	0.192	0.327
United States	0.390	0.355	0.420	0.427	0.421	0.574	0.437	0.495	0.780

Table 2.B.6: Emissions Embodied in Exports, % of PBE

	1995			2005			2015		
Country	EEX	EIEEX	TEEX	EEX	EIEEX	TEEX	EEX	EIEEX	TEEX
Australia	16.126	25.871	42.867	18.023	27.727	33.462	21.093	30.343	33.276
Austria	16.606	38.568	88.540	20.640	47.889	88.921	24.990	65.863	146.979
Belgium	36.898	49.166	87.239	37.662	59.954	97.462	40.232	59.863	118.685
Brazil	9.293	11.564	25.006	23.644	20.498	30.504	20.546	16.910	24.753
Bulgaria	37.438	18.437	23.834	26.451	18.417	20.312	45.210	51.829	55.172
Canada	36.110	25.038	48.146	29.424	30.058	51.293	35.738	22.466	43.511
China	17.291	7.501	2.882	24.806	18.292	7.559	19.904	18.100	10.939
Croatia	20.741	21.848	24.506	21.568	25.541	29.012	38.456	86.971	651.042
Cyprus	38.620	48.934	47.267	19.441	21.440	16.168	39.831	32.546	35.998
Czech Republic	23.760	23.327	48.339	33.326	38.577	60.685	32.493	44.222	76.310
Denmark	19.032	40.398	73.416	32.296	76.295	168.761	41.424	84.842	122.310
Estonia	32.861	22.263	34.827	38.631	21.437	48.289	34.962	54.734	122.348
Finland	27.273	53.959	211.289	28.412	53.507	116.523	30.687	59.288	146.609
France	20.427	39.238	64.919	19.992	43.479	65.836	24.446	49.957	68.290
Germany	14.132	23.244	50.437	22.527	36.722	70.291	28.717	40.224	85.460
Greece	6.516	5.499	6.321	14.809	13.852	24.476	24.800	14.897	26.824
Hungary	22.441	22.357	46.054	19.364	55.984	91.282	30.597	67.033	156.412
India	11.908	9.148	4.453	16.096	10.024	9.596	13.551	8.138	10.421
Indonesia	18.745	17.786	23.407	31.055	15.066	15.886	23.578	12.414	14.486
Ireland	24.561	46.754	58.989	30.227	63.158	116.199	56.737	119.178	194.482
Italy	17.403	31.265	59.446	17.697	35.211	50.720	21.375	49.243	79.223
Japan	13.424	30.602	23.173	18.290	33.087	24.635	21.541	30.814	26.880
Latvia	21.208	6.727	10.482	28.246	19.405	46.798	48.814	50.306	112.038
Lithuania	14.078	7.512	15.695	16.816	28.202	39.527	28.405	66.110	73.113
Luxembourg	30.744	40.530	77.368	50.864	70.797	118.911	76.196	110.732	198.064
Malta	13.187	15.332	12.624	33.318	37.766	26.788	47.120	119.653	110.695
Mexico	15.920	16.227	22.915	17.249	14.258	20.841	28.914	13.973	24.551
Netherlands	25.122	43.575	81.690	36.982	62.583	101.137	41.191	54.668	104.638
Norway	54.286	91.338	119.723	46.304	167.763	203.032	45.081	129.955	162.064
Poland	12.321	18.433	30.659	18.363	29.989	29.304	21.087	37.309	48.002
Portugal	17.471	28.605	29.863	15.561	27.964	31.735	28.965	51.303	66.787
Romania	17.644	7.586	4.231	20.487	18.099	11.586	22.224	40.624	33.337
RoW (Latin) America	17.493	19.640	44.079	29.683	26.538	46.285	21.337	18.317	37.794
RoW Africa	13.134	20.916	45.904	16.268	27.492	47.710	8.653	14.362	32.056
RoW Asia and Pacific	36.829	25.252	47.651	47.350	31.216	65.196	43.243	35.325	70.582
RoW Europe	30.943	9.329	12.665	29.234	14.472	21.097	36.139	22.740	37.411
RoW Middle East	21.578	14.143	28.171	30.552	22.494	36.611	31.670	20.286	37.164
Russia	32.395	11.873	8.767	38.871	15.262	19.058	30.405	15.290	24.871
Slovakia	15.371	5.080	9.452	33.892	25.137	37.011	37.943	48.686	82.408
Slovenia	21.336	43.444	79.788	26.356	40.967	74.548	35.670	83.346	197.730
South Africa	12.150	8.155	6.534	29.792	14.846	16.808	31.607	12.919	14.909
South Korea	16.287	22.583	24.599	25.921	37.124	32.958	31.795	45.145	44.891
Spain	13.720	18.778	23.376	20.824	28.877	36.532	30.215	56.033	70.877
Sweden	21.349	62.048	121.175	32.097	108.436	256.695	40.781	124.858	357.137
Switzerland	21.630	62.398	92.401	25.801	67.321	89.726	24.739	119.942	174.693
Taiwan	44.599	58.401	40.928	44.577	45.230	39.314	58.372	78.525	47.335
Turkey	13.851	14.387	18.043	18.108	21.898	29.048	22.425	18.731	31.908
United Kingdom	17.862	23.257	38.162	21.343	34.229	47.977	20.595	41.020	70.019
United States	7.560	6.866	8.141	7.338	7.238	9.857	8.490	9.623	15.159

Table 2.B.7: Production-Based Emissions, GtCO2

Country	1995	2005	2015
Australia	0.291	0.372	0.393
Austria	0.057	0.072	0.063
Belgium	0.113	0.114	0.097
Brazil	0.260	0.362	0.497
Bulgaria	0.057	0.049	0.044
Canada	0.453	0.556	0.567
China	3.211	5.910	9.930
Croatia	0.017	0.023	0.017
Cyprus	0.007	0.010	0.013
Czech Republic	0.128	0.122	0.104
Denmark	0.069	0.064	0.054
Estonia	0.016	0.016	0.015
Finland	0.057	0.059	0.047
France	0.365	0.395	0.320
Germany	0.948	0.915	0.886
Greece	0.151	0.183	0.148
Hungary	0.058	0.057	0.046
India	0.730	1.125	2.118
Indonesia	0.213	0.335	0.478
Ireland	0.034	0.053	0.050
Italy	0.430	0.492	0.352
Japan	1.187	1.242	1.230
Latvia	0.011	0.010	0.010
Lithuania	0.017	0.018	0.016
Luxembourg	0.006	0.010	0.010
Malta	0.003	0.003	0.002
Mexico	0.304	0.431	0.457
Netherlands	0.184	0.190	0.185
Norway	0.058	0.059	0.062
Poland	0.345	0.305	0.292
Portugal	0.054	0.064	0.050
Romania	0.119	0.095	0.071
RoW (Latin) America	0.494	0.644	0.827
RoW Africa	0.305	0.447	0.681
RoW Asia and Pacific	1.035	1.373	1.824
RoW Europe	0.532	0.448	0.346
RoW Middle East	0.929	1.455	2.189
Russia	1.561	1.507	1.475
Slovakia	0.043	0.039	0.030
Slovenia	0.014	0.016	0.012
South Africa	0.259	0.345	0.392
South Korea	0.407	0.507	0.647
Spain	0.254	0.371	0.278
Sweden	0.063	0.055	0.042
Switzerland	0.054	0.055	0.045
Taiwan	0.171	0.261	0.261
Turkey	0.173	0.244	0.366
United Kingdom	0.557	0.594	0.467
United States	5.163	5.819	5.145

Table 2.B.8: Sectors in EXIOBASE3

Sector	Code
Cultivation of paddy rice	i01.a
Cultivation of wheat	i01.b
Cultivation of cereal grains nec	i01.c
Cultivation of vegetables, fruit, nuts	i01.d
Cultivation of oil seeds	i01.e
Cultivation of sugar cane, sugar beet	i01.f
Cultivation of plant-based fibers	i01.g
Cultivation of crops nec	i01.h
Cattle farming	i01.i
Pigs farming	i01.j
Poultry farming	i01.k
Meat animals nec	i01.l
Animal products nec	i01.m
Raw milk	i01.n
Wool, silk-worm cocoons	i01.o
Manure treatment (conventional), storage and land application	i01.w.1
Manure treatment (biogas), storage and land application	i01.w.2
Forestry, logging and related service activities (02)	i02
Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing (05)	i05
Mining of coal and lignite; extraction of peat (10)	i10
Extraction of crude petroleum and services related to crude oil extraction, excluding surveying	i11.a
Extraction of natural gas and services related to natural gas extraction, excluding surveying	i11.b
Extraction, liquefaction, and regasification of other petroleum and gaseous materials	i11.c
Mining of uranium and thorium ores (12)	i12
Mining of iron ores	i13.1
Mining of copper ores and concentrates	i13.20.11
Mining of nickel ores and concentrates	i13.20.12
Mining of aluminium ores and concentrates	i13.20.13
Mining of precious metal ores and concentrates	i13.20.14
Mining of lead, zinc and tin ores and concentrates	i13.20.15
Mining of other non-ferrous metal ores and concentrates	i13.20.16
Quarrying of stone	i14.1
Quarrying of sand and clay	i14.2

Table 2.B.8: *(continued)*

Sector	Code
Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	i14.3
Processing of meat cattle	i15.a
Processing of meat pigs	i15.b
Processing of meat poultry	i15.c
Production of meat products nec	i15.d
Processing vegetable oils and fats	i15.e
Processing of dairy products	i15.f
Processed rice	i15.g
Sugar refining	i15.h
Processing of Food products nec	i15.i
Manufacture of beverages	i15.j
Manufacture of fish products	i15.k
Manufacture of tobacco products (16)	i16
Manufacture of textiles (17)	i17
Manufacture of wearing apparel; dressing and dyeing of fur (18)	i18
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19)	i19
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials (20)	i20
Re-processing of secondary wood material into new wood material	i20.w
Pulp	i21.1
Re-processing of secondary paper into new pulp	i21.w.1
Paper	i21.2
Publishing, printing and reproduction of recorded media (22)	i22
Manufacture of coke oven products	i23.1
Petroleum Refinery	i23.2
Processing of nuclear fuel	i23.3
Plastics, basic	i24.a
Re-processing of secondary plastic into new plastic	i24.a.w
N-fertiliser	i24.b
P- and other fertiliser	i24.c
Chemicals nec	i24.d
Manufacture of rubber and plastic products (25)	i25
Manufacture of glass and glass products	i26.a

Table 2.B.8: *(continued)*

Sector	Code
Re-processing of secondary glass into new glass	i26.a.w
Manufacture of ceramic goods	i26.b
Manufacture of bricks, tiles and construction products, in baked clay	i26.c
Manufacture of cement, lime and plaster	i26.d
Re-processing of ash into clinker	i26.d.w
Manufacture of other non-metallic mineral products n.e.c.	i26.e
Manufacture of basic iron and steel and of ferro-alloys and first products thereof	i27.a
Re-processing of secondary steel into new steel	i27.a.w
Precious metals production	i27.41
Re-processing of secondary preciuos metals into new preciuos metals	i27.41.w
Aluminium production	i27.42
Re-processing of secondary aluminium into new aluminium	i27.42.w
Lead, zinc and tin production	i27.43
Re-processing of secondary lead into new lead, zinc and tin	i27.43.w
Copper production	i27.44
Re-processing of secondary copper into new copper	i27.44.w
Other non-ferrous metal production	i27.45
Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	i27.45.w
Casting of metals	i27.5
Manufacture of fabricated metal products, except machinery and equipment (28)	i28
Manufacture of machinery and equipment n.e.c. (29)	i29
Manufacture of office machinery and computers (30)	i30
Manufacture of electrical machinery and apparatus n.e.c. (31)	i31
Manufacture of radio, television and communication equipment and apparatus (32)	i32
Manufacture of medical, precision and optical instruments, watches and clocks (33)	i33
Manufacture of motor vehicles, trailers and semi-trailers (34)	i34
Manufacture of other transport equipment (35)	i35
Manufacture of furniture; manufacturing n.e.c. (36)	i36
Recycling of waste and scrap	i37
Recycling of bottles by direct reuse	i37.w.1
Production of electricity by coal	i40.11.a
Production of electricity by gas	i40.11.b
Production of electricity by nuclear	i40.11.c
Production of electricity by hydro	i40.11.d
Production of electricity by wind	i40.11.e

Table 2.B.8: *(continued)*

Sector	Code
Production of electricity by petroleum and other oil derivatives	i40.11.f
Production of electricity by biomass and waste	i40.11.g
Production of electricity by solar photovoltaic	i40.11.h
Production of electricity by solar thermal	i40.11.i
Production of electricity by tide, wave, ocean	i40.11.j
Production of electricity by Geothermal	i40.11.k
Production of electricity nec	i40.11.l
Transmission of electricity	i40.12
Distribution and trade of electricity	i40.13
Manufacture of gas; distribution of gaseous fuels through mains	i40.2
Steam and hot water supply	i40.3
Collection, purification and distribution of water (41)	i41
Construction (45)	i45
Re-processing of secondary construction material into aggregates	i45.w
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	i50.a
Retail sale of automotive fuel	i50.b
Wholesale trade and commission trade, except of motor vehicles and motorcycles (51)	i51
Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52)	i52
Hotels and restaurants (55)	i55
Transport via railways	i60.1
Other land transport	i60.2
Transport via pipelines	i60.3
Sea and coastal water transport	i61.1
Inland water transport	i61.2
Air transport (62)	i62
Supporting and auxiliary transport activities; activities of travel agencies (63)	i63
Post and telecommunications (64)	i64
Financial intermediation, except insurance and pension funding (65)	i65
Insurance and pension funding, except compulsory social security (66)	i66
Activities auxiliary to financial intermediation (67)	i67
Real estate activities (70)	i70
Renting of machinery and equipment without operator and of personal and household goods (71)	i71

Table 2.B.8: *(continued)*

Sector	Code
Computer and related activities (72)	i72
Research and development (73)	i73
Other business activities (74)	i74
Public administration and defence; compulsory social security (75)	i75
Education (80)	i80
Health and social work (85)	i85
Incineration of waste: Food	i90.1.a
Incineration of waste: Paper	i90.1.b
Incineration of waste: Plastic	i90.1.c
Incineration of waste: Metals and Inert materials	i90.1.d
Incineration of waste: Textiles	i90.1.e
Incineration of waste: Wood	i90.1.f
Incineration of waste: Oil/Hazardous waste	i90.1.g
Biogasification of food waste, incl. land application	i90.2.a
Biogasification of paper, incl. land application	i90.2.b
Biogasification of sewage slugde, incl. land application	i90.2.c
Composting of food waste, incl. land application	i90.3.a
Composting of paper and wood, incl. land application	i90.3.b
Waste water treatment, food	i90.4.a
Waste water treatment, other	i90.4.b
Landfill of waste: Food	i90.5.a
Landfill of waste: Paper	i90.5.b
Landfill of waste: Plastic	i90.5.c
Landfill of waste: Inert/metal/hazardous	i90.5.d
Landfill of waste: Textiles	i90.5.e
Landfill of waste: Wood	i90.5.f
Activities of membership organisation n.e.c. (91)	i91
Recreational, cultural and sporting activities (92)	i92
Other service activities (93)	i93
Private households with employed persons (95)	i95
Extra-territorial organizations and bodies	i99

Table 2.B.9: Countries in EXIOBASE3

Code	Country	Code	Country
AUS	Australia	KOR	South Korea
AUT	Austria	LTU	Lithuania
BEL	Belgium	LUX	Luxembourg
BGR	Bulgaria	LVA	Latvia
BRA	Brazil	MEX	Mexico
CAN	Canada	MLT	Malta
CHE	Switzerland	NLD	Netherlands
CHN	China	NOR	Norway
CYP	Cyprus	POL	Poland
CZE	Czech Republic	PRT	Portugal
DEU	Germany	ROM	Romania
DNK	Denmark	RUS	Russia
ESP	Spain	SVK	Slovakia
EST	Estonia	SVN	Slovenia
FIN	Finland	SWE	Sweden
FRA	France	TUR	Turkey
GBR	United Kingdom	TWN	Taiwan
GRC	Greece	USA	United States
HRV	Croatia	WWA	RoW Asia and Pacific
HUN	Hungary	WWE	RoW Europe
IDN	Indonesia	WWF	RoW Africa
IND	India	WWL	RoW (Latin) America
IRL	Ireland	WWM	RoW Middle East
ITA	Italy	ZAF	South Africa
JPN	Japan		

Chapter 3

Which Countries Have Offshored Carbon Dioxide Emissions in Net Terms?

We estimate the extent of emission offshoring at the country level in net terms. We define net emission onshoring as the difference between the emissions domestic producers generate by exporting and the emissions they avoid by importing. Using the multi-regional input-output (MRIO) model and the OECD Inter-Country Input-Output (ICIO) Table, we report levels and trends in net emission onshoring for 45 countries between 1995–2018. Service-oriented economies with trade deficits (USA, UK, India) are net offshoring emissions. China is net onshoring emissions. The scale of net onshoring is rather small relative to production-based emissions. National emissions and GDP have decoupled in many developed countries, even when accounting for trade. In a cross-section of countries, there is no robust association between net onshoring and per-capita income.

This chapter is under review at *Ecological Economics*.

3.1 Introduction

Emissions embodied in exports (EEX) measures the domestic emissions associated with foreign final demand, emissions embodied in imports (EEM) measures the foreign emissions associated with domestic final demand. The difference between EEX and EEM, which also equals the gap between production-based emissions (PBE) and consumption-based emissions (CBE), measures the net emission transfers, or the balance of emissions embodied in trade (BEET). There has been a spatio-temporal variation of international emission transfers across income levels documented by past studies (Peters and Hertwich, 2008b; Hertwich and Peters, 2009; Davis and Caldeira, 2010). Kanemoto et al. (2014) discover the decrease in the Kyoto-relevant territorial emissions (PBE) and the increase in the CBE for the developed countries between 1990 and 2011. Between 2005 and 2015, OECD countries record higher CBE than PBE while the opposite holds for non-OECD countries (Yamano and Guilhoto, 2020). In general, the developed countries import more than they export emissions (EEX < EEM) and record lower PBE than CBE (PBE < CBE). The developing countries export more than they import emissions (EEX > EEM) and record higher PBE than CBE (PBE > CBE). Studies also reveal a positive cross-country correlation between per-capita CBE and per-capita income (Hertwich and Peters, 2009) and a negative cross-country correlation between net emission transfers and per-capita income (Wu et al., 2022).

The optimistic interpretation of these facts is that the developed countries have reduced domestic carbon emissions (e.g. through efficiency improvement) and have managed to do so while maintaining economic growth. The pessimistic side is rather skeptical of this achievement: trade liberalization allows for "emission outsourcing", in which the developed countries reduce domestic emissions by relocating production (and thus, emissions) to developing countries, increasing the domestic emissions in the latter. In this case, the "decoupling" (i.e. the growth in economy that is in parallel with the emissions reduction) in developed countries might just be a mirage since it hardly translates into global emission decreases (Jiborn et al., 2018). Moreover, the rise in domestic emissions in developing countries is of particular concern because it poses a significant challenge in meeting national climate target, because the policy-relevant emissions are still PBE, not CBE.

Jakob and Marschinski (2013) demonstrate that the cross-country difference in technology – that is, the carbon intensity of energy and energy intensity of value added – is as consequential as the net trade flows to drive the international emission transfers. In the existence of technology difference, exchanging the same amount of identical products between two countries implies emission transfers. By standardizing cross-country difference in technology, Jiborn et al. (2018), Baumert et al. (2019) and Jiborn et al. (2020) discover that the scale of developed countries' emissions outsourcing is small, hence there is no clear distinction between developed and developing countries in terms of emissions outsourcing. Most of the developed countries are in fact "insourcing" rather than "outsourcing" emissions (Baumert et al., 2019). Darwili and Schröder (2022) evaluate the net effect of a country's trade on foreign emissions – measured by the gap between foreign emissions avoided by exports and foreign emissions generated by imports – and discover that many of the developed countries are in fact net avoiding foreign emissions. By using the emissions embodied in bilateral trade (EEBT) approach, Wu et al. (2022) appraise the net effect of trade on domestic emission and find that the developed countries' decoupling is "genuine". We seek to confirm the claim whether the international trade indeed allows developed countries to reduce domestic emissions, which then increases the emissions in the rest of the world. We do this by evaluating the net effect of trade on domestic emissions as the *net emissions onshoring* (NetOn), measured by the difference between the domestic emissions generated by exports (EEX) and domestic emissions avoided by imports (EAM). We use the multi-regional input-output (MRIO) model to measure the conventional emission accounts and implement our technology-adjustment method to measure the emissions avoided by imports.

We are not the first to bring the concept of emissions avoided by trade and to evaluate the impact of trade on domestic emissions. By using MRIO tables, Chen and Chen (2011), Zhang et al. (2017), and López et al. (2018) examine the significance of Pollution Haven Hypothesis (PHH) on the global level and evaluate whether the observed trade flows reduce global emissions as opposed to a hypothetical no-trade scenario. Other studies investigate the emissions avoided by trade on country and regional levels. Arto et al. (2014) assess the domestic emissions avoided by Spain's imports for the period 1995-2007. Ackerman et al. (2007) use the 1995 Input-Output Table to estimate the domestic emissions avoided by imports in Japan-US trade. Similarly, Dietzenbacher and Mukhopadhyay (2007) and Peters et al. (2007) evaluate the case for India and China, subsequently. Wu et al. (2022) use the same concept of the emissions avoided by imports but differ from the previous studies, in that they investigate the net contribution of trade on domestic (i.e. production-based) emissions. To evaluate whether decoupling is not an illusion, they observe whether the PBE differ when the offshoring (i.e. the emissions avoided by imports) is taken into account. Our aim is similar to that of Wu et al. (2022), we want to evaluate the net effect of trade on domestic emissions by using the MRIO (instead of the EEBT model).

The EEBT and MRIO differ in the allocation of intermediate imports used to produce exports. The EEBT model allocates imports of intermediate and final products to the importing countries, even if the intermediate imports will later be re-exported. The MRIO passes-on the imported intermediate products until it is eventually embodied in the final consumption (Ferng, 2003; Peters, 2007, 2008b). Thus, the EEBT does not split the bilateral trade flow into components of intermediate and final consumption. The MRIO, on the other hand, distinguishes between trade that goes into intermediate and final consumption. This difference is consequential because what comprises 'production technique' (i.e. technical coefficient matrix) of a country differs between the EEBT and MRIO. The EEBT recognizes 'production technique' as a set of domestic intermediate inputs required to produce output. The MRIO recognizes 'production technique' as a set of domestic *and* imported intermediate inputs to produce output. For the MRIO model, Motor vehicles, trailers and semi-trailers sector in Germany requires 0.63 dollars worth of inputs per unit worth of output, while for the EEBT model, the same sector in Germany only requires 0.45 dollars. We use to the MRIO model, we want to preserve the endogeneity of the intermediate imports in production matrix as it better reflects "production technology" and aligns with the technology-adjustment method we are about to implement in this study.

The calculated emissions from both the EEBT and MRIO disagree on cross-country allocation of emissions embodied in trade (Peters, 2007, 2008b), because both models differ in the allocation of intermediate imports. To account for EEX, the EEBT does not divide between the emissions embodied in the exported intermediates that return home (then embodied in domestic consumption) and those that do not. The MRIO separates these and accounts for the emissions embodied in products that are not re-imported (that do not return home). To account for EEM, the EEBT accounts only the emissions embodied in *direct* intermediate imports and does not account for the multi-layers intermediate use in the previous stages of intermediate production (we use the term *indirect* for the latter). The MRIO includes the emissions embodied in the indirect intermediate imports. The EEBT does not separate between the emissions embodied in direct and indirect imported intermediates that pass-on to the final consumers in the rest of the world and those that are used to produce final products to be consumed domestically. The MRIO separates these and accounts only those that pass-on to domestic consumers. This can be consequential when accounting for the NetOn because the resulting account of the domestic emissions generated by exports (EEX) and the domestic emissions avoided by imports (EAM) can differ substantially. For this reason, we stick to the MRIO to measure NetOn.

In section 3.2, we discuss the relevant literature and key concepts concerning this study. We explain the concept behind the onshoring and net onshoring of emissions. We also explain why the application of the MRIO in measuring the avoided emissions by imports might be desireable and what the EEBT fails to measure. In section 3.3, we explain the environmentally-extended MRIO model to measure the emissions embodied in exports and imports, and how it is further developed to calculate the emissions avoided by imports.

Section 3.4 discusses the database used in this study and section 3.5 discusses the results. The analysis reveals that the USA, the UK, and India – service-oriented economies with trade deficits – are net offshoring emissions. China is net onshoring emissions, but on a modest scale relative to national production-based emissions. Net onshoring does nto account for the decoupling of national emissions and economic growth observed in many OECD countries in the 21st century. In a cross-section of countries, there is no robust associated between net onshoring and per-capita income.

3.2 Related Literature and Key Concepts

The conventional indicator of emission transfers, the BEET, cannot directly measure the net contribution of trade to domestic emissions, hence to validate the claim on economy-emission decoupling. Jakob and Marschinski (2013) implement the perspective from the classic trade theory to evalute the net effect of trade, this requires answering a but-for question: what would the emissions be without trade? Kander et al. (2015) suggest that to assume for a hypothetical no-trade scenario, one has to consider "what would be the case if a certain commodity were not to be exported from the country in question" (Kander et al., 2015, p. 432). In reality, the counter-factual producer in the absence of trade cannot simply be determined. Thus, the least-demanding assumption presumes the export were to be produced at the world-average emission intensity for the relevant sector. Kander et al. (2015) and Jiborn et al. (2020) adjust only on the export side of the BEET and construct a 'technology-adjusted' consumption-based emissions accounting that gives the incentives for "actions that contribute to reduced global emissions". When adjustment is applied only on one side, the resulting BEET violates scale invariance (Domingos et al., 2016). In carbon accounting scheme, scale invariance ensures the sum of the attributed emissions of an aggregated region equals the sum of the sub-regions within. To satisfy scale invariance, Jiborn et al. (2018) and Baumert et al. (2019) adjust the technology on both the export and import sides. However, the resulting variable becomes difficult to interpret, as there is no clear interpretation for the emissions generated when imports were produced using the world-average technology. To maintain clean interpretation on ex-post analysis of trade and emission flows, Darwili and Schröder (2022) adjust only on the export side and interpret the resulting variable as the *net weak carbon leakage*, that is, the net impact of trade on *foreign emissions*, calculated as the difference between the foreign emissions generated by imports and foreign emissions avoided by exports. In the same spirit, Wu et al. (2022) adjust *only* on the import side of the BEET: the resulting variable becomes the *net onshoring* of emissions, that is, the net impact of trade on *domestic emissions*, calculated as the difference between the domestic emissions generated by exports and the domestic emissions avoided by imports.

Past studies differ in what 'technology adjustment' actually comprises. Kander et al. (2015); Jiborn et al. (2018); Baumert et al. (2019) and Jiborn et al. (2020) adjust for technology by standardizing only direct emission intensities, that is, the ratios of emissions to gross outputs. In input-output analysis, input intensities reflect the production technology (or 'production recipes'). To produce one unit of identical product, a similar industry in two different countries might require different amount of intermediate inputs, which implies different environmental impacts. For this reason, Darwili and Schröder (2022) and Wu et al. (2022) adjust for technology by standardizing both emission intensities and input intensities (the ratios of intermediate inputs to gross outputs) as the "technology". Darwili and Schröder (2022) standardize emission intensities and input intensities to calculate world-average production technology. Wu et al. (2022) replace other countries' production technologies (emission intensities and input intensities) with that of the focus country to assume the imports were produced domestically. We settle for the latter implementation of technology adjustment: production technology includes both emission intensities and input intensities.

In trade, a country onshores emissions by producing exports for the ROW and offshore emissions by avoiding domestic emissions by importing from the ROW. The *net emissions onshoring* (NetOn) compares the domestic emissions generated by exports (EEX) to the domestic emissions avoided by imports (EAM), defined as: NetOn = EEX - EAM. Positive NetOn means that in trade a country generates more than it avoids domestic emissions, in other words, it onshores more than it offshores emissions. Negative NetOn, on the other hand, indicates that a country avoids more than generates domestic emissions. Alternatively, negative NetOn implies a country offshores more than it onshores emissions. An alternative term for EAM we also use in this study is the emission 'offshoring', for it truly captures the amount of domestic emissions being avoided because imports are produced by foreign countries.

3.3 Methods

Our goal is to estimate net emission onshoring, understood as the emissions embodied in exports minus the emissions avoided by imports. The emissions avoided by imports are conventionally calculated on the basis of the EEBT approach. Here we propose a calculation on the basis of the MRIO approach.

As a preliminary step, we introduce the notation for input-output model and the formulas for the emissions embodied in trade. The environmentally-extended MRIO model (Leontief, 1970; Miller and Blair, 2009) can be written in general form for n sectors and m

countries, but for ease of exposition we present the two-country model written compactly as:

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{3.1}$$

On the left-hand side is the global emissions matrix E. The first object on the right-hand side contains the diagonalized global direct emission intensity vector q (the hat denotes diagonalization). The second object on the right-hand side is the global Leontief inverse matrix L, and the third object is the global final demand matrix Y. The objects are composed of sub-matrices and sub-vectors for the countries 1 and 2 (the focus country and the rest of the world). Country 1's emissions embodied in exports are given by:

$$EEX^1 = e^{12} = \hat{q}^1 L^{11} y^{12} + \hat{q}^1 L^{12} y^{22} \tag{3.2}$$

Net emission transfers are given by $BEET^1 = EEX^1 - EEM^1$, where EEM^1 represent the emissions embodied in imports ($e^{21} = \hat{q}^2 L^{21} y^{11} + \hat{q}^2 L^{22} y^{21}$). When the BEET is positive ($EEX^1 > EEM^1$), the focus country net transfers emissions to the ROW.

We are interested in the emissions avoided by imports, meaning the emissions that focus country producers would generate if they produced the foreign products consumed by focus country end-users. We postulate that imports are produced on the basis of the focus country's emission intensities and production recipes. The meaning of "production recipe" is slightly different in the EEBT model and the MRIO model. In the EEBT model, a sector's production recipe is given by n technical coefficients, which reflect inputs from producing sectors in the focus country. In the MRIO model, a sector's production recipe is given by $n \cdot m$ technical coefficients, which reflect inputs from producing sectors in the focus country and the ROW. As an example, consider Germany's automotive sector using intermediate inputs from German and foreign producers. Given our MRIO approach, we regard all sectors supplying inputs to Germany's automotive sector as part of Germany's automotive value chain. The production recipe of Germany's automotive sector includes inputs from producers located abroad.

To estimate the emissions avoided by imports, we adjust the MRIO model:

$$\begin{bmatrix} \dot{e}^{11} & \dot{e}^{12} \\ \dot{e}^{21} & \dot{e}^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^1 \end{bmatrix} \begin{bmatrix} \dot{L}^{11} & \dot{L}^{12} \\ \dot{L}^{21} & \dot{L}^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix} \tag{3.3}$$

The equation system (3.3) reflects the focus country's production recipes. The focus country's (country 1's) emission intensities, $\hat{q}^1$, have replaced the ROW's (country 2's) emission intensities, $\hat{q}^2$. The adjusted Leontief inverse, $\dot{L}$, has replaced the Leontief inverse, L. The adjustment to the Leontief inverse is explained further below. The formula for country 1's emissions avoided by imports is:

$$EAM^1 = \dot{e}^{21} = \hat{q}^1 \dot{L}^{21} y^{11} + \hat{q}^1 \dot{L}^{22} y^{21} \tag{3.4}$$

It is analogous to the formula for the emissions embodied in imports, but it uses $\hat{q}^1$ and $\dot{L}$ in place of $\hat{q}^2$ and L.

Net emission onshoring is defined as:

$$NetOn^1 = EEX^1 - EAM^1 \tag{3.5}$$

Net onshoring compares the focus country's observed emissions generated by domestic production for foreign final demand ("emission onshoring") and the focus country's hypothetical emissions that would have been generated had the focus country satisfied its final demand for foreign products through the technology of its own value chains ("emission offshoring"). When $NetOn > 0$, the focus country is net onshoring emissions.

3.3.1 Details on the Adjusted Leontief Inverse

The adjusted Leontief inverse is based on a decomposition, which was first introduced by Xu and Dietzenbacher (2014) and is explained in the original paper and in this section[1].

We decompose a sector's production recipe into the product of *n technological coefficients*, which represent the intermediate input requirements regardless of geographical origin; and *m* import shares, which represent the shares of a given intermediate input in the total intermediate inputs required.

Let a_{ij}^{sr} be an element of the global technical coefficient matrix A, representing the purchase of intermediate input by sector j in country r from sector i in country s. The sum over all supplying countries s yields the technological coefficient:

$$h_{ij}^r = \sum_{s=1}^{m} a_{ij}^{sr} \tag{3.6}$$

These coefficients are collected in country r's technological coefficient matrix H^r, which has the dimension $n \times n$:

$$H^r = \sum_{s=1}^{m} A^{sr} \tag{3.7}$$

where A^{sr} is a sub-matrix of the global technical coefficient matrix A with the dimension

[1]This decomposition method is also used in chapter 2

$n \times n$.

The trade structure matrix of the intermediate inputs reflecting the origin (geographical composition) is given by:

$$T = \begin{bmatrix} T^{11} & \cdots & T^{1m} \\ \vdots & \ddots & \vdots \\ T^{m1} & \cdots & T^{mm} \end{bmatrix} \tag{3.8}$$

Each element in the trade structure matrix represents the share of every input i in country r that is required by sector j in country r:

$$t_{ij}^{sr} = a_{ij}^{sr} / h_{ij}^{r} \tag{3.9}$$

The sum over all supplying countries s adds up to one.

The global technical coefficient matrix can be written as ($\otimes$ represents the Hadamard product of element-wise multiplication):

$$A = \begin{bmatrix} T^{11} \otimes H^{1} & \cdots & T^{1m} \otimes H^{m} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes H^{1} & \cdots & T^{mm} \otimes H^{m} \end{bmatrix} \tag{3.10}$$

To capture the idea that country 1's imports are produced using the technology of country 1's value chains, the foreign technological coefficients are replaced by country 1's technological coefficients, H^1, resulting in the adjusted global technical coefficient matrix $\dot{A}$:

$$\dot{A} = \begin{bmatrix} T^{11} \otimes H^{1} & \cdots & T^{1m} \otimes H^{1} \\ \vdots & \ddots & \vdots \\ T^{m1} \otimes H^{1} & \cdots & T^{mm} \otimes H^{1} \end{bmatrix} \tag{3.11}$$

The adjusted Leontief inverse follows as $\dot{L} = (I - \dot{A})^{-1}$. It is used in system (3.3). The emissions avoided by imports are calculated on the basis of system (3.3) and reflect the focus country's emission intensities and production recipes.

3.4 Data

We use the 2021 edition of the OECD Inter-Country Input-Output (ICIO) Table (OECD, 2021). This database provides the monetary industry-by-industry transactions between 1995-2018 for 45 sectors and 66 countries (93% of global GDP) and a ROW aggregate. It includes 38 OECD countries and 28 non-OECD economies.

The vector of the direct emission intensity by sector comes from OECD (2022). The emission intensity is measured in tonnes per million USD. The emission intensities are based on the IEA's CO2 Emissions from Fossil Fuel Combustion (IEA, 2018) and their construction is described in Yamano and Guilhoto (2020). Direct emissions from household consumption (e.g. fuel combustion in private cars) are given separately. These emissions are part of a country's PBE and CBE, but not part of traded emissions.

We complement the IO data with population and gross domestic product (GDP) variables from the Penn World Table Version 10 (PWT10, Feenstra et al. (2015)). We calculate income per capita by dividing the output-side real GDP at chained PPPs in 2017 US$ by population.

The complete data set covers 66 countries between 1995-2018.[2] We exclude small countries from the analysis because the domestic technology assumption is most appropriate for large economies capable of producing most of the products consumed (we return to this issue in section 3.5). We set the small-country threshold at a 2018 population of 7.5 million people.[3] The final sample includes 45 countries.

3.5 Results and Discussion

3.5.1 Net Emission On/Off-Shoring Over Time

Figure 3.5.1 plots the evolution of net emission onshoring and the conventional emission balance (BEET) in six major economies from 1995–2018: two large developed countries with trade deficits and large service sectors (the USA and the UK), two large developed countries with export orientation and large manufacturing sectors (Japan and Germany), and the two largest developing countries (China and India). The USA and China are polar opposites: the USA net offshores emissions, meaning the Americans avoid more emissions by importing than they generate by exporting; while China net onshores emissions, meaning the Chinese generate more emissions by exporting than they avoid by importing. The BEET has attracted a lot of attention, and indeed the magnitudes are large in both countries. Net onshoring, by contrast, occurs on a smaller scale. At the beginning of the analysis period and towards the end, China neither onshores emissions nor offshores emissions in net terms (net onshoring is essentially zero in 1995 and 2018).

[2]The Supplementary Material lists all countries and all sectors (Table 3.A.1 and Table 3.A.2).

[3]In the interest of transparency: we initially set the threshold at a nice and round 10 million. We lowered the threshold after noticing it would exclude Sweden and Switzerland. Both countries are worth studying on account of their trade-intensive economies with exceptionally clean energy systems.

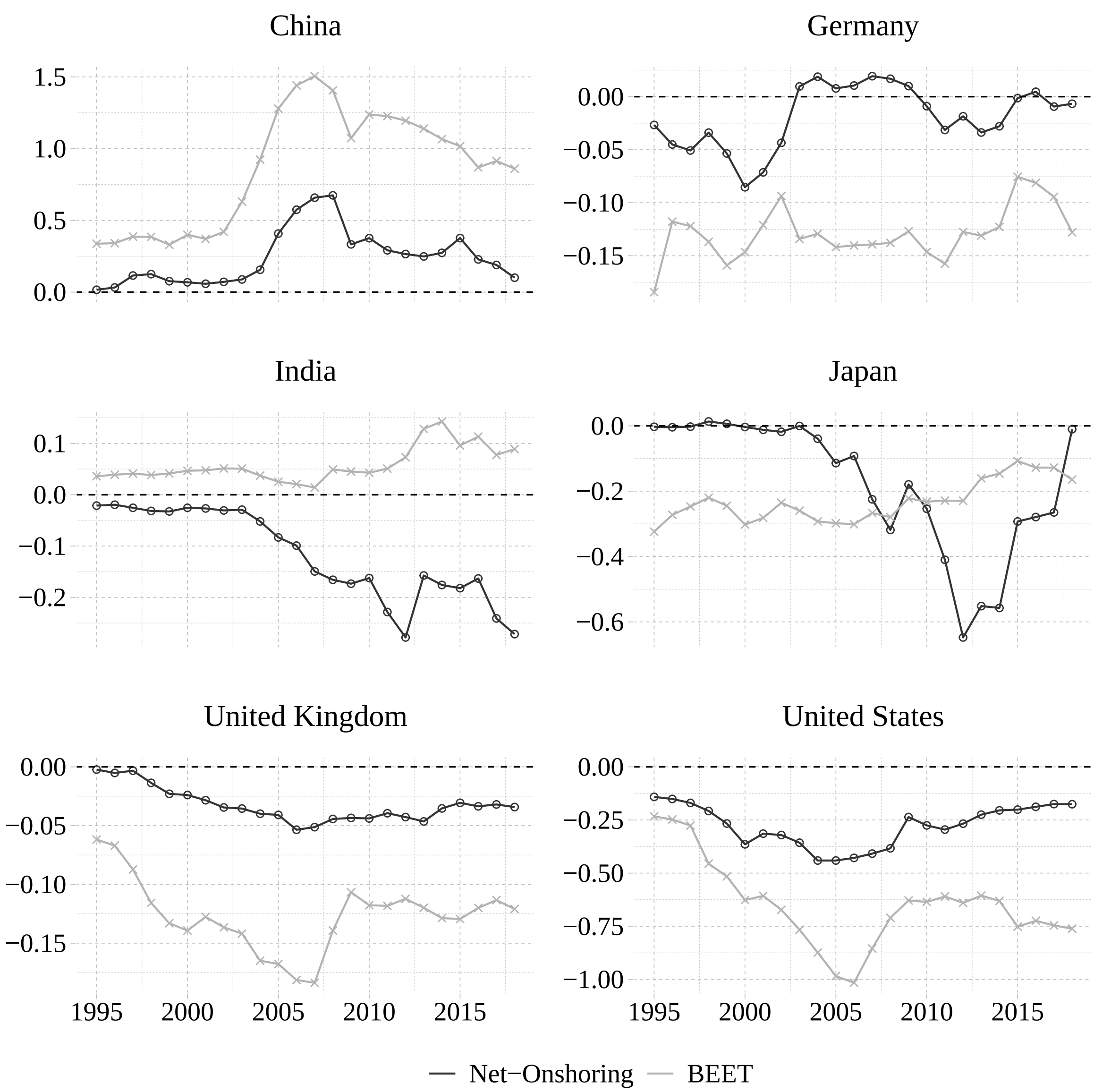


Figure 3.5.1: Net onshoring and the BEET in six major economies 1995–2018, $GtCO_2$

Notes: own calculations. Net onshoring represents the difference between the emissions embodied in exports and the emissions avoided by imports. The BEET represents the difference between the emissions embodied in exports and the emissions embodied in imports.

In China and Germany, the big trade-surplus countries, changes in net onshoring roughly track changes in the trade balance: net onshoring increases along with the emergence of the trade surpluses in the early 2000s. Yet, at the end of the analysis period, neither of the two trade-surplus economies is onshoring emissions. Germany would be net onshoring emissions if not for the contribution of the energy mining sector.[4] Germany's tiny energy mining sector operates with a high emission intensity (relative to other sectors in Germany and relative to the same sector in other countries). The high emission intensity combines with a relatively large quantity of imported energy products, so that on balance the sector helps Germany to avoid emissions.

India is an interesting case: the BEET is positive, as is typical in many developing countries, but India is net offshoring emissions throughout the analysis period. The observed trade flows are in effect reducing India's production-based emissions. We expect to see this pattern in an economy exporting services (low emission intensity) and importing manufactured goods and raw materials (high emission intensity). A decomposition analysis to quantify the importance of trade-balance effects and composition effects is beyond the scope of this paper. In general, a trade-deficit country produces less than it consumes; ceteris paribus, it will net offshore emissions. The USA and the UK are service-oriented economies running persistent trade deficits; as expected, they are net offshoring emissions.

As in Germany, energy products also play an important role in Japan's (somewhat peculiar) net onshoring trend. The energy mining sector is small and its emission intensity is extremely high. The share of energy in Japan's total imports was rising, with peaks in 2008 and 2012, when oil prices were high. By 2018, the share of energy products in Japanese imports had returned to the levels recorded at the beginning of the analysis period.

Domestic-Technology CBE

Do national emission trends change when we adjust for emission onshoring and offshoring? To explore the question, we adjust the PBE by adding the offshored emissions and subtracting the onshored emissions:

$$\text{Domestic-technology CBE} = \text{PBE} - \text{Net Onshoring} \tag{3.12}$$

The "domestic-technology CBE" represent the emissions the focus country would record if it did not produce its exports (products consumed by foreign end-users) and instead produced its imports (product consumed by domestic end-users).

The domestic-technology CBE and the PBE are both increasing in India and China,

[4] OECD-ICIO sector title and code: "Mining and quarrying, energy producing products" (D05T06).

are decreasing in Germany, and are first increasing and then decreasing in the USA and the UK (Figure 3.5.2). Overall, the two variables are highly correlated and display the same trends. This is not surprising, because the magnitude of net onshoring is small in relation to PBE. Accounting for net onshoring does not dramatically change national emission trends.

Japan is an unusual case. The country demonstrates the limits of the domestic technology assumption. Japan is notoriously scarce in natural resources, meaning it cannot, and does not, produce the imported energy products in significant quantities.[5] The energy mining sector is tiny, its input-output coefficients are volatile. The coefficients probably do not reflect the technology that would be employed if Japan mined energy products at much larger scales. To be clear, all applications of the domestic technology assumption face this problem, including all studies estimating the balance of avoided emissions (Ackerman et al., 2007; Dietzenbacher and Mukhopadhyay, 2007; Arto et al., 2014; Wu et al., 2022). The domestic technology assumption is most appropriate for large, diversified economies producing most of the products consumed. Japan's economy is large and diversified in comparison with many other economies; still, the energy mining sector appears to be a crucial determinant of net onshoring.

3.5.2 Net Emission On/Off-Shoring Across Countries

There is a well-known negative association between per-capita income and the BEET. The BEET tends to be lower in rich countries (Davis and Caldeira, 2010; Peters et al., 2011). The right column of Figure 3.5.3 plots the cross-country relationship in the years 1995, 2007, and 2018. Recall that the BEET compares the emissions embodied in exports and the emissions embodied in imports. The BEET is largely driven by international technology differences: countries with relatively clean energy sectors and low intermediate inputs requirements tend to record negative BEETs (Jakob and Marschinski, 2013). The cross-country pattern is easily explained: in general, production is more efficient in advanced economies and, moreover, energy systems become cleaner over the course of development as countries climb up the "energy ladder". The energy mix tends to become less carbon-intensive as coal is replaced first by oil and then by gas, nuclear power, as well as wind and solar (e.g. Burke, 2013).[6]

For the same years, the left column of Figure 3.5.3 plots the relationship between per-capita income and net onshoring. There is a positive association between the two variables, but it is a weak relationship. Table 3.5.1 reports the cross-country regressions corresponding

[5] In the jargon of input-output analysis, the energy products can be viewed as non-competing imports.

[6] At very low income levels, economic growth may increase the energy system's carbon intensity as fossil fuels replace traditional energy. Our data set does not include low-income countries.

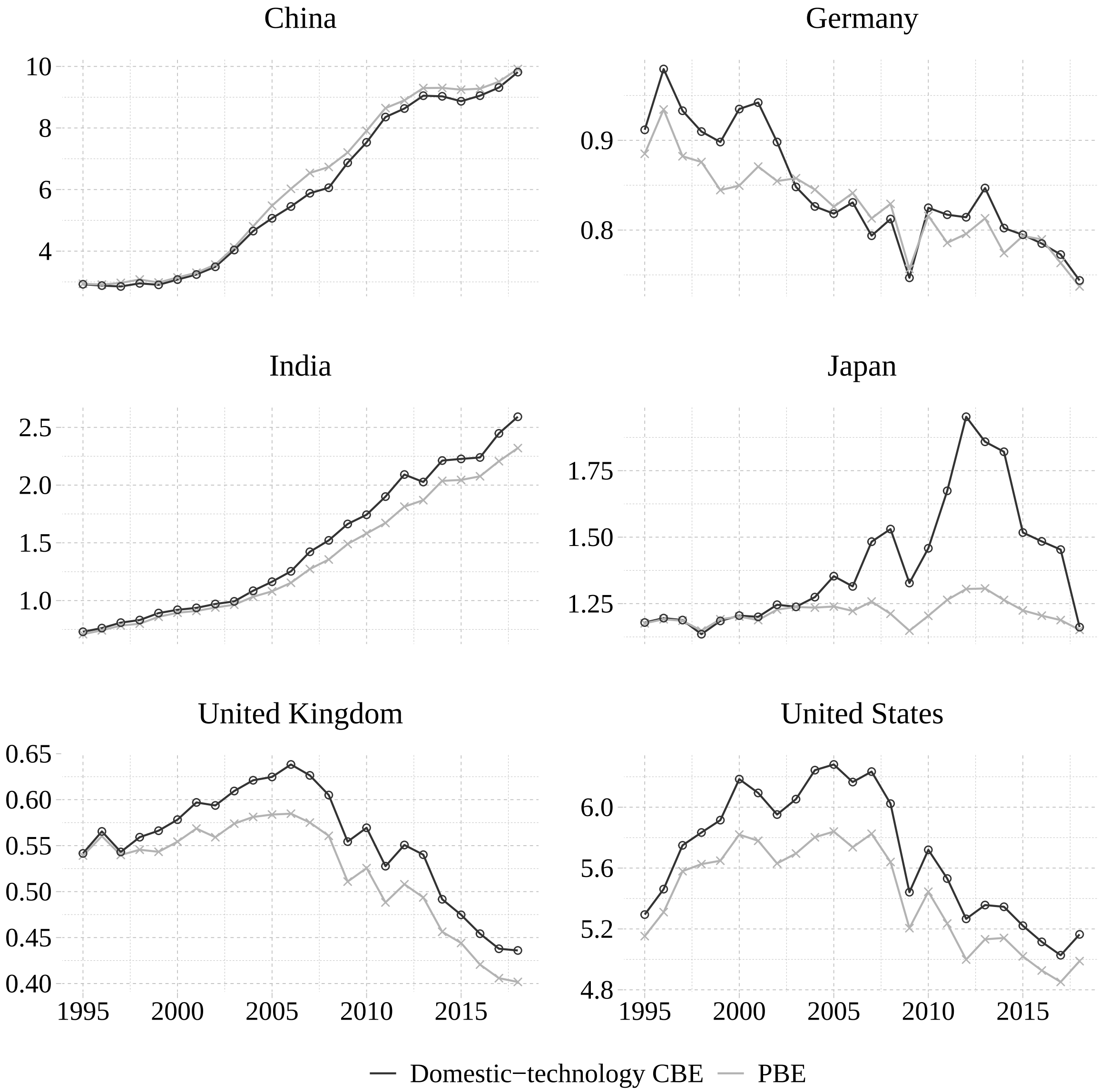


Figure 3.5.2: National emissions, $GtCO_2$

Notes: own calculations. PBE = production-based emissions. Domestic-technology CBE represent PBE minus the emissions embodied in exports plus the emissions avoided by imports.

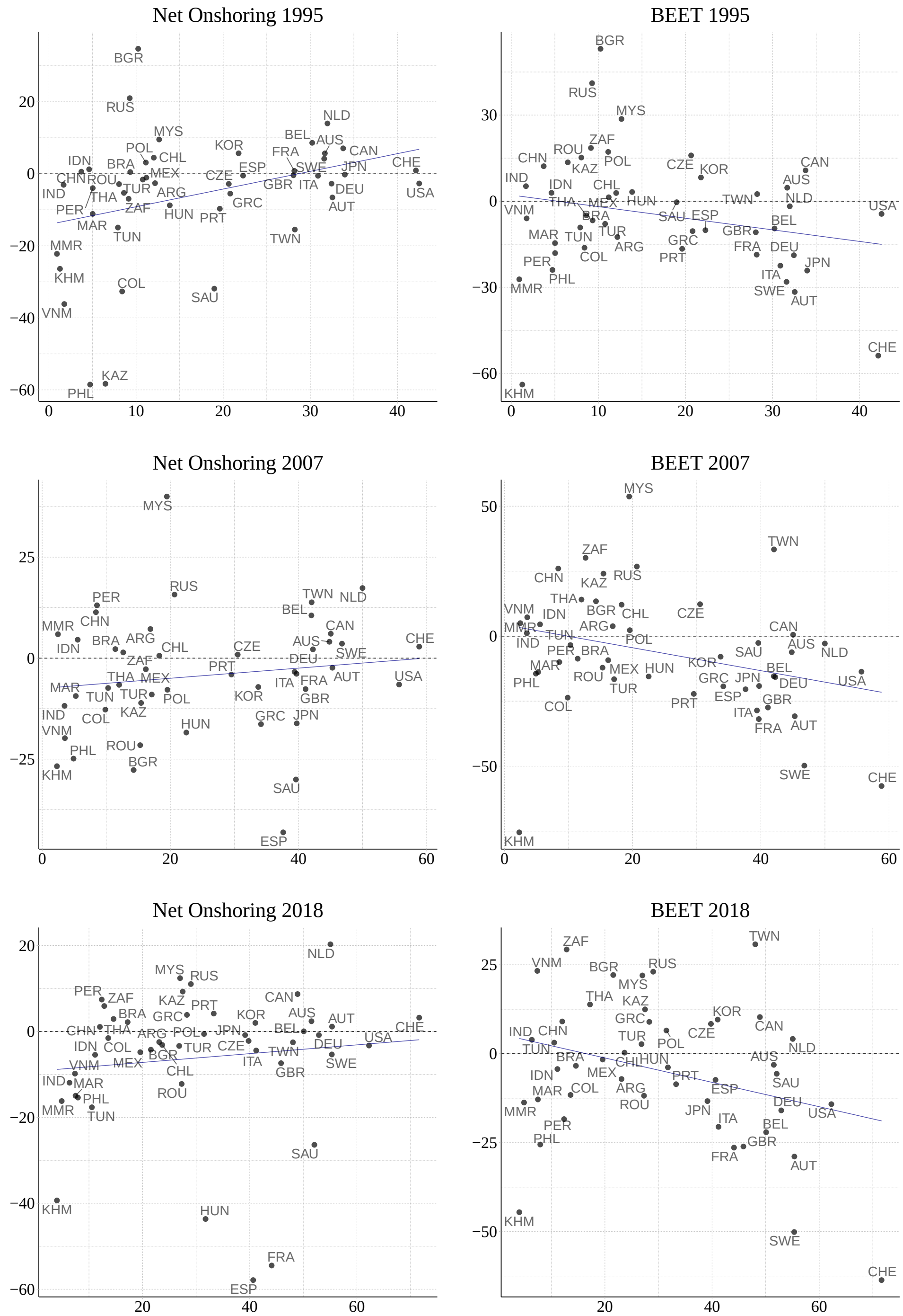


Figure 3.5.3: Net Onshoring (and the BEET) vs. Income per Capita

Notes: own calculations. The BEET and net onshoring are expressed in percent of emissions (the mean of PBE and CBE). Income per capita is expressed in thousand PPP-adjusted US$. Small countries are excluded.

to the lines in Figure 3.5.3.[7] The cross-country variation in net onshoring can hardly be explained by income, and only in 1995 is the correlation statistically significant ($\alpha = 0.05$). The largest slope coefficient (in column 1) is still small: 0.49 means that one thousand dollars higher per-capita income is associated with half a percentage point higher net onshoring.

Theoretically grounded and empirically robust theories that could explain the cross country pattern are hard to come by. The Pollution Haven Hypothesis (PHH) implies that countries with strict environmental regulations import emission-intensive ("dirty") products and countries with lax environmental regulations export them (Copeland and Taylor, 1994; Taylor, 2005). Environmental regulations tend to be strict and tightly enforced in rich countries and lax and loosely enforced in poor countries. Therefore, according to the hypothesis, rich countries import dirty products and poor countries export them, meaning rich countries should be net offshoring emissions (assuming balanced trade). The econometric evidence, on the whole, does not support the PHH (Taylor, 2005; Copeland et al., 2022). The PHH cannot explain the cross-country net onshoring pattern – if anyting, rich countries are net onshoring emissions (Figure 3.5.3 and Table 3.5.1).[8]

The scatter plots and cross-country regressions should not be misunderstood as exercises designed to test the PHH, or more generally to test the Heckscher-Ohlin factor-endowment theory of comparative advantage and international trade. The net onshoring variable reflects monetary trade imbalances while the pure theory of trade abstracts from trade imbalances.[9]

3.6 Summary and Concluding Remarks

We focus on net onshoring and apply the domestic technology assumption to estimate the variable. Once international technology differences are eliminated, only the composition of economic activity and the overall trade balance determine net onshoring. We find that

[7] We estimate the models $NetOn_i = \beta_0 + \beta_1 Income_i + u_i$ and $BEET_i = \beta_0 + \beta_1 Income_i + u_i$ by OLS based on cross-sectional data from the year 1995, 2007, or 2018. $Income$ refers to PPP-adjusted GDP per capita in thousand international dollars. Net onshoring and the BEET are expressed in percent of emissions, which are calculated as the simple mean of PBE and CBE. The reported standard errors are robust with respect to heteroskedasticity.

[8] The PHH can be viewed as an application of the Heckscher-Ohlin theory of comparative advantage, which holds that a country specializes in the products that intensively use the abundant production factor. Lax environmental regulations are tantamount to an abundance of natural capital (the use of which generates emissions) and thus imply specialization in dirty products. However, dirty products tend to be capital-intensive. As rich countries are abundant in produced capital, a theory of specialization based on factor endowments can also generate the prediction that rich countries export dirty products (Antweiler et al., 2001)

[9] Dietzenbacher and Mukhopadhyay (2007) "control" for trade imbalance by scaling exports and imports to one dollar each, and they reject the PHH using the national input-output table for India.

Table 3.5.1: Cross-country regressions of net onshoring on income per capita

	Net Onshoring			BEET		
	(1)	(2)	(3)	(4)	(5)	(6)
	1995	2007	2018	1995	2007	2018
Income	0.491**	0.126	0.102	−0.404	−0.441**	−0.343*
	(0.205)	(0.135)	(0.136)	(0.262)	(0.209)	(0.162)
Constant	−14.062***	−7.492	−9.247*	2.148	4.345	5.662
	(4.292)	(4.066)	(4.839)	(5.463)	(6.291)	(5.784)
N	45	45	45	45	45	45
R squared	0.117	0.020	0.013	0.053	0.093	0.094

Notes: own calculations. Simple OLS regressions of net onshoring (and the BEET), expressed in percent of emissions (the mean of PBE and CBE), on per-capita income in thousand PPP-adjusted US$. The standard errors in parentheses are heteroskedasticity-robust (Huber-White). * indicates $p<0.1$; ** $p<0.05$; and *** $p<0.01$.

service-oriented economies running trade deficits, e.g., the USA, UK, and India, are net offshoring emissions. These countries record lower emissions than they would if they ceased to produce for foreign final demand and instead satisfied their final demand through domestic production. They benefit from trade in the sense that the observed trade flows are reducing the policy-relevant production-based emissions.

In a cross-section of countries, there is no robust association between net onshoring and per-capita income. Some OECD countries are net offshoring emissions (e.g., the USA) while other OECD countries are net onshoring emissions (e.g., the Netherlands); some developing countries are net offshoring emissions (e.g., India) while other developing countries are net onshoring emissions (e.g., China). The scale of emission on- and off shoring is relatively small in net terms.

Net onshoring does not change national emission trends. Consumption-based emissions, when estimated using the domestic technology assumption (“domestic-technology CBE”), behave similarly as production-based emissions. National emissions have peaked in many OECD countries (Quéré et al., 2019), while they are rising in the developing countries.

Appendix

3.A Other Results and Supplementary Information

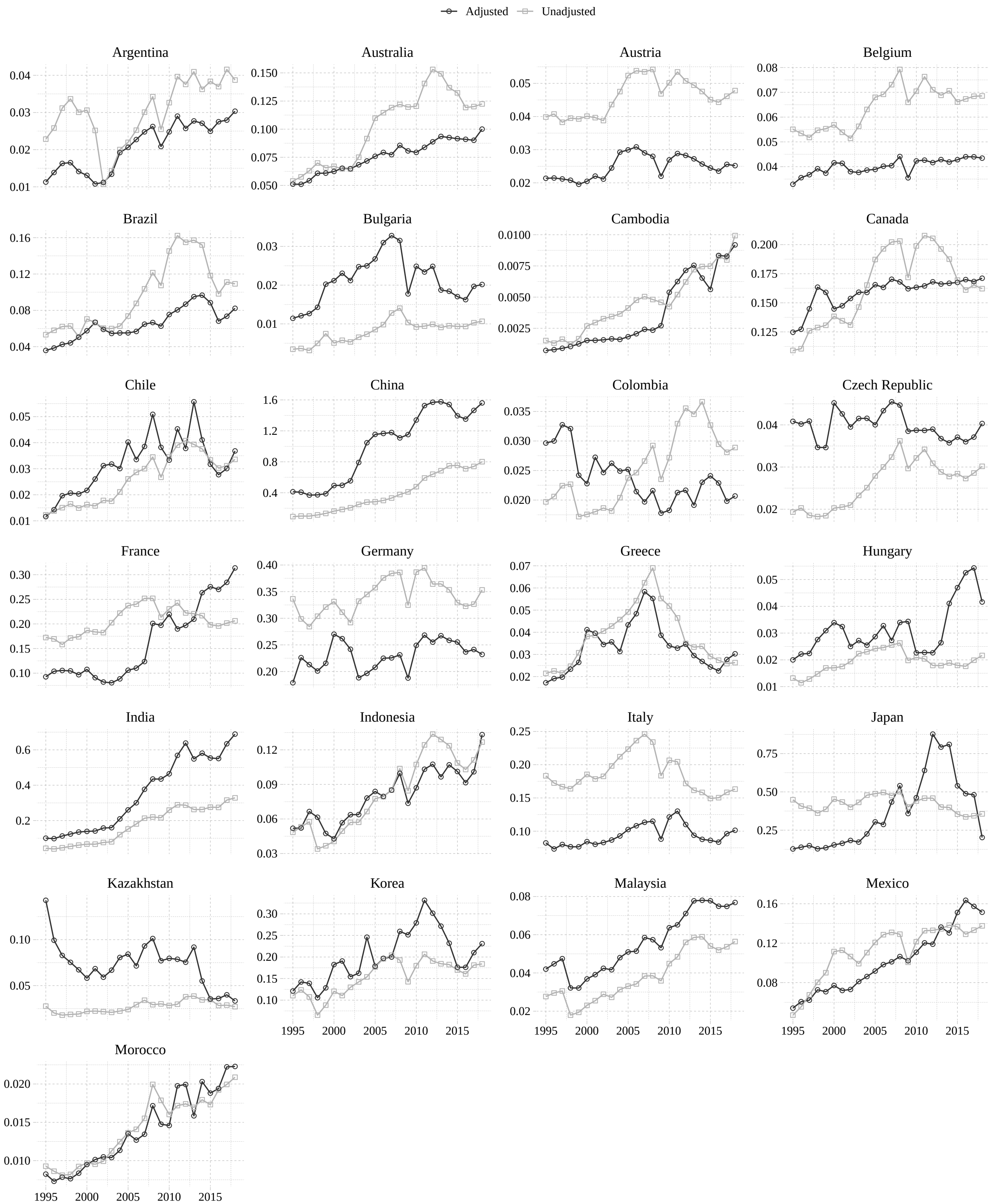


Figure 3.A.1: Emissions Embodied in Imports 1995–2018, line plots by country

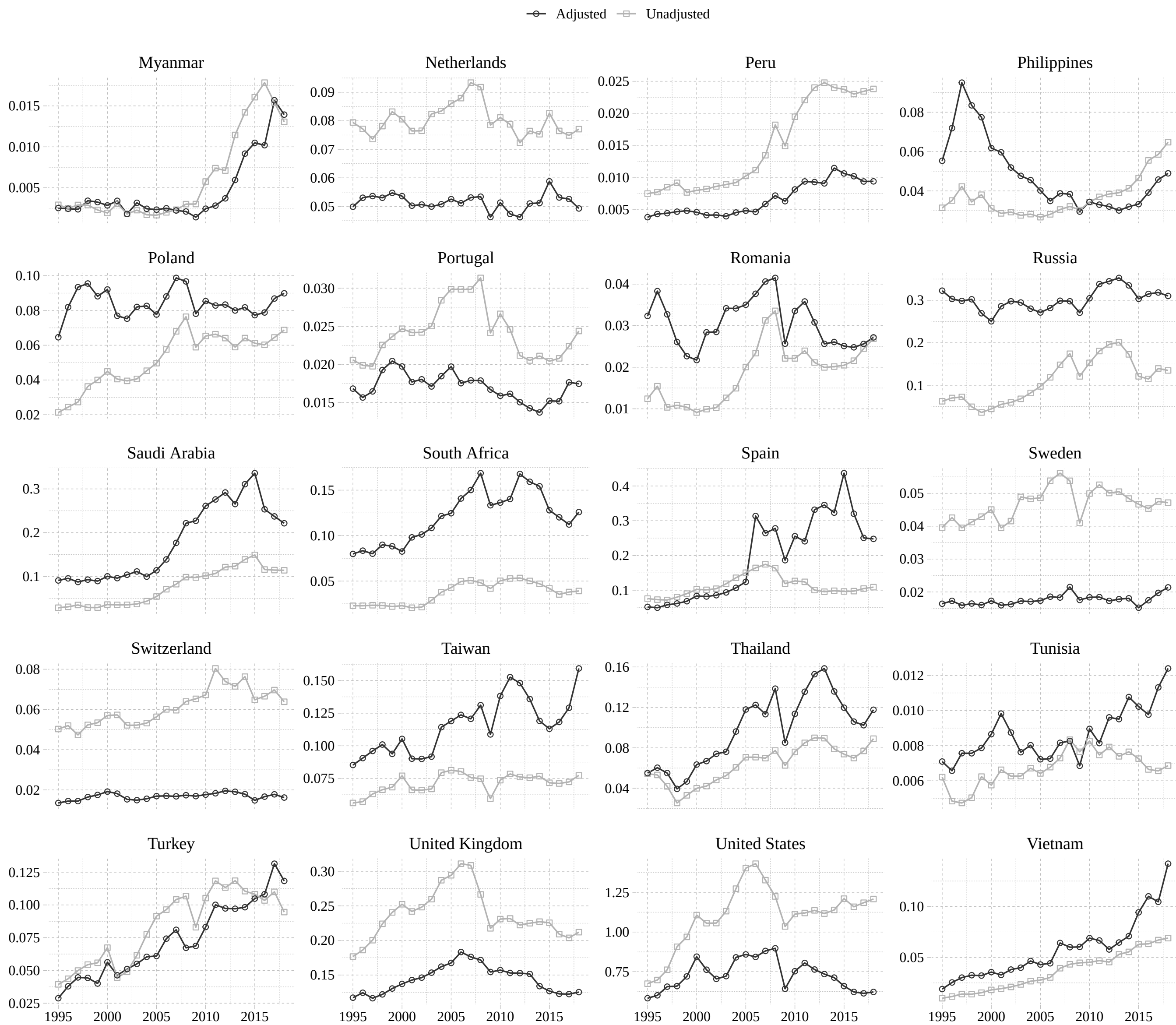


Figure 3.A.1: Emissions Embodied in Imports 1995–2018, line plots by country *(continued)*

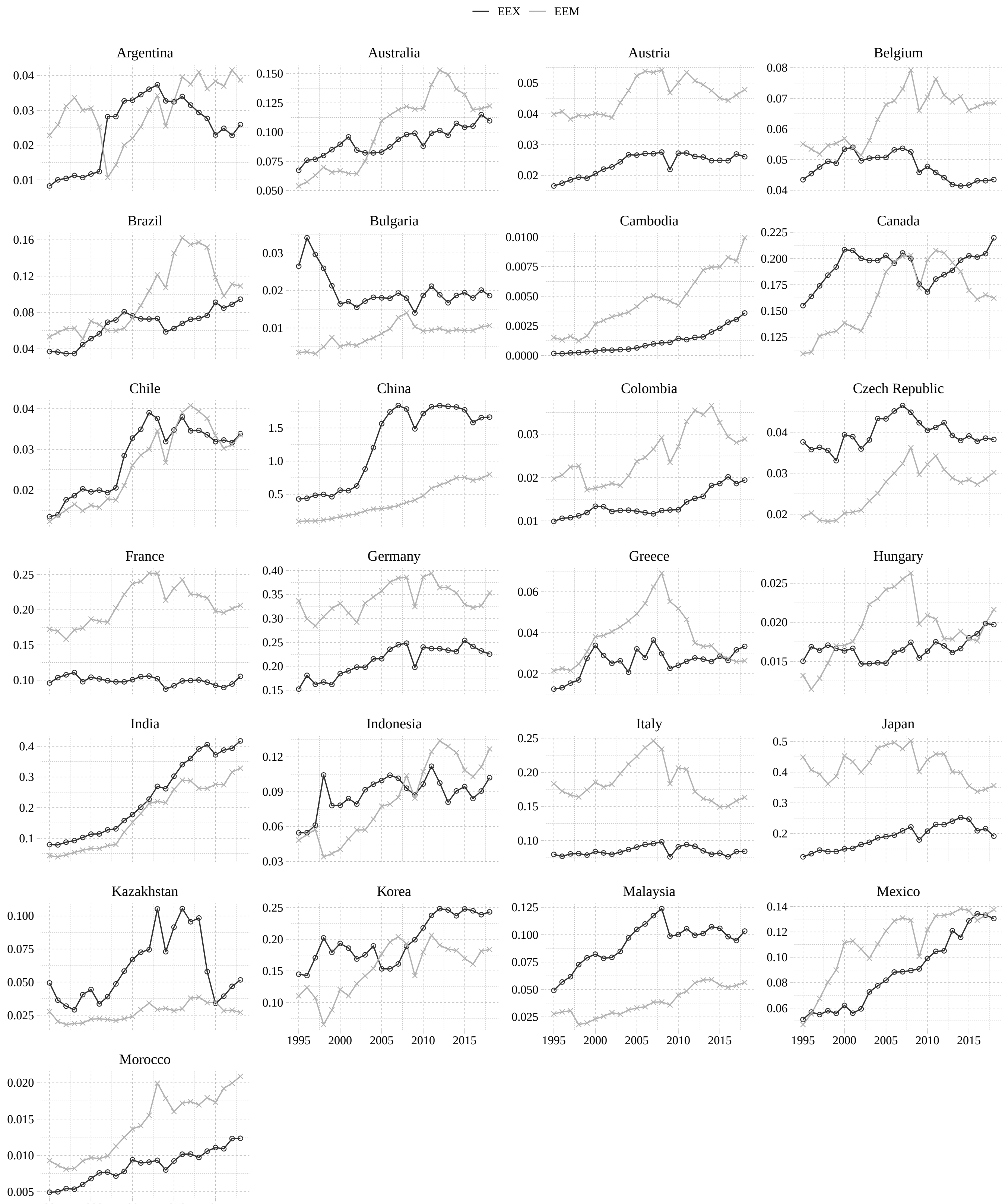


Figure 3.A.2: Emissions Embodied in Trade 1995–2018, line plots by country

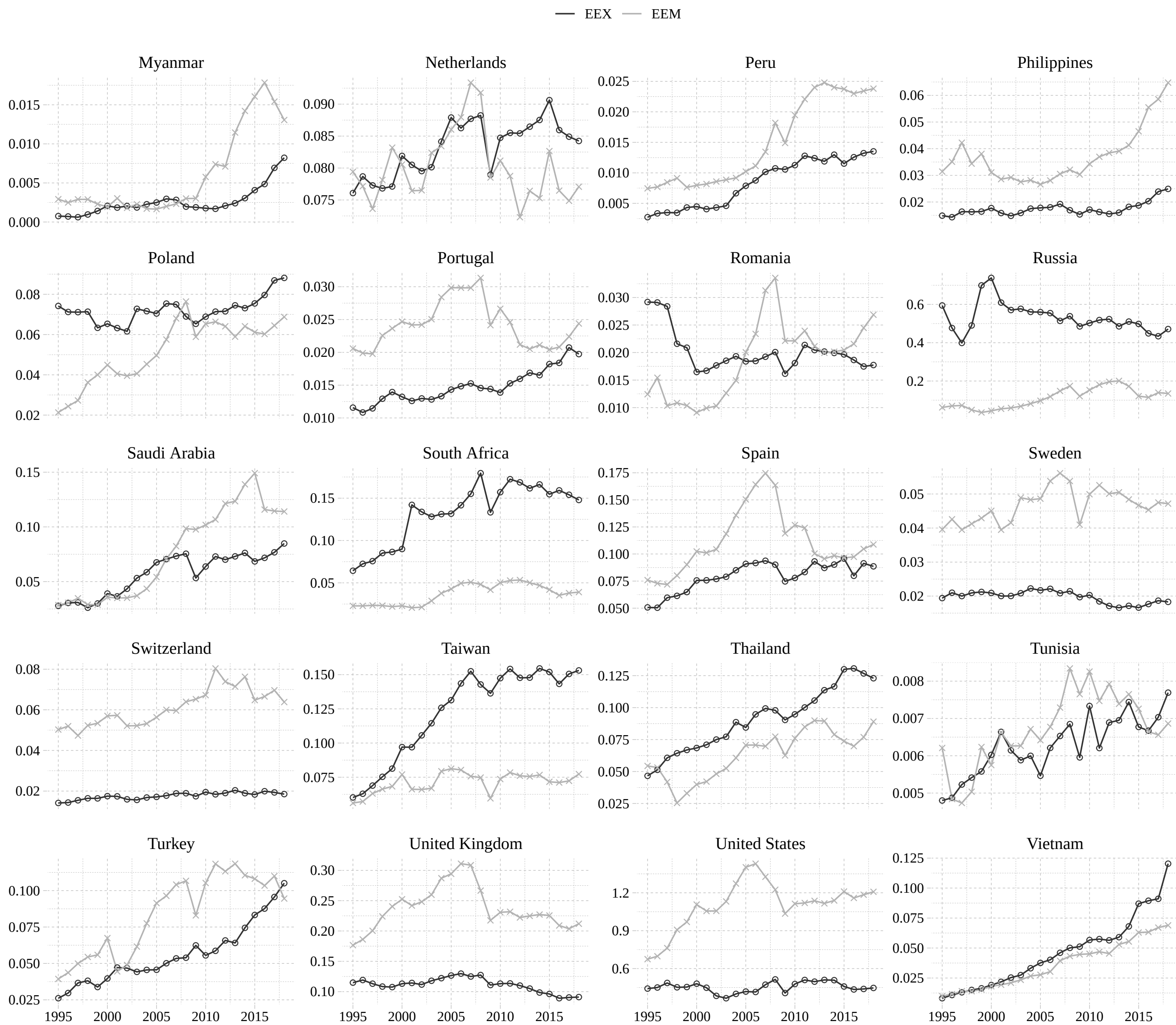


Figure 3.A.2: Emissions Embodied in Trade 1995–2018, line plots by country *(continued)*

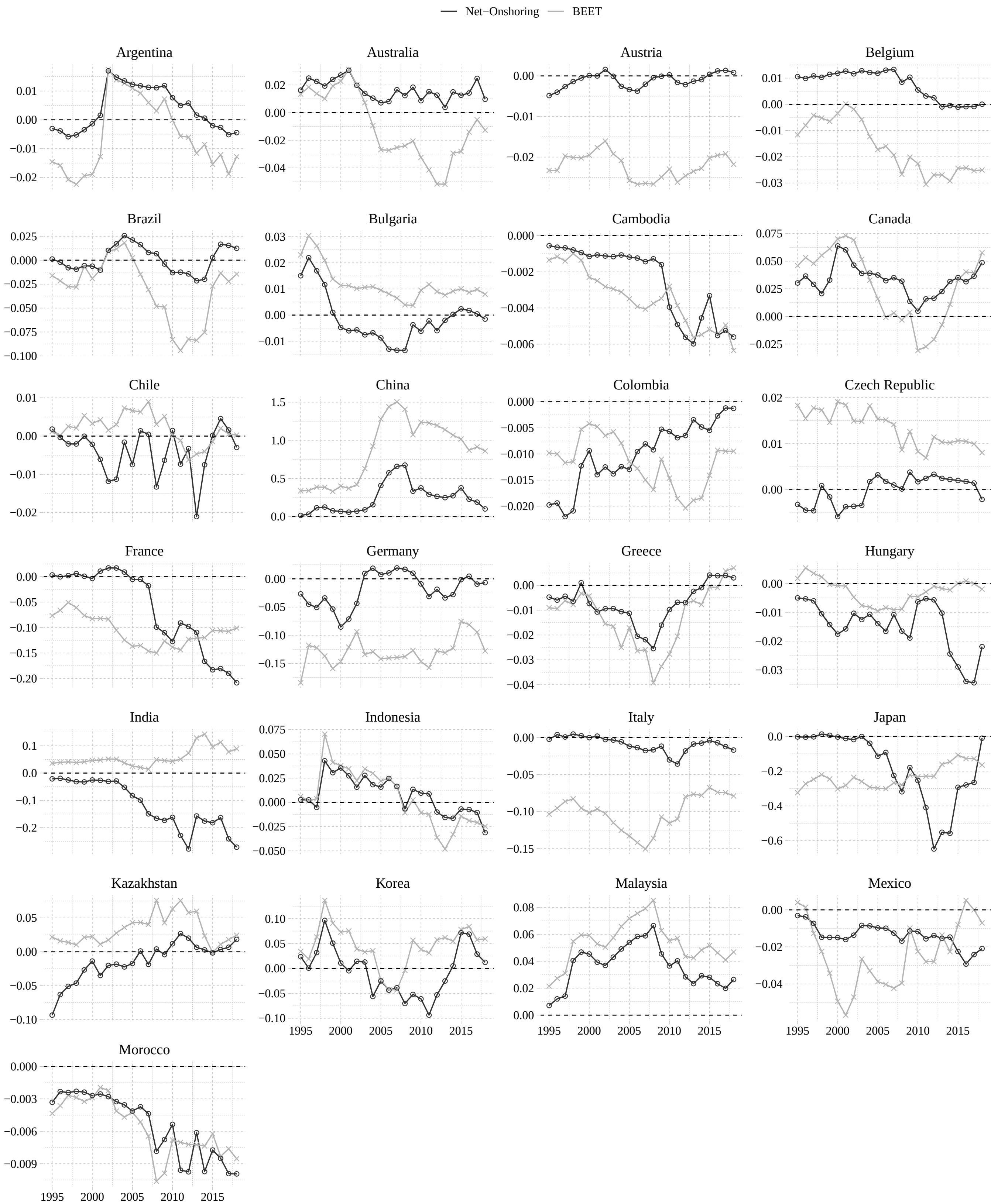


Figure 3.A.3: Balance of Emissions Embodied in Trade 1995–2018, line plots by country

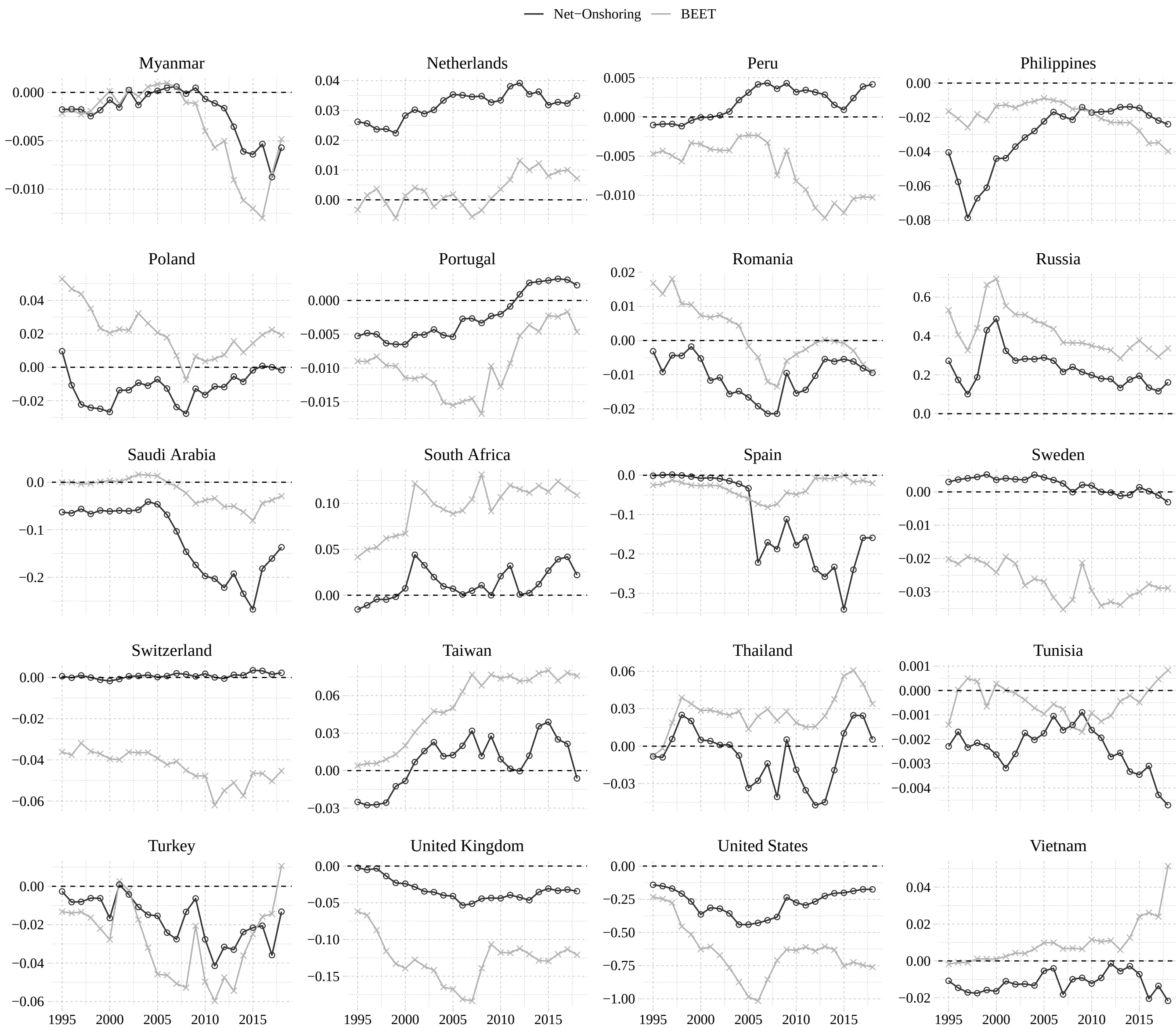


Figure 3.A.3: Balance of Emissions Embodied in Trade 1995–2018, line plots by country *(continued)*

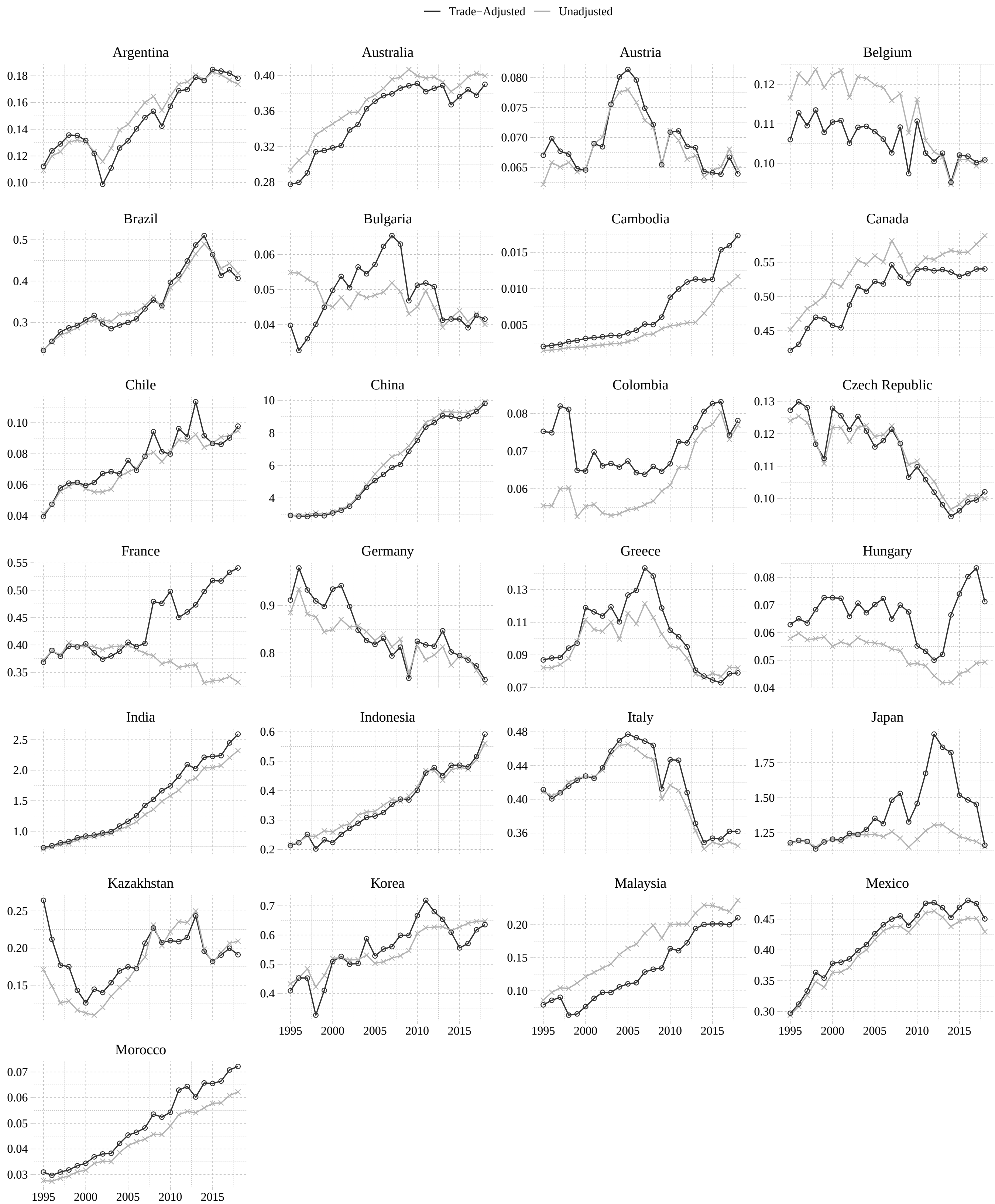


Figure 3.A.4: Production-Based Emissions 1995–2018, line plots by country

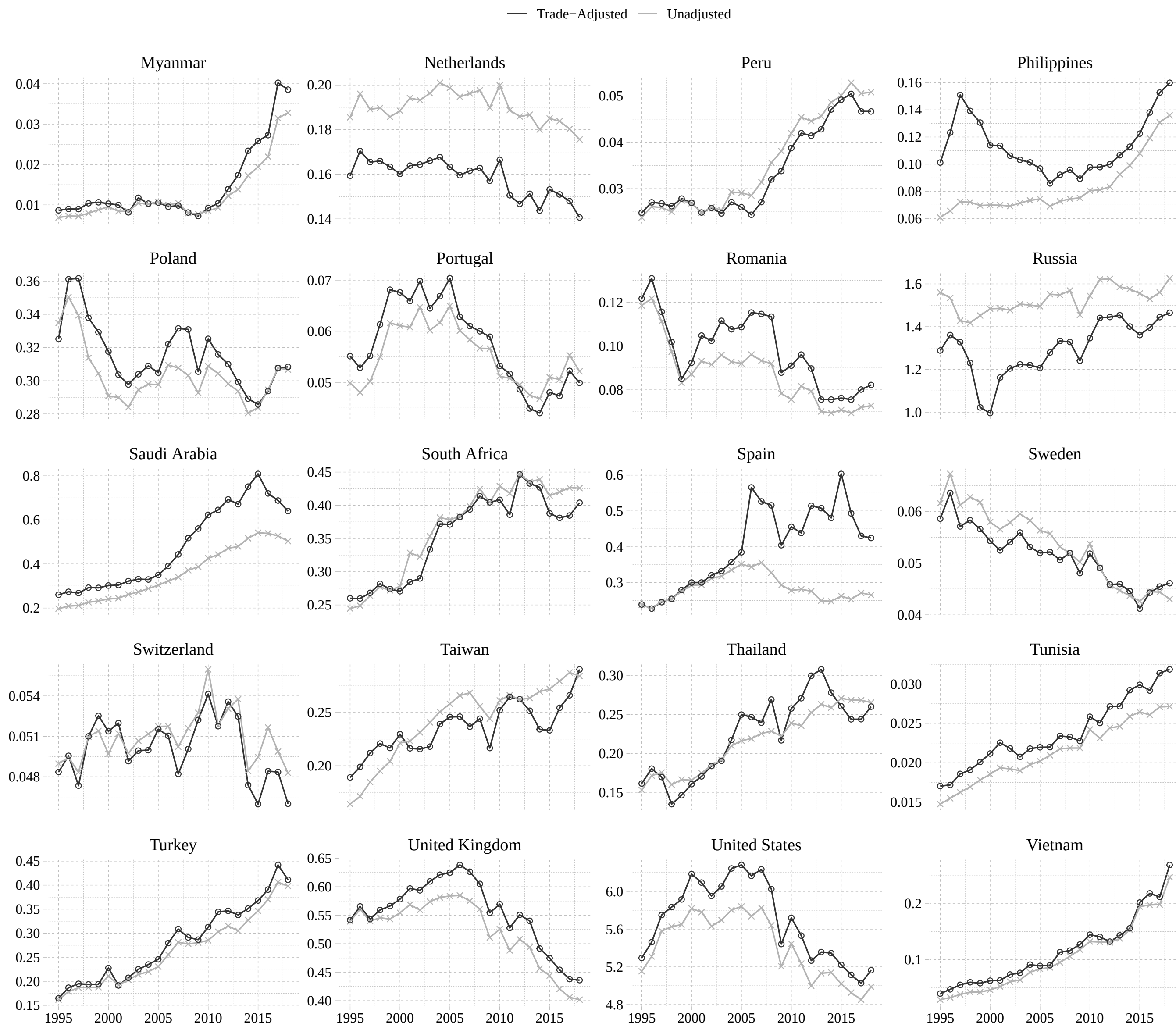


Figure 3.A.4: Production-Based Emissions 1995–2018, line plots by country *(continued)*

Table 3.A.1: List of Countries

Code	Country	Code	Country	Code	Country
AUS	Australia	ARG	Argentina	AUT	Austria
BEL	Belgium	BRN	Brunei Darussalam	CAN	Canada
CHL	Chile	KHM	Cambodia	COL	Colombia
CRI	Costa Rica	HRV	Croatia	CZE	Czech Republic
DNK	Denmark	IND	India	EST	Estonia
FIN	Finland	HKG	Hong Kong	FRA	France
DEU	Germany	LAO	Laos	GRC	Greece
HUN	Hungary	MLT	Malta	ISL	Iceland
IRL	Ireland	MMR	Myanmar	ISR	Israel
ITA	Italy	PHL	Philippines	JPN	Japan
KOR	Korea	RUS	Russia	LVA	Latvia
LTU	Lithuania	SAU	Saudi Arabia	LUX	Luxembourg
MEX	Mexico	TWN	Chinese Taipei	NLD	Netherlands
NZL	New Zealand	TUN	Tunisia	NOR	Norway
POL	Poland	ROW	Rest of the World	PRT	Portugal
SVK	Slovak Republic	ESP	Spain	SWE	Sweden
CHE	Switzerland	TUR	Turkey	GBR	United Kingdom
USA	United States				

Table 3.A.2: List of Sectors

Code	Industry	ISIC Rev.4
D01T02	Agriculture, hunting, forestry	01, 02
D03	Fishing and aquaculture	03
D05T06	Mining and quarrying, energy producing products	05, 06
D07T08	Mining and quarrying, non-energy producing products	07, 08
D09	Mining support service activities	09
D10T12	Food products, beverages and tobacco	10, 11, 12
D13T15	Textiles, textile products, leather and footwear	13, 14, 15
D16	Wood and products of wood and cork	16
D17T18	Paper products and printing	17, 18
D19	Coke and refined petroleum products	19
D20	Chemical and chemical products	20
D21	Pharmaceuticals, medicinal chemical and botanical products	21
D22	Rubber and plastics products	22
D23	Other non-metallic mineral products	23
D24	Basic metals	24
D25	Fabricated metal products	25
D26	Computer, electronic and optical equipment	26
D27	Electrical equipment	27
D28	Machinery and equipment, nec	28
D29	Motor vehicles, trailers and semi-trailers	29
D30	Other transport equipment	30
D31T33	Manufacturing nec; repair and installation of machinery and equipment	31, 32, 33
D35	Electricity, gas, steam and air conditioning supply	35
D36T39	Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39
D41T43	Construction	41, 42, 43
D45T47	Wholesale and retail trade; repair of motor vehicles	45, 46, 47
D49	Land transport and transport via pipelines	49
D50	Water transport	50
D51	Air transport	51
D52	Warehousing and support activities for transportation	52
D53	Postal and courier activities	53
D55T56	Accommodation and food service activities	55, 56
D58T60	Publishing, audiovisual and broadcasting activities	58, 59, 60
D61	Telecommunications	61
D62T63	IT and other information services	62, 63
D64T66	Financial and insurance activities	64, 65, 66
D68	Real estate activities	68
D69T75	Professional, scientific and technical activities	69 to 75
D77T82	Administrative and support services	77 to 82
D84	Public administration and defence; compulsory social security	84
D85	Education	85
D86T88	Human health and social work activities	86, 87, 88
D90T93	Arts, entertainment and recreation	90, 91, 92, 93
D94T96	Other service activities	94,95, 96
D97T98	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	97, 98

Table 3.A.3: Balance of Emissions Embodied in Trade (Gt of CO2 Emissions)

	1995			2007			2018		
Country	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO
Argentina	-0.015	-0.003	-0.003	0.006	0.012	0.011	-0.013	-0.002	-0.004
Australia	0.013	0.019	0.016	-0.025	0.022	0.017	-0.013	0.016	0.010
Austria	-0.023	-0.004	-0.005	-0.026	-0.003	-0.002	-0.022	0.000	0.001
Belgium	-0.012	0.007	0.011	-0.019	0.009	0.013	-0.025	-0.002	0.000
Brazil	-0.016	0.002	0.001	-0.031	0.007	0.008	-0.015	0.012	0.012
Brunei Darussalam	0.000	0.000	0.000	0.001	-0.002	-0.002	0.000	-0.001	-0.001
Bulgaria	0.023	0.013	0.015	0.007	-0.008	-0.013	0.008	-0.003	-0.002
Cambodia	-0.001	0.000	-0.001	-0.004	-0.001	-0.001	-0.006	-0.004	-0.006
Canada	0.046	0.024	0.030	0.003	0.033	0.035	0.058	0.053	0.049
Chile	0.001	0.002	0.002	0.009	0.003	0.000	0.000	0.003	-0.003
China	0.338	0.011	0.016	1.505	0.470	0.658	0.861	-0.014	0.101
Colombia	-0.010	-0.015	-0.020	-0.015	-0.007	-0.008	-0.009	0.001	-0.001
Costa Rica	-0.003	-0.001	-0.002	-0.004	-0.001	-0.001	-0.006	0.000	0.000
Croatia	-0.001	-0.010	-0.011	-0.005	-0.002	-0.003	-0.003	-0.002	-0.002
Cyprus	-0.001	0.000	0.000	-0.001	-0.003	-0.004	-0.002	-0.003	-0.003
Czech Republic	0.018	-0.001	-0.003	0.014	-0.002	0.001	0.008	-0.006	-0.002
Denmark	-0.003	0.011	0.013	0.025	0.043	0.045	0.006	0.021	0.022
Estonia	0.003	-0.001	-0.002	0.002	0.001	-0.001	0.001	0.001	0.001
Finland	-0.004	0.005	0.007	-0.007	-0.004	0.001	-0.008	0.002	0.003
France	-0.076	0.002	0.003	-0.146	-0.016	-0.018	-0.101	-0.185	-0.208
Germany	-0.184	-0.031	-0.027	-0.139	0.000	0.019	-0.128	-0.014	-0.007
Greece	-0.009	-0.004	-0.005	-0.026	-0.016	-0.022	0.007	-0.005	0.003
Hong Kong	-0.058	-0.001	-0.003	-0.034	-0.003	-0.002	0.003	0.013	0.003
Hungary	0.002	-0.004	-0.005	-0.009	-0.010	-0.011	-0.002	-0.020	-0.022
Iceland	0.000	0.001	0.001	-0.001	0.001	0.001	0.000	0.002	0.002
India	0.036	-0.018	-0.021	0.014	-0.128	-0.149	0.089	-0.236	-0.272
Indonesia	0.006	0.006	0.003	0.016	0.017	0.016	-0.025	-0.024	-0.031
Ireland	0.000	0.002	0.004	-0.008	0.002	0.004	0.003	0.008	0.013
Israel	-0.012	-0.001	-0.001	-0.012	-0.006	-0.006	-0.026	-0.004	-0.007
Italy	-0.103	-0.006	-0.003	-0.150	-0.017	-0.018	-0.079	-0.019	-0.017
Japan	-0.324	-0.004	-0.003	-0.267	-0.226	-0.225	-0.164	-0.015	-0.010
Kazakhstan	0.022	-0.073	-0.093	0.040	-0.008	-0.019	0.025	0.019	0.018
Korea	0.034	0.017	0.024	-0.043	-0.054	-0.039	0.059	-0.043	0.012
Laos	-0.001	0.000	0.000	-0.001	0.000	0.000	0.007	0.009	0.008
Latvia	-0.003	-0.001	-0.002	-0.006	-0.001	-0.002	-0.002	-0.007	-0.007
Lithuania	-0.002	-0.001	-0.001	-0.007	-0.001	-0.001	-0.006	0.000	0.000
Luxembourg	-0.002	0.003	0.003	0.000	0.002	0.003	-0.003	0.000	0.001
Malaysia	0.021	0.011	0.007	0.079	0.046	0.059	0.047	0.019	0.026
Malta	-0.001	0.000	-0.001	0.000	-0.002	-0.002	-0.001	-0.005	-0.005
Mexico	0.004	-0.004	-0.003	-0.042	-0.011	-0.013	-0.007	-0.019	-0.021
Morocco	-0.004	-0.003	-0.003	-0.006	-0.003	-0.004	-0.009	-0.006	-0.010
Myanmar	-0.002	-0.001	-0.002	0.001	0.001	0.001	-0.005	-0.004	-0.006

Table 3.A.3: *(continued)*

Country	1995 BEET	1995 Adjusted EEBT	1995 Adjusted MRIO	2007 BEET	2007 Adjusted EEBT	2007 Adjusted MRIO	2018 BEET	2018 Adjusted EEBT	2018 Adjusted MRIO
Netherlands	-0.003	0.021	0.026	-0.006	0.026	0.035	0.007	0.021	0.035
New Zealand	-0.003	0.000	-0.001	-0.011	-0.002	-0.003	-0.012	-0.002	-0.004
Norway	0.001	0.014	0.014	-0.018	0.010	0.011	-0.010	0.012	0.010
Peru	-0.005	-0.001	-0.001	-0.003	0.004	0.004	-0.010	0.004	0.004
Philippines	-0.017	-0.035	-0.040	-0.011	-0.016	-0.019	-0.040	-0.017	-0.024
Poland	0.053	0.009	0.010	0.007	-0.015	-0.024	0.019	-0.001	-0.002
Portugal	-0.009	-0.003	-0.005	-0.015	-0.001	-0.003	-0.005	0.003	0.002
Rest of the World	0.070	-0.144	-0.205	0.015	-0.153	-0.263	-0.116	-0.178	-0.273
Romania	0.017	-0.003	-0.003	-0.012	-0.015	-0.021	-0.009	-0.008	-0.009
Russia	0.532	0.279	0.272	0.366	0.225	0.215	0.336	0.175	0.161
Saudi Arabia	-0.001	-0.041	-0.063	-0.009	-0.065	-0.103	-0.029	-0.112	-0.137
Singapore	0.016	0.008	0.014	0.048	0.029	0.054	0.064	0.036	0.075
Slovak Republic	0.010	0.003	0.003	-0.003	-0.010	-0.009	-0.003	-0.010	-0.008
Slovenia	-0.003	-0.001	-0.001	-0.003	-0.015	-0.016	-0.001	-0.013	-0.012
South Africa	0.041	-0.013	-0.015	0.104	0.013	0.005	0.109	0.031	0.022
Spain	-0.025	0.000	-0.001	-0.081	-0.140	-0.171	-0.020	-0.192	-0.159
Sweden	-0.020	0.002	0.003	-0.035	0.001	0.003	-0.029	-0.004	-0.003
Switzerland	-0.036	0.000	0.001	-0.041	0.001	0.002	-0.045	0.001	0.002
Taiwan	0.004	-0.027	-0.025	0.077	-0.001	0.032	0.076	-0.036	-0.006
Thailand	-0.008	-0.001	-0.008	0.030	-0.022	-0.014	0.034	-0.008	0.005
Tunisia	-0.001	-0.001	-0.002	-0.001	-0.001	-0.002	0.001	-0.002	-0.005
Turkey	-0.013	0.000	-0.003	-0.051	-0.018	-0.028	0.011	0.000	-0.013
United Kingdom	-0.062	0.000	-0.002	-0.184	-0.036	-0.051	-0.121	-0.026	-0.034
United States	-0.233	-0.116	-0.141	-0.854	-0.335	-0.408	-0.761	-0.136	-0.176
Vietnam	-0.002	-0.007	-0.011	0.007	-0.005	-0.018	0.051	-0.007	-0.022

Table 3.A.4: Balance of Emissions Embodied in Trade in Percentage of PBE

	1995			2007			2018		
Country	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO
Argentina	-13.348	-2.533	-2.776	3.743	7.446	7.058	-7.383	-1.210	-2.560
Australia	4.582	6.582	5.538	-6.375	5.440	4.184	-3.176	3.888	2.415
Austria	-37.476	-6.450	-7.789	-36.335	-4.054	-2.800	-33.625	-0.604	1.313
Belgium	-9.990	5.944	9.050	-16.711	7.675	11.473	-24.849	-1.716	0.033
Brazil	-6.926	0.676	0.505	-9.081	1.931	2.346	-3.469	2.776	2.957
Brunei Darussalam	1.285	-3.223	-8.971	8.293	-20.884	-25.475	-3.910	-8.797	-15.974
Bulgaria	41.943	23.903	27.426	12.550	-15.857	-25.929	19.882	-6.416	-3.817
Cambodia	-90.581	-28.000	-37.398	-110.132	-32.596	-39.036	-54.250	-34.246	-47.900
Canada	10.176	5.269	6.706	0.530	5.674	6.033	9.792	8.934	8.267
Chile	2.810	5.532	4.408	11.394	3.479	0.568	0.296	3.234	-3.135
China	11.483	0.379	0.552	23.015	7.188	10.064	8.678	-0.142	1.015
Colombia	-17.682	-26.659	-35.620	-26.842	-11.678	-14.463	-12.314	0.685	-1.640
Costa Rica	-54.537	-25.805	-41.645	-54.240	-6.696	-12.616	-66.107	-2.802	-4.947
Croatia	-5.699	-54.288	-63.503	-22.763	-8.541	-14.794	-17.709	-12.986	-15.270
Cyprus	-15.504	0.834	-4.433	-4.534	-28.347	-37.436	-33.616	-43.469	-49.804
Czech Republic	14.768	-1.108	-2.595	11.566	-1.442	0.832	8.046	-5.881	-2.114
Denmark	-3.988	16.515	18.052	23.980	41.607	43.589	9.118	33.437	35.658
Estonia	21.109	-4.532	-11.631	10.741	2.731	-2.473	9.011	7.968	6.857
Finland	-6.518	8.175	11.579	-9.420	-5.572	0.805	-16.820	3.982	5.753
France	-20.549	0.427	0.910	-37.954	-4.094	-4.611	-30.415	-55.813	-62.775
Germany	-20.823	-3.464	-3.016	-17.131	0.005	2.376	-17.344	-1.892	-0.909
Greece	-10.959	-5.309	-5.780	-21.349	-13.042	-18.046	8.542	-5.488	3.686
Hong Kong	-126.807	-3.024	-7.304	-54.411	-5.131	-3.506	4.224	18.158	4.722
Hungary	3.155	-7.211	-8.600	-16.805	-17.969	-19.943	-3.912	-39.907	-44.428
Iceland	10.548	34.109	34.237	-26.583	17.325	14.130	7.292	33.040	37.532
India	5.093	-2.561	-2.985	1.108	-10.083	-11.735	3.832	-10.186	-11.705
Indonesia	2.861	2.897	1.239	4.442	4.685	4.455	-4.405	-4.215	-5.563
Ireland	-1.270	5.711	11.427	-14.763	3.441	6.500	5.883	14.012	24.644
Israel	-24.434	-1.303	-2.700	-17.349	-8.301	-8.602	-40.181	-6.685	-10.070
Italy	-25.293	-1.385	-0.614	-33.335	-3.744	-3.941	-22.898	-5.533	-4.941
Japan	-27.548	-0.356	-0.252	-21.228	-18.000	-17.881	-14.287	-1.307	-0.900
Kazakhstan	12.679	-42.940	-54.604	21.468	-4.353	-9.902	11.728	9.014	8.740
Korea	7.942	3.924	5.465	-8.247	-10.429	-7.439	9.165	-6.656	1.901
Laos	-441.665	-50.928	-71.984	-54.868	2.818	-3.951	35.431	47.903	44.376
Latvia	-27.902	-13.702	-20.227	-68.526	-13.418	-25.846	-30.506	-91.068	-92.100
Lithuania	-18.316	-6.622	-9.453	-54.775	-4.253	-6.691	-48.838	-0.851	1.879
Luxembourg	-20.997	28.607	37.137	0.759	15.124	24.081	-26.787	1.056	9.250
Malaysia	25.004	13.158	8.321	42.216	24.393	31.451	19.777	7.865	11.152
Malta	-34.229	-16.580	-22.857	-9.827	-59.021	-67.737	-19.658	-152.561	-146.947

Table 3.A.4: *(continued)*

	1995			2007			2018		
Country	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO	BEET	Adjusted EEBT	Adjusted MRIO
Mexico	1.352	-1.317	-1.057	-9.685	-2.417	-2.871	-1.647	-4.377	-4.865
Morocco	-15.723	-10.765	-11.997	-14.704	-5.854	-9.975	-13.713	-10.138	-15.971
Myanmar	-31.471	-15.820	-25.708	4.875	6.184	5.780	-14.735	-11.288	-17.397
Netherlands	-1.795	11.424	14.125	-2.885	13.073	17.630	4.080	12.206	19.904
New Zealand	-13.045	-1.662	-2.598	-31.660	-5.383	-7.821	-32.666	-6.169	-10.730
Norway	1.195	27.348	28.601	-30.694	17.841	18.023	-18.001	21.821	18.779
Peru	-19.872	-3.494	-4.361	-10.492	13.523	13.756	-20.237	8.530	8.175
Philippines	-27.195	-57.920	-66.504	-15.540	-22.569	-26.802	-29.313	-12.559	-17.670
Poland	15.799	2.783	2.870	2.263	-4.732	-7.729	6.317	-0.286	-0.567
Portugal	-18.073	-6.896	-10.558	-24.959	-1.707	-4.558	-8.922	5.360	4.340
Rest of the World	3.423	-7.055	-10.030	0.539	-5.417	-9.291	-3.384	-5.195	-7.975
Romania	14.134	-2.130	-2.657	-12.912	-16.193	-22.929	-12.557	-11.096	-12.984
Russia	34.103	17.855	17.427	23.624	14.530	13.890	20.678	10.733	9.900
Saudi Arabia	-0.354	-21.028	-31.927	-2.646	-19.158	-30.388	-5.808	-22.251	-27.150
Singapore	21.313	10.765	18.865	41.162	25.081	45.916	41.807	23.442	48.889
Slovak Republic	25.241	7.114	7.670	-9.619	-28.350	-24.522	-10.116	-30.255	-24.343
Slovenia	-17.439	-5.093	-6.673	-18.532	-95.534	-98.849	-6.055	-96.096	-88.568
South Africa	16.970	-5.499	-6.339	26.174	3.250	1.235	25.549	7.209	5.163
Spain	-10.610	-0.154	-0.526	-22.711	-39.424	-47.919	-7.603	-72.180	-59.934
Sweden	-32.728	2.904	4.879	-66.355	2.085	4.780	-67.081	-8.849	-7.160
Switzerland	-73.815	0.823	1.260	-81.195	2.182	4.017	-93.892	2.432	4.741
Taiwan	2.454	-16.581	-15.292	28.597	-0.244	11.849	26.662	-12.648	-2.192
Thailand	-5.054	-0.802	-5.423	13.108	-9.740	-6.154	12.790	-3.043	2.006
Tunisia	-9.551	-9.959	-15.555	-3.500	-5.182	-7.487	3.051	-8.947	-17.325
Turkey	-8.190	-0.296	-1.660	-18.037	-6.570	-9.812	2.647	-0.038	-3.324
United Kingdom	-11.472	-0.080	-0.436	-31.938	-6.231	-8.919	-30.099	-6.524	-8.521
United States	-4.524	-2.252	-2.744	-14.665	-5.743	-7.011	-15.261	-2.725	-3.524
Vietnam	-6.163	-24.261	-37.197	6.990	-5.360	-19.096	20.857	-2.783	-8.797

Table 3.A.5: Production-Based Emissions (Gt of CO_2 Emissions)

	1995			2007			2018		
Country	PBE	Adjusted EEBT	Adjusted MRIO	PBE	Adjusted EEBT	Adjusted MRIO	PBE	Adjusted EEBT	Adjusted MRIO
Argentina	0.109	0.112	0.112	0.160	0.148	0.149	0.174	0.176	0.178
Australia	0.294	0.274	0.277	0.396	0.374	0.379	0.400	0.384	0.390
Austria	0.062	0.066	0.067	0.073	0.076	0.075	0.065	0.065	0.064
Belgium	0.117	0.110	0.106	0.116	0.107	0.103	0.101	0.103	0.101
Brazil	0.233	0.232	0.232	0.341	0.334	0.333	0.419	0.407	0.406
Brunei Darussalam	0.006	0.006	0.006	0.008	0.010	0.010	0.008	0.009	0.009
Bulgaria	0.055	0.042	0.040	0.052	0.060	0.065	0.040	0.043	0.042
Cambodia	0.001	0.002	0.002	0.004	0.005	0.005	0.012	0.016	0.017
Canada	0.451	0.428	0.421	0.581	0.548	0.546	0.589	0.536	0.540
Chile	0.041	0.039	0.040	0.079	0.076	0.078	0.095	0.092	0.098
China	2.940	2.928	2.923	6.539	6.069	5.881	9.916	9.930	9.815
Colombia	0.055	0.070	0.075	0.056	0.062	0.064	0.077	0.076	0.078
Costa Rica	0.005	0.007	0.007	0.008	0.008	0.009	0.008	0.009	0.009
Croatia	0.018	0.028	0.030	0.023	0.025	0.026	0.016	0.018	0.019
Cyprus	0.008	0.008	0.008	0.011	0.014	0.015	0.007	0.010	0.010
Czech Republic	0.124	0.125	0.127	0.122	0.124	0.121	0.100	0.106	0.102
Denmark	0.070	0.058	0.057	0.103	0.060	0.058	0.062	0.042	0.040
Estonia	0.016	0.017	0.018	0.020	0.020	0.021	0.016	0.014	0.015
Finland	0.060	0.055	0.053	0.070	0.074	0.070	0.050	0.048	0.047
France	0.372	0.370	0.369	0.385	0.401	0.403	0.332	0.517	0.541
Germany	0.885	0.916	0.912	0.813	0.813	0.794	0.737	0.751	0.744
Greece	0.082	0.087	0.087	0.121	0.137	0.143	0.082	0.087	0.079
Hong Kong	0.046	0.047	0.049	0.063	0.066	0.065	0.073	0.060	0.069
Hungary	0.058	0.062	0.063	0.054	0.064	0.065	0.049	0.069	0.071
Iceland	0.003	0.002	0.002	0.004	0.003	0.004	0.005	0.003	0.003
India	0.709	0.727	0.730	1.273	1.401	1.422	2.320	2.557	2.592
Indonesia	0.216	0.209	0.213	0.370	0.352	0.353	0.561	0.584	0.592
Ireland	0.034	0.032	0.030	0.056	0.054	0.053	0.054	0.047	0.041
Israel	0.049	0.050	0.050	0.070	0.075	0.075	0.065	0.069	0.071
Italy	0.409	0.415	0.411	0.451	0.468	0.469	0.345	0.364	0.362
Japan	1.176	1.180	1.179	1.258	1.484	1.483	1.151	1.166	1.162
Kazakhstan	0.171	0.245	0.264	0.188	0.196	0.207	0.209	0.190	0.191
Korea	0.433	0.416	0.410	0.522	0.576	0.561	0.648	0.691	0.636
Laos	0.000	0.000	0.000	0.002	0.002	0.002	0.019	0.010	0.010
Latvia	0.009	0.011	0.011	0.009	0.010	0.011	0.008	0.015	0.015
Lithuania	0.014	0.014	0.015	0.013	0.013	0.014	0.011	0.012	0.011
Luxembourg	0.009	0.006	0.006	0.012	0.010	0.009	0.010	0.010	0.009
Malaysia	0.086	0.075	0.079	0.187	0.142	0.128	0.237	0.218	0.211
Malta	0.003	0.003	0.003	0.004	0.006	0.006	0.003	0.009	0.008
Mexico	0.294	0.298	0.297	0.437	0.448	0.450	0.429	0.448	0.450
Morocco	0.028	0.031	0.031	0.044	0.046	0.048	0.062	0.069	0.072
Myanmar	0.007	0.008	0.009	0.010	0.010	0.010	0.033	0.037	0.039

Table 3.A.5: *(continued)*

Country	1995 PBE	1995 Adjusted EEBT	1995 Adjusted MRIO	2007 PBE	2007 Adjusted EEBT	2007 Adjusted MRIO	2018 PBE	2018 Adjusted EEBT	2018 Adjusted MRIO
Netherlands	0.186	0.164	0.159	0.196	0.171	0.162	0.176	0.154	0.141
New Zealand	0.026	0.026	0.026	0.036	0.038	0.039	0.036	0.038	0.040
Norway	0.050	0.036	0.036	0.058	0.048	0.048	0.055	0.043	0.044
Peru	0.024	0.025	0.025	0.031	0.027	0.027	0.051	0.046	0.047
Philippines	0.061	0.096	0.101	0.073	0.089	0.092	0.136	0.153	0.160
Poland	0.335	0.325	0.325	0.308	0.322	0.332	0.307	0.307	0.308
Portugal	0.050	0.053	0.055	0.058	0.059	0.061	0.052	0.049	0.050
Rest of the World	2.042	2.186	2.246	2.827	2.981	3.090	3.420	3.598	3.693
Romania	0.119	0.121	0.122	0.093	0.108	0.115	0.073	0.081	0.082
Russia	1.560	1.282	1.288	1.548	1.323	1.333	1.626	1.452	1.465
Saudi Arabia	0.197	0.239	0.260	0.340	0.405	0.443	0.503	0.615	0.640
Singapore	0.074	0.066	0.060	0.117	0.088	0.063	0.154	0.118	0.079
Slovak Republic	0.041	0.038	0.038	0.036	0.046	0.045	0.032	0.041	0.039
Slovenia	0.014	0.015	0.015	0.016	0.031	0.032	0.014	0.027	0.026
South Africa	0.244	0.258	0.260	0.399	0.386	0.394	0.426	0.395	0.404
Spain	0.238	0.238	0.239	0.356	0.496	0.527	0.265	0.457	0.425
Sweden	0.062	0.060	0.059	0.053	0.052	0.051	0.043	0.047	0.046
Switzerland	0.049	0.049	0.048	0.050	0.049	0.048	0.048	0.047	0.046
Taiwan	0.164	0.191	0.189	0.268	0.269	0.237	0.284	0.320	0.290
Thailand	0.153	0.154	0.161	0.226	0.248	0.240	0.265	0.274	0.260
Tunisia	0.015	0.016	0.017	0.022	0.023	0.023	0.027	0.030	0.032
Turkey	0.162	0.162	0.164	0.281	0.299	0.309	0.398	0.398	0.411
United Kingdom	0.539	0.540	0.542	0.575	0.611	0.626	0.402	0.428	0.436
United States	5.153	5.269	5.295	5.825	6.160	6.234	4.989	5.125	5.164
Vietnam	0.029	0.036	0.040	0.095	0.100	0.113	0.246	0.253	0.268

Table 3.A.6: Balance of Emissions Embodied in Import (Gt of CO_2 Emissions)

Country	1995			2007			2018		
	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO
Argentina	0.023	0.011	0.011	0.030	0.024	0.025	0.039	0.028	0.030
Australia	0.054	0.048	0.051	0.119	0.073	0.077	0.122	0.095	0.100
Austria	0.040	0.021	0.021	0.053	0.030	0.029	0.048	0.027	0.025
Belgium	0.055	0.037	0.033	0.073	0.045	0.040	0.069	0.046	0.043
Brazil	0.053	0.036	0.036	0.104	0.067	0.065	0.109	0.084	0.082
Brunei Darussalam	0.002	0.002	0.003	0.002	0.004	0.005	0.003	0.004	0.004
Bulgaria	0.003	0.013	0.011	0.013	0.028	0.033	0.011	0.021	0.020
Cambodia	0.002	0.001	0.001	0.005	0.002	0.002	0.010	0.008	0.009
Canada	0.109	0.133	0.125	0.202	0.175	0.170	0.162	0.170	0.171
Chile	0.012	0.011	0.012	0.030	0.036	0.039	0.034	0.031	0.037
China	0.092	0.422	0.413	0.332	1.402	1.179	0.801	1.737	1.561
Colombia	0.020	0.025	0.030	0.027	0.018	0.020	0.029	0.019	0.021
Costa Rica	0.004	0.003	0.004	0.007	0.003	0.003	0.008	0.002	0.002
Croatia	0.006	0.015	0.016	0.011	0.008	0.010	0.008	0.007	0.007
Cyprus	0.005	0.003	0.004	0.006	0.008	0.009	0.004	0.005	0.005
Czech Republic	0.019	0.039	0.041	0.032	0.049	0.045	0.030	0.044	0.040
Denmark	0.026	0.011	0.010	0.038	0.020	0.018	0.031	0.016	0.014
Estonia	0.003	0.007	0.008	0.006	0.007	0.008	0.005	0.005	0.005
Finland	0.024	0.016	0.014	0.033	0.031	0.026	0.027	0.016	0.015
France	0.172	0.096	0.093	0.252	0.124	0.124	0.206	0.293	0.314
Germany	0.336	0.189	0.179	0.384	0.253	0.226	0.353	0.247	0.232
Greece	0.021	0.017	0.017	0.062	0.052	0.058	0.026	0.038	0.030
Hong Kong	0.081	0.024	0.026	0.075	0.044	0.043	0.098	0.088	0.097
Hungary	0.013	0.019	0.020	0.026	0.026	0.027	0.022	0.039	0.042
Iceland	0.002	0.001	0.001	0.004	0.002	0.002	0.003	0.002	0.002
India	0.043	0.098	0.101	0.213	0.357	0.377	0.328	0.657	0.689
Indonesia	0.048	0.049	0.052	0.085	0.085	0.085	0.127	0.127	0.133
Ireland	0.012	0.010	0.008	0.030	0.020	0.018	0.031	0.026	0.021
Israel	0.021	0.010	0.011	0.026	0.020	0.020	0.039	0.018	0.020
Italy	0.183	0.086	0.082	0.246	0.114	0.113	0.163	0.104	0.101
Japan	0.449	0.133	0.128	0.476	0.440	0.434	0.356	0.210	0.202
Kazakhstan	0.028	0.123	0.143	0.034	0.083	0.093	0.027	0.033	0.033
Korea	0.110	0.129	0.121	0.204	0.217	0.200	0.184	0.288	0.231
Laos	0.001	0.000	0.000	0.002	0.001	0.001	0.006	0.003	0.004
Latvia	0.005	0.004	0.004	0.009	0.004	0.005	0.006	0.010	0.010
Lithuania	0.005	0.003	0.004	0.010	0.003	0.004	0.010	0.004	0.004
Luxembourg	0.007	0.002	0.001	0.006	0.004	0.003	0.008	0.005	0.004
Malaysia	0.028	0.038	0.042	0.038	0.072	0.059	0.056	0.085	0.077
Malta	0.002	0.002	0.002	0.002	0.004	0.004	0.003	0.008	0.008
Mexico	0.047	0.055	0.054	0.131	0.100	0.101	0.138	0.151	0.151
Morocco	0.009	0.008	0.008	0.016	0.012	0.013	0.021	0.019	0.022
Myanmar	0.003	0.002	0.003	0.002	0.002	0.002	0.013	0.012	0.014

Table 3.A.6: *(continued)*

Country	1995			2007			2018		
	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO
Netherlands	0.079	0.056	0.050	0.093	0.063	0.053	0.077	0.063	0.049
New Zealand	0.011	0.008	0.008	0.021	0.012	0.012	0.022	0.012	0.014
Norway	0.029	0.016	0.015	0.052	0.024	0.024	0.043	0.022	0.023
Peru	0.007	0.004	0.004	0.013	0.006	0.006	0.024	0.009	0.009
Philippines	0.031	0.050	0.055	0.031	0.036	0.039	0.065	0.042	0.049
Poland	0.021	0.065	0.065	0.068	0.090	0.099	0.069	0.090	0.090
Portugal	0.021	0.015	0.017	0.030	0.016	0.018	0.024	0.017	0.017
Rest of the World	0.305	0.524	0.579	0.679	0.865	0.957	0.783	0.864	0.940
Romania	0.012	0.032	0.032	0.031	0.034	0.041	0.027	0.026	0.027
Russia	0.062	0.318	0.323	0.148	0.294	0.299	0.135	0.300	0.310
Saudi Arabia	0.029	0.069	0.091	0.082	0.139	0.177	0.114	0.197	0.222
Singapore	0.034	0.042	0.036	0.045	0.064	0.039	0.065	0.094	0.054
Slovak Republic	0.009	0.016	0.016	0.021	0.028	0.027	0.019	0.026	0.024
Slovenia	0.006	0.005	0.005	0.009	0.022	0.022	0.007	0.019	0.018
South Africa	0.023	0.078	0.080	0.051	0.143	0.150	0.039	0.117	0.126
Spain	0.076	0.051	0.052	0.175	0.235	0.264	0.109	0.281	0.248
Sweden	0.040	0.018	0.016	0.056	0.020	0.018	0.047	0.022	0.021
Switzerland	0.050	0.014	0.014	0.060	0.018	0.017	0.064	0.017	0.016
Taiwan	0.056	0.088	0.085	0.076	0.154	0.121	0.077	0.190	0.159
Thailand	0.054	0.048	0.055	0.070	0.122	0.113	0.089	0.131	0.118
Tunisia	0.006	0.006	0.007	0.007	0.008	0.008	0.007	0.010	0.012
Turkey	0.039	0.027	0.029	0.104	0.072	0.081	0.095	0.106	0.118
United Kingdom	0.177	0.117	0.117	0.309	0.163	0.176	0.212	0.119	0.125
United States	0.675	0.593	0.583	1.327	0.847	0.881	1.208	0.618	0.622
Vietnam	0.010	0.015	0.019	0.039	0.051	0.064	0.069	0.127	0.142

Table 3.A.7: Emissions Embodied in Import in Percentage of PBE

	1995			2007			2018		
Country	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO
Argentina	20.905	10.105	10.333	18.807	15.163	15.492	22.292	16.154	17.469
Australia	18.373	16.517	17.416	30.087	18.484	19.528	30.612	23.760	25.021
Austria	64.064	33.257	34.378	73.397	41.424	39.861	73.830	41.137	38.892
Belgium	47.264	31.658	28.224	63.032	39.010	34.847	67.948	45.153	43.066
Brazil	22.815	15.272	15.384	30.442	19.559	19.015	26.071	19.946	19.645
Brunei Darussalam	35.853	40.365	46.109	24.049	53.229	57.817	41.255	46.164	53.319
Bulgaria	6.322	24.374	20.839	24.675	53.147	63.154	26.623	53.011	50.322
Cambodia	101.806	39.226	48.623	136.588	59.059	65.491	84.857	64.858	78.507
Canada	24.159	29.444	27.629	34.794	30.096	29.291	27.534	28.813	29.059
Chile	29.696	27.005	28.098	38.147	46.134	48.973	35.430	32.551	38.860
China	3.121	14.360	14.053	5.075	21.435	18.027	8.081	17.513	15.744
Colombia	35.493	44.497	53.431	47.682	32.547	35.303	37.589	24.624	26.915
Costa Rica	84.012	55.284	71.119	85.279	37.739	43.655	90.213	26.912	29.053
Croatia	32.784	81.470	90.588	50.098	35.917	42.130	46.952	42.271	44.513
Cyprus	59.638	43.310	48.566	48.963	72.801	81.864	60.769	70.632	76.957
Czech Republic	15.571	31.812	32.934	26.429	39.655	37.163	30.178	44.328	40.339
Denmark	36.828	16.454	14.788	37.099	19.771	17.490	49.442	25.320	22.902
Estonia	19.300	44.984	52.040	27.488	35.574	40.702	29.642	30.763	31.796
Finland	40.911	26.353	22.813	47.234	43.546	37.009	53.533	32.871	30.960
France	46.341	25.883	24.883	65.441	32.148	32.098	62.129	88.132	94.489
Germany	38.019	21.341	20.212	47.256	31.111	27.749	47.920	33.469	31.484
Greece	26.118	20.489	20.939	51.362	43.157	48.059	32.074	46.187	36.930
Hong Kong	175.503	51.958	55.999	119.779	70.669	68.874	134.120	121.446	133.622
Hungary	22.771	33.168	34.525	47.209	48.462	50.347	43.876	79.990	84.392
Iceland	50.697	27.143	27.008	86.352	42.463	45.639	65.264	39.533	35.024
India	6.118	13.791	14.196	16.761	28.044	29.604	14.157	28.308	29.694
Indonesia	22.454	22.512	24.076	23.024	22.948	23.011	22.600	22.617	23.758
Ireland	35.140	28.209	22.443	53.658	35.552	32.395	56.632	48.683	37.871
Israel	43.277	20.166	21.543	37.642	28.612	28.895	61.144	27.673	31.034
Italy	44.817	21.133	20.138	54.518	25.237	25.124	47.355	30.255	29.398
Japan	38.144	11.275	10.847	37.842	34.986	34.496	30.951	18.257	17.564
Kazakhstan	16.202	71.851	83.485	18.152	44.060	49.523	12.953	15.711	15.941
Korea	25.483	29.679	27.960	39.113	41.539	38.306	28.372	44.490	35.636
Laos	468.099	77.364	98.418	83.839	26.155	32.922	30.425	18.195	21.479
Latvia	53.167	38.998	45.491	96.053	41.051	53.372	73.981	134.684	135.576
Lithuania	36.968	25.292	28.105	76.738	26.289	28.654	85.370	37.506	34.653
Luxembourg	71.907	22.326	13.774	48.038	33.724	24.716	73.857	46.077	37.820
Malaysia	32.222	44.355	48.906	20.496	38.525	31.260	23.817	35.871	32.441
Malta	87.100	69.459	75.728	65.143	114.343	123.053	95.929	228.844	223.217
Mexico	15.991	18.744	18.400	29.935	22.867	23.121	32.038	35.090	35.256
Morocco	33.510	28.562	29.784	35.421	26.584	30.692	33.552	29.997	35.810
Myanmar	42.431	26.782	36.668	22.214	20.911	21.309	39.787	36.381	42.449

Table 3.A.7: *(continued)*

Country	1995			2007			2018		
	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO	EEM	Adjusted EEBT	Adjusted MRIO
Netherlands	42.804	29.945	26.884	47.583	31.987	27.068	43.892	36.159	28.068
New Zealand	42.608	31.299	32.161	58.506	32.271	34.667	60.416	33.951	38.480
Norway	57.951	32.159	30.544	89.178	41.001	40.460	78.851	39.421	42.071
Peru	31.364	14.994	15.854	42.806	18.820	18.557	46.840	18.104	18.428
Philippines	51.690	82.437	90.999	41.982	49.059	53.244	47.651	30.948	36.008
Poland	6.366	19.433	19.295	22.098	29.270	32.090	22.431	29.251	29.315
Portugal	41.282	30.161	33.767	51.114	27.964	30.712	46.751	32.588	33.488
Rest of the World	14.919	25.667	28.371	24.028	30.606	33.858	22.891	25.249	27.481
Romania	10.483	26.766	27.274	33.531	36.904	43.549	36.924	35.568	37.351
Russia	3.996	20.411	20.673	9.569	19.007	19.303	8.298	18.471	19.075
Saudi Arabia	14.481	35.176	46.054	24.225	40.808	51.967	22.661	39.162	44.004
Singapore	46.235	57.102	48.682	38.268	54.607	33.515	42.120	60.724	35.039
Slovak Republic	20.841	39.327	38.412	59.696	78.662	74.599	60.341	80.752	74.568
Slovenia	44.498	32.231	33.732	57.195	134.343	137.512	47.636	137.820	130.149
South Africa	9.335	31.856	32.644	12.732	35.756	37.671	9.171	27.566	29.558
Spain	31.965	21.671	21.881	49.053	66.117	74.261	40.984	105.954	93.315
Sweden	64.232	28.844	26.625	105.568	37.483	34.433	109.606	51.677	49.685
Switzerland	102.666	28.145	27.590	118.677	35.435	33.465	132.192	35.987	33.558
Taiwan	34.265	53.470	52.011	28.206	57.331	44.955	27.206	66.724	56.059
Thailand	35.539	31.389	35.908	30.935	53.926	50.197	33.543	49.530	44.327
Tunisia	42.125	42.546	48.129	33.503	35.206	37.490	25.276	37.294	45.652
Turkey	24.323	16.456	17.793	37.057	25.663	28.832	23.763	26.573	29.734
United Kingdom	32.766	21.741	21.730	53.660	28.401	30.641	52.753	29.561	31.175
United States	13.092	11.502	11.312	22.776	14.540	15.122	24.215	12.390	12.477
Vietnam	34.275	52.380	65.309	41.439	53.870	67.524	27.973	51.734	57.626

Chapter 4

Distributional Implications of Carbon Taxation Policy in Indonesia

We combine the Environmentally-Extended Multi-Regional Input-Output (EE MRIO) analysis with a microsimulation analysis to estimate the distributional implications of carbon policy reform, a combination of carbon tax and revenue recycling initiatives, on households in Indonesia. We consider two relevant scenarios: an 'economy-wide' carbon tax versus an 'electricity-only' carbon tax. The impact of carbon policy reform is measured by the net impact of carbon tax and cash transfer relative to initial expenditure. Carbon policy reform in Indonesia tends to be progressive, meaning the relative net impact on households decreases as income increases. Carbon tax in Indonesia primarily affects households through the price increase in electricity and fuel products. The distributional impacts of a carbon policy reform are determined more by the percentage of tax revenue recycled and taxation scenario and less by the tax rate. In order to protect the poorest 40% of Indonesian households from inflationary pressure, the Indonesian government needs to recycle 25% of tax revenue.

This chapter is under review at *Energy and Climate Change*.

4.1 Introduction

Indonesia faces the dual challenge of reducing carbon emissions while maintaining its development objective of improving the living standards of its people (Dyarto and Setyawan, 2021); 9.5% of the 277.5 million Indonesians live below the national poverty line in 2022 (Asian Development Bank, 2023). During the past decades, the country has been highly reliant on fossil-based energy provisions to fuel its economic growth, making it one of the biggest carbon emitters in the world (Friedlingstein et al., 2022)[1]. To minimize the future negative impacts inflicted by climate change and to halt the country's increasing reliance on fossil fuels, Indonesia has pledged to reduce carbon emissions and scheduled to implement various climate-related policy measures (Setyowati and Quist, 2022), including the initiative to experiment levying a $2 per ton of CO_2 carbon tax on coal-fired power plants. Following this experimentation, Indonesia plans to gradually raise the tax rate and widen the sectoral coverage (Basri and Riefky, 2023). However, the consequences of such a plan on households' budgets remain relatively unexplored. Understanding the distributional impacts of a carbon tax in Indonesia is instrumental; without a clear insight into how a carbon tax affects the expenditure of Indonesian households across income spectrum, there is a risk that the policy could place a disproportionate burden on lower-income households. This study investigates how alternative carbon tax designs would affect households across different income levels in Indonesia.

Two studies assessing the impacts of carbon taxation policy in Indonesia find that a carbon tax has similar effects on low- and high-income households. Yusuf and Resosudarmo (2015), based on a Computable General Equilibrium (CGE) model calibrated with 2003 data, estimate the distributional impacts of a carbon tax on households. The authors estimate the percent change in households' expenditure and income and find that the relative impact of introducing a $30 carbon tax on fuel products (e.g. coal, gasoline, diesel, kerosene and natural gas) does not differ significantly for households across income levels. Steckel et al. (2021), based on an input-output model calibrated with 2019 data, evaluate the short-run impacts of carbon taxes in several developing Asian countries, including Indonesia. They report that the relative impacts of a carbon tax in Indonesia on low-income households are not significantly different than that on the high-income households. However, in Steckel et al. (2021) Indonesia stands out from other countries in developing Asia. Only in Indonesia

[1]This study focuses only on CO_2 emissions and excludes other GHG emissions. According to World Bank data, total greenhouse gas (GHG) emissions in Indonesia in 2019 were 1.24 Gt CO_2eq (measured in CO_2-equivalent), excluding GHG emissions from land-use, land-use changes and forestry. Roughly half of the country's GHG emissions consist of CO_2. Indonesia's CO_2 emissions in 2019 were 0.65 Gt CO_2; these carbon emissions are primarily due to the combustion of fossil fuels (including coal). Electricity generation and heat producers are responsible for circa 45% of the CO_2 emissions in Indonesia.

is the carbon tax neutral in the sense that the relative impact (the additional tax burden in percent of household income) is roughly the same for each income group. In the other countries studied, the carbon tax is regressive, meaning that the additional tax burden falls disproportionally on the poorer households. This result is striking and worth investigating further, for it may have to do with the input-output table and the household survey data of that particular year.

To this end, we offer a new analysis of the distributional impacts of carbon taxation in Indonesia. We focus on a single country and investigate the net impacts arising from alternative revenue recycling schemes; to the best of our knowledge, this has not been done for Indonesia before. We report novel estimates how much of the collected carbon tax revenue the Indonesian government would need to recycle to offset the negative effects of carbon taxation on Indonesia's poorest households. We consider two carbon taxation scenarios that directly speak to Indonesia's recent climate policy plan. The government plans to introduce a carbon tax in the electricity sector first before widening the tax base to the whole economy. In some of our simulations, the government prioritizes the bottom 40% of households to receive the relief package while in other simulations all households receive transfers. In the past, the Indonesian government has used cash transfers to protect low-income households in various instances of economic shocks and natural disasters (Cahyadi et al., 2020). We analyze what percentage of the collected tax revenue would need to be recycled to the bottom 40% of households until they become net beneficiaries of the carbon policy reform and can maintain their initial expenditure level. Compared to the earlier studies, our estimates of the (direct and indirect) carbon intensity of household consumption are more disaggregated, because we use more detailed input-output matrix. The EXIOBASE3, our main data source, offers finer sector detail than the Multi-Regional Input-Output (MRIO) tables used by the earlier studies, and this is a clear advantage because EXIOBASE3 disaggregates the electricity sector by energy source. The dis-aggregation is key to analyze the specific contribution of CO_2-intensive electricity sectors on carbon tax impacts.

Our methodological approach follows previous studies of carbon pricing impacts (for instance, Steckel et al. (2021)). We estimate, first, the relative impact of a carbon tax on Indonesian households by income decile. Second, we explore the consequences of different carbon tax rates and revenue recycling schemes. While households incur extra costs due to the carbon tax, they also receive extra benefits in the form of transfers. We use a multi-regional input-output model to estimate price increases by sector, assuming full cost pass-through (producers pass the tax cost through to output prices). We map the price increases by sector to the expenditure categories found in household expenditure surveys using the latest household expenditure survey.

This study is structured as follows. Section 4.2 discusses the related literature and important concepts related to carbon taxation. Section 4.3 discusses the model framework, the notation for the environmentally-extended MRIO (EE MRIO) model, and the integration between the MRIO model and the microsimulation model. Section 4.4 explains the use and the harmonization of the MRIO and household expenditure survey data. Section 4.5 discusses the results and section 4.6 concludes this study. We find that carbon policy reform in Indonesia has a tendency to be progressive. A carbon tax in Indonesia mainly affects households through price increases in electricity and fuel for private vehicles and cooking activities. The distribution of relative net impacts of a carbon policy reform in Indonesia is determined by revenue recycling percentages and taxation scenario (e.g., to which sectors a carbon tax is levied). The Indonesian government would need to recycle at least 25% of tax revenue to compensate the impacts of carbon tax on the poorest 40% of Indonesian households.

4.2 Related Literature and Key Concepts

A carbon tax is, in theory, an economically-efficient policy for reducing carbon emissions as it holds polluters accountable for the negative externalities of the emissions associated with their activities (Pigou, 1924; Pearce, 1991; Cramton et al., 2017). By assigning a price to carbon emissions, a carbon tax creates a financial incentive for both producers and consumers to reduce carbon emissions. A carbon tax encourages behavioral changes: as the cost of emitting carbon increases, producers and consumers are stimulated to either substitute emission-intensive for less-polluting energy sources or to increase the energy efficiency of their activities. Further, a carbon tax generates fiscal revenue, which can be recycled into various government programs for promoting sustainable development and facilitating the transition to a cleaner energy system. Compared to a cap-and-trade system, a carbon tax ensures greater transparency and predictability (Goulder and Schein, 2013). Getting the public to accept a new carbon tax can be challenging due to the short-run economic consequences (Baumol et al., 1988; Baranzini et al., 2000). A carbon tax raises the prices of fossil fuels and, through inter-industry linkages, the prices of other products. In Indonesia, the public has frequently opposed similar policies, as is shown by the mass protests that happened immediately after the government's decision to eliminate fossil fuel subsidies in 2008 (Mourougane, 2010; Renner et al., 2019), or in 2022 (Jones and Cardinale, 2023).

Wang et al. (2016) and Ohlendorf et al. (2021) document how the distributional implications of carbon pricing policy (e.g., carbon tax) vary across countries and by the modelling approach used in the analysis. The impacts of carbon tax are deemed 'regressive' when it disproportionately affects low-income households. The effects of carbon tax are deemed 'progressive' when higher-income classes are hurt more by it than lower-income classes. Studies using various methods find that carbon pricing policies tend to be regressive in many developed economies, for instance in the case of Canada (Araar et al., 2011), the US (Hassett et al., 2009), the Netherlands (Kerkhof et al., 2008), the UK (Feng et al., 2010), Sweden (Brännlund and Nordström, 2004). However, a few studies report neutral impacts (the impacts increase proportionally with the income level), e.g., in the case of Spain (Labandeira and Labeaga, 1999) and Australia Sajeewani et al. (2015). Results also vary among the developing economies (see Steckel et al. (2021) for developing Asia and Vogt-Schilb et al. (2019) for Latin America and the Caribbean countries). Carbon tax has been found to hurt higher income classes relatively more than lower income classes in the case of ASEAN countries such as Vietnam, Malaysia, the Philippines, and Thailand (Nurdianto and Resosudarmo, 2016). Yusuf and Resosudarmo (2015) conclude that carbon pricing is not necessarily regressive for Indonesia. Similarly, Steckel et al. (2021) find that, under certain pricing scenarios, the carbon pricing policy in Indonesia would have a relatively larger impact on high-income groups. Different studies for the same country obtain different results. Using different methods, Brenner et al. (2007) find that the the direct carbon tax has progressive results while Liang et al. (2013) conclude that the carbon tax in China is regressive. In the case of Italy, Tiezzi (2005) finds that the outcome of a carbon tax is progressive, whereas Symons et al. (2000) conclude that the distributional impacts are rather 'neutral' for Italian households.

When evaluating the distributional effects of carbon pricing policy, three methods are popular. The econometric model is used to statistically estimate the effect of carbon pricing policy on related variables such as household expenditures and incomes (for instance, the study by Bureau (2011) for France). The so-called hybrid model combines the EE MRIO analysis with the microsimulation analysis to assess the short-run implications of carbon pricing policy. The EE MRIO analysis accounts for the direct and indirect emissions embodied[2] in aggregate final demand while microsimulation analysis simulates the effects of levying an emission tax on micro (e.g. households) levels (Li and O'Donoghue, 2013). The existing studies implement the hybrid model while assuming no change in demand (see Dorband et al. (2019), Vogt-Schilb et al. (2019), Feindt et al. (2021), and Steckel et al. (2021)) or including demand-side response (see Burtraw et al. (2009), Datta (2010), and Douenne (2020)). As a MRIO-based model, the hybrid model incorporates the cost-of

[2]We use the traditional nomenclature in the environmentally-extended multi-regional input-output (EE MRIO) study, the 'direct and indirect emissions' refer to the direct and indirect emissions – generated along the production chains – that are embodied in final demand. The direct and indirect emissions embodied in final demand exclude the direct households' emissions generated from fuel use.

production structure of dozens of industrial sectors; most econometric models do not have a similar degree of industry-level disaggregation and detail (Wang et al., 2016). The CGE model takes into account both the income- and expenditure-side to assess the distributional implications of carbon pricing (for instance, Yusuf and Resosudarmo (2015) in the case of Indonesia). However, the production cost structure of industries in CGE models tends to be less disaggregated and detailed than in hybrid models and as a result, the impacts of a carbon tax on costs and prices are less well captured in these models than in hybrid IO-micro simulation models. The strength of CGE models is their capacity to trace the indirect (general equilibrium) effects of a carbon tax, that mostly operate through relative price changes. We focus on the immediate real income impacts of a carbon tax on lower-income households, which are arguably the most significant effects, because the price elasticities of demand for energy are low.

Hence, using the hybrid model, our goal is to evaluate the first-order effects of a carbon tax on lower-income households in Indonesia. This is because lower-income households have limited resources to adapt to the immediate price increase, while in longer term they have more room to change behavior as a response to the price changes and subsidies (Dorband et al., 2019; Steckel et al., 2021; Malerba et al., 2021).

4.3 Methods

4.3.1 Model Framework

Our model is a static model that simulates the short-run effects of implementing a carbon tax, assuming that the price elasticities of producer and consumer demand functions are zero. The assumption of zero price elasticities means that consumers do not change the scale and pattern of their consumption and producers do not change their production technology (intermediate input structure) in response to changing relative prices. We estimate not only the carbon tax burden due to embodied emissions but also the burden due to households' direct emissions from fuel combustion (private vehicle transport and cooking activities). We treat the total expenditure of each household as a proxy of its income (Blundell and Preston, 1998; Atkinson et al., 2014) and then categorize households into ten income deciles based on their total expenditures.

We use a hybrid approach that consists of two modules: the EE MRIO model and the microsimulation analysis. The EE MRIO analysis extends the traditional Input-Output (IO) analysis (Leontief, 1941) and combines it with environmental impact variables. The EE MRIO model tracks the flow of goods and services through the economy and links

Table 4.3.1: Carbon tax reform scenarios

Tax rate (per tonne CO_2)	Tax base	Size of cash transfer	Eligibility of cash transfer
• \$2 • \$40 • \$100 • \$120	• "Economy-wide" • "Economy-wide + BTA" • "Electricity-only" • "Fuel-only"	• \$100 flat • X% recycling	• All households • Bottom 40%

final consumption expenditure to the associated environmental impacts (Leontief, 1941; Miller and Blair, 2009). The outcome of this model are carbon tax burdens by expenditure category, where tax burden refers to the additional expenditure required to maintain the same consumption level. The microsimulation analysis then permits the analysis of the distributional implications; it maps the carbon tax burden by expenditure category to the household level, using survey data on the scale and pattern of consumption, to estimate the carbon tax burden by household (Wang et al., 2016).

We create carbon tax reform scenarios that combine carbon taxes with cash transfers to estimate net impacts at the household level. Our model uses annual IO data; the final demand, tax revenues, and cash transfers are annual flows. The cash transfers compensate households for the carbon tax burden; in some cases, the cash transfers are so high that households net gain from carbon tax reform. In general, the net impact depends on the size of the transfer, and the scale and pattern of consumption.

We explore the net impacts of alternative carbon tax reform scenarios. The scenarios differ in terms of the carbon tax rate, the tax base, the size of the cash transfer, and the eligibility criteria of the cash transfer. All scenarios reported in the main text are based on a tax rate of \$40 per tonne of CO_2[3]. To explore the implications of different tax bases, the "Economy- wide" scenario places a carbon tax on all producing sectors in the Indonesian economy, while the "Electricity-only" scenario places a tax only on the electricity sector.[4]

The simplest cash transfer scheme is one that does not depend on the magnitude of carbon tax revenues; we explore the consequences of transferring \$100 to each household. In alternative cash transfer schemes, we let the size of the cash transfer per household to depend on the carbon tax rate (which, together with the total number of households, determines the total carbon tax revenue) and the fraction of tax revenues recycled (e.g., 100% revenue recycling means that 100% of the carbon tax revenues are transferred to households in full).

[3]The Appendix explores alternative tax rates (\$2, \$40, \$100 and \$120 per tonne of CO_2.)

[4]In addition, the Appendix explores the "Economy-wide tax + BTA" scenario, which presumes that imported products are taxed in proportion to their total embodied carbon content. It also explores the "Fuel-only" scenario, which narrows the tax base to fuel products.

We also explore a variation of the cash transfer eligibility criterion: instead of awarding the same cash transfer to every household, the “Bottom-40% only” scheme simulates cash transfers to only the poorest 40% of households.

The rationale for the different scenarios is as follows. Indonesia has tested the effects of the carbon cap-and-trade system as applied to the national coal-based electricity sector on the basis of the Presidential Regulation Number 98/2021 and ESDM Ministerial Regulation Number 16/2022 (Basri and Riefky, 2023). While the outcome of this test is yet to be made public, Indonesia plans to gradually introduce the carbon taxation system in the near future. $2 per tonne CO_2 carbon tax will first be introduced to the coal-based electricity sector in the form of cap-and-tax system which combines the elements of cap-and-trade and tax. In this system, only the excess emissions beyond the regulated (or the capped) amount are subject to taxation, which makes it different from a straightforward taxation approach. The limited scope combined with the low tax rate ($2) means that the impacts on households’ expenditures will be very small. The government intends to broaden the tax base to cover the whole electricity sector, and later other sectors in the economy; moreover, it intends to include not only the excess quantity of carbon emissions, but all emissions. 80% of Indonesia’s electricity is produced from fossil-based energy sources (International Energy Agency, 2022).

Our main goal is to understand the impacts of an ambitious carbon tax scheme that might be implemented in the future. Our base tax rate is $40 per tonne of CO_2 emissions, a rate regarded as the lower bound required to achieve the target of the Paris Agreement (Stiglitz et al., 2017). The implications of alternative tax rates are explored in the Appendix. Stern and Stiglitz (2021) suggest a tax of $100 per tonne of CO_2. Different integrated assessment models yield different values for the social cost of carbon (Tol, 2019). The IPCC Sixth Assessment Report suggests a carbon tax of $115 per tonne of CO_2 emissions (see World Bank (2023) page 20, box 4). The $120 reported in the Appendix is at the upper bound of carbon tax rates suggested by those studies.

Besides the “Electricity-only” and the “Economy-wide” scenarios reported in the main text, the appendix explores the “Fuel-only” scenario, which 1) taxes fuel producers based on the emissions from fuel production processes, and 2) taxes fuel suppliers based on the estimated emissions generated by the vehicles that are used in the transportation services, and on the estimated household’s emissions from direct use of fuel for private vehicle and cooking activities. The Appendix also reports the “Economy-wide tax + BTA” scenario, which simulates a border tax adjustment (BTA), whereby importers pay a tax proportional to the carbon embodied in the imported good.

4.3.2 The Input-Output and Microsimulation Module

In input-output (IO) analysis, the total output of the economy can be determined by the following system:

$$x = (I - A)^{-1} y \tag{4.1}$$

Where x is the total (gross) output vector, I is identity matrix, A is technical coefficient matrix, and y is a vector of final demand. $(I - A)^{-1}$ is known as the Leontief inverse matrix which captures the total inputs required by each sector to produce one unit of final demand. The embodied carbon tax in household h's consumption, can be determined by

$$\sum_{n,m} t^{emb}_{h,n,m} = \hat{\tau} q^T (I - A)^{-1} y_{h,n,m} \tag{4.2}$$

Where $t^{emb}_{h,n,m}$ denotes the vector of direct and indirect carbon tax embodied in household h's consumption, containing n sectors and m countries. $\hat{\tau}$ is the vector of carbon tax rates in dollar per tonne of CO_2 (the hat denotes diagonalization) and q^T is the vector of direct carbon emissions per unit of gross output, or simply emission intensities (the superscript T denotes the transposition of a vector). We assume that in a carbon taxation scenario, the carbon tax rate is always equal across sectors in the economy. $y_{h,n,m}$ denotes the column vector of household h's consumption, containing n sectors and m countries, which is constructed by first harmonizing the Indonesian household survey product classification into the EXIOBASE product classification, and then estimating[5] it using the share of household final demand from the EXIOBASE final demand data,

$$y_{h,n,m} = \frac{y_{n,m}}{\sum_m y_{n,m}} \cdot y_{h,n} \tag{4.3}$$

where $y_{n,m}$ denotes the column vector of household final demand (from the EXIOBASE) and $y_{h,n}$ denotes household h's consumption bundle containing n sectors (from the Indonesian household survey that has been mapped into EXIOBASE product classification).

The carbon tax associated with household h's direct emissions, t^{dir}_h, is calculated by multiplying the corresponding carbon tax rate with household h's direct emissions from fuel combustion h, $e_{h,fuel}$,

$$t^{dir}_h = \tau \cdot e_{h,fuel} \tag{4.4}$$

[5]Indonesia household survey data does not differentiate between domestically-sourced and imported consumption items.

In EXIOBASE, direct household emissions are available as a single-entry aggregate and interpreted as 'the aggregate households' direct emissions associated with fuel combustion from using private vehicles and cooking activities. Thus, we estimate the direct emissions of household h, $e_{h,fuel}$, by the share of its monetary expenditure for fuel in the total fuel monetary expenditures of all households and its household survey weight:

$$e_{h,fuel} = \frac{y_{h,fuel}}{\sum_h y_{h,fuel}} \cdot e^{dir}_{fuel} \cdot \frac{1}{\omega_h} \tag{4.5}$$

Where e^{dir}_{fuel} denotes the (aggregate) direct household emissions and ω_h denotes household h's survey weight (household survey weight determines the number of households in real life the corresponding household represents).

The total carbon tax of household h is the sum of the direct and the embodied carbon tax in its expenditure,

$$t_h = t^{dir}_h + \sum_{n,m} t^{emb}_{h,n,m} \tag{4.6}$$

To include only the relevant region or products to which a carbon tax is levied, the emission intensities of foreign countries or products are set to 0. The total carbon tax revenue T the government collects from the implementation of carbon tax is the sum of the additional cost of all households:

$$T = \sum_h t^{dir}_h + \sum_{h,n,m} t^{emb}_{h,n,m} \tag{4.7}$$

The relative net impact of a carbon tax on household h after a carbon tax and cash transfer program is the ratio between the absolute net impact of carbon tax and the initial expenditure,

$$I_h = \frac{-t_h + s_h}{\sum_{n,m} y_{h,n,m}} \tag{4.8}$$

I_h denotes the relative net impact of carbon tax on household h's expenditure. s_h denotes the cash household h receives from the corresponding cash transfer program, which is assumed to be consumed entirely in proportion to its initial consumption. Otherwise, s_h is 0 when the cash transfer is non-existent.

The relative net impact of the first income decile q_1 is then determined by,

$$I_{q_1} = \sum_{h=1}^{q1} V_h \cdot I_h = \sum_{h=1}^{q1} V_h \cdot \frac{-\sum_n t_{h,n} + s_h}{\sum_{n,m} y_{h,n,m}} \tag{4.9}$$

Where V_h denotes the share of household h's survey weight in total survey weight of households belonging in the first income decile,

$$V_h = \frac{\omega_h}{\sum_{h=1}^{q_1} \omega_h} \tag{4.10}$$

4.4 Data

For the EE MRIO module, we use the monetary product-by-product EXIOBASE 3.8.2 MRIO tables (Stadler et al., 2018). The EXIOBASE 3.8.2 data are constructed on the basis of the existing macroeconomic data published by multiple official sources such as the UN Accounts Main Aggregate Database, the services trade data from the UN Service Trade Database, the Detailed Tables of the UN National Accounts Statistics and national statistical offices for product and industry output, goods and trade data from BACI (Gaulier and Zignago, 2010), and the additional supply and use tables from national statistical offices. The EXIOBASE 3.8.2 consists of 44 countries (including Indonesia) and five ROW (rest of the world) aggregate regions, covering 200 product categories per country with electricity sector disaggregated on the basis of energy source. The EXIOBASE Supply-Use Table (SUT) disaggregates the electricity sector on the basis of the International Energy Agency (IEA) energy balance by taking into consideration the share of electricity that goes both to industry as well as residential use and the countries' energy mix (Stadler et al., 2018). The EXIOBASE 3.8.2 also provides detailed environmental satellite accounts, including the CO_2 emissions (kg) as the environmental stressor variable and the direct emissions from fuel combustion by households. We add the latter to the emissions embodied in motor gasoline product before calculating the emission intensity of household final demand. We use the EXIOBASE 3.8.2 2019 table instead of the latest available year to avoid any economic anomaly caused by the Global Pandemic.

For microsimulation, we use household expenditure survey data of Indonesia, documented in SUSENAS (The National Economic Survey) 2019 by Badan Pusat Statistik (The Indonesia Statistical Office). SUSENAS is a series of comprehensive surveys to record socioeconomic data at the household level. SUSENAS covers around 300.000 household samples across 34 provinces in Indonesia. The data document the amount (in Indonesian Rupiah) each household spends on 315 consumption items. Since we are the first to combine the EXIOBASE 3.8.2. with the Indonesia household survey data for 2019, we construct our own concordance table (or 'bridge matrix') to harmonize SUSENAS item classification to EXIOBASE 3.8.2 product classification. To do this, we take inspiration from the various concordance tables provided by the EXIOBASE and the study done by Steckel et al. (2021) which also uses Indonesia household survey data. This concordance table is provided in the Appendix. We split electricity consumption for each household in the SUSENAS data into the EXIOBASE 12 electricity sub-products (coal, hydro, etc.) by using the final demand share of electricity sub-products in total electricity final demand by households.

4.5 Results and Discussion

4.5.1 Distributional Implications of Carbon Tax

To estimate the impacts of the carbon policy reform on Indonesian households, we simulate an economy-wide carbon tax of $40 per tonne of CO_2 under three recycling schemes: (1) A 'No transfer' scheme where there is no cash transfer program in place, hence the household impacts are asserted only by the carbon tax. (2) A '100% recycling' scheme in which 100% of the carbon tax revenues are transferred back to households, and every household receives the same amount. 3) A cash transfer of $100 to each household. Figure 4.5.1 reports the net impacts by income decile.

Both the '100% recycling' and the '$100 flat' scheme tend to be progressive: low-income households net gain (the relative net impact is positive) and high-income households net lose (the relative net impact is negative). However, without an accompanying cash transfer policy, a carbon tax per se is neither progressive nor regressive, as it would affect households almost equally in proportional terms. In the '100% recycling' scheme, the cash transfer per household amounts to $316. The bottom 90% of households would net benefit from such a carbon tax reform. However, only the bottom 50% of households would net benefit from the '$100 flat' scheme. If the carbon tax rate was set at $40 per tonne of CO_2, the '$100 flat' scheme would only require 32% of the total carbon tax revenue collected. In the past, BLT cash transfer programs in Indonesia were not tied to the magnitude of particular tax revenues (Basri and Riefky, 2023).

The average carbon tax burden of a $40 carbon tax is roughly 4.8% across all income deciles. This (almost) uniform tax burden reflects the consumption patterns in Indonesia where all households, regardless of income, bear the tax proportionally to their expenditure on consumption goods. The distributional implications change with the introduction of a revenue recycling mechanism. In the '100% recycling' scheme, for the poorest 10% of

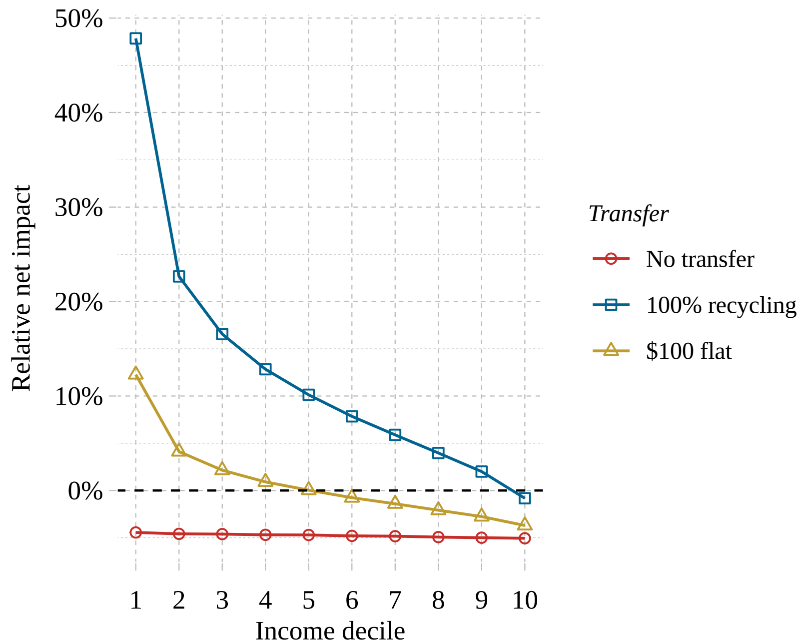


Figure 4.5.1: Relative net impact of a $40 national economy-wide carbon Tax.

Notes: Own calculations. The values represent the net impacts (in percent of initial expenditure) of a $40/tonne economy-wide carbon tax and three alternative cash transfer schemes. The ‘No transfer’ scenario shows the impacts of the carbon tax only. The ‘100% recycling’ scheme assumes that 100% of the carbon tax revenues are transferred back to households (every household receives the same amount). The ‘$100 flat’ scheme transfers $100 to every household.

households, the transfers received are far greater than the additional expenditure required to maintain the old consumption bundle. The net gain is substantial (the relative net impact is 48%). For the richest 10% of households, the relative net impact amounts to minus 0.8%, meaning the ‘100% recycling’ does not fully offset the carbon tax impact on higher-income households. The relative net impact significantly decreases from the 1st to the 2nd decile; it then decreases gradually from the 2nd to the 10th decile. Cash transfers greatly benefit the poorest 10% of households.

Which consumption categories contribute to the incidence of the carbon tax? We aggregate household consumption categories into four groups (electricity, fuel, food, and all other categories) and investigate how these groups contribute to the total impacts (Figure 4.5.2). Irrespective of the income group, the economy-wide implementation of a carbon tax primarily affects households through price increases in electricity and fuel, with electricity price increases having a greater impact than fuel price increases. For households in the lowest income decile, electricity consumption is responsible for more than half of the burden (57%) and fuel use contributes 32%. Together, these two sectors account for 89% of the carbon tax burden for this income group. In contrast, food and other consumption items contribute much less, 1% and 10% respectively. The carbon tax significantly impacts the lowest income households through their expenditures on fuel and electricity. This pattern is consistent across the income spectrum, with fuel and electricity consumption contributing between 86% and 89% to the carbon tax for households in the middle- and high-income deciles as well.

While the carbon tax impacts all households mainly through price increases in electricity and fuel, both electricity and fuel constitute only a small portion of households’ expenditures (Figure 4.5.2). Most household expenditure is directed towards food and other consumption items.

For households in the lowest income decile, electricity and fuel account for only 10% of their expenditure, while food and other consumption items account for 63% and 27%, respectively. The consumption pattern of the top 10% households differs from that of the bottom 10%. Food accounts for 35% of their expenditure, while other consumption items contribute 53% to the total. However, the top 10% households only spend 12% on electricity and fuel. Despite the higher absolute spending on electricity and fuel in dollar terms, the expenditure shares of these emission-intensive categories is comparable in magnitude to the bottom 10% households. A similar expenditure pattern is observed for households between these two income groups, with the share of food in expenditure gradually decreases as income increases.

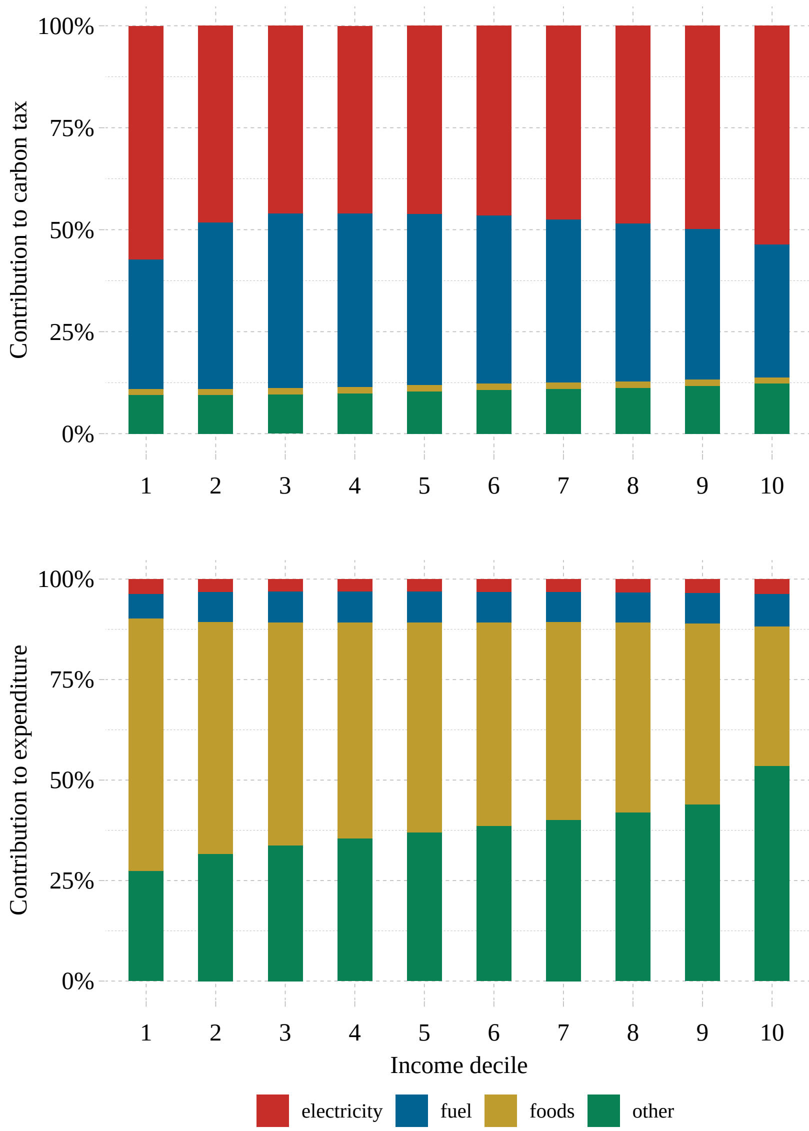


Figure 4.5.2: Distribution of carbon tax incidence and expenditure by consumption category across income deciles

Notes: Own calculations. The top chart displays the percentage contribution of electricity, fuel, foods, and other goods to the total carbon tax burden by income decile (see Table 4.A.9 and Table 4.A.10 in the Appendix). The bottom chart displays the corresponding expenditure distribution by income decile (see Table 4.A.12 in the Appendix).

4.5.2 Key Takeaways of the Appendix

In the Appendix, we report results for four revenue recycling rates (0%, 25%, 75%, and 100%), four different tax rates ($2, $40, $100, and $120) and four tax bases (the 'economy-wide', the 'electricity-only', the 'fuel-only', and the 'economy-wide tax + BTA' scenario). The distributional implications of a carbon tax, with no transfers, do not depend on the tax rate. This is because the MRIO model is linear; therefore, changing tax rates will only change the overall magnitude of the impacts, but not their distribution. The choice of the tax base and recycling rate determine which income groups will net benefit from a carbon policy reform. For instance, when the carbon tax revenue is 100% recycled, the top 20% of households will experience a net loss when the tax base is confined to 'electricity-only', whereas they will experience a net benefit under an 'economy-wide' tax base (Appendix Table 4.A.1).

Introducing a BTA mechanism on imports alongside an economy-wide carbon tax does not significantly affect the distribution of the relative net impacts. The BTA mechanism, which is designed to level the playing field between domestic products subject to carbon tax and imported goods, only marginally alters the relative net impacts by income decile. The distributional effects are broadly unchanged.

4.5.3 What Percentage of the Carbon Tax Revenue Would Need to be Recycled to Protect the Poor?

If the carbon policy reform varies more by the recycling rates and scenarios, and if the Indonesian government would want to raise the initial carbon tax rate of $2 per tonne CO_2 because the impacts are fairly minimal, to what extent the government would need to recycle the carbon tax revenue? We use a $40 per tonne CO_2 carbon tax rate to explore the percentage of revenue that would need to be uniformly recycled in two policy-relevant carbon tax scenarios: the national carbon tax and the 'electricity-only' carbon tax. In both scenarios, we find that uniformly recycling at least a quarter of the expected tax revenue net benefits 40% poorest households (Figure 4.5.3). This is shown by the recovery experienced by households in the first four income deciles in both taxation scenarios. This distribution will not change if the carbon tax rate is raised, whether the carbon tax is levied only on the electricity sectors or on the entire economy. Therefore, Indonesia would need to focus more on how the carbon tax revenue is recycled and on the carbon taxation scenarios.

Figure 4.5.3: Relative net impact (expressed in % of initial expenditure) of a \$40 'Economy-wide' carbon tax (left) and a \$40 'Electricity-only' carbon tax (right) on the poorest 40% of households.

Notes: Own calculations. A darker color indicates lower percentage of relative net impact. The bottom four deciles are shown along the horizontal axis.

4.6 Summary and Concluding Remarks

This study combines the Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model with microsimulation to measure the direct and indirect impacts of carbon policy reform (a carbon tax and revenue recycling program) on households across different income levels in Indonesia. The impact of the carbon policy reform on households is measured by the relative net impact, that is, the net effect of the carbon tax (negative) and accompanying cash transfer (positive) relative to initial household expenditure. In general, carbon policy reform in Indonesia has a progressive tendency: the relative net impact of carbon policy reform becomes smaller and eventually turns negative as household income increases. A carbon policy reform would need to be evaluated not only by its progressiveness (or regressiveness) but also by considering whether low-income households recover from the carbon policy reform. A compensation scheme, at least for the poorest households, is necessary to increase the public's acceptability of the carbon policy reform (Klenert et al., 2018; Carattini et al., 2017; Drews and Van den Bergh, 2016). The Indonesian government would need to recycle at least 25% of the carbon tax revenue to the bottom 40% households in order for them to maintain their initial consumption levels.

The tax on carbon emissions in Indonesia mainly affects households through the price increases of electricity and fuel for private vehicles and cooking activities. Electricity contributes more to the total price increase than fuel. These two products, however, only make up a fraction of the total annual expenditure of households, regardless of income level. Most of the households' annual expenditure consists of spending on food products and other consumption items. A carbon tax only on electricity and fuel products will involve lower administrative cost compared to an economy-wide national carbon tax, while being almost as effective.

The distribution of relative net impacts across households by income deciles is determined primarily by the revenue recycling percentages and the carbon tax scenario. The rate of the carbon tax only influences the magnitude of the relative net impact, but not the distribution of impacts. The low-income households can be restored to their pre-tax consumption levels when enough tax revenue is redistributed to those households. This analysis has shown that this can already be done by recycling 25% of the carbon tax revenue to support the poorest 40% of Indonesian households. However, in practice, a carbon tax may be administratively complex to implement and the Indonesian state may not be able to collect the carbon tax revenue in its entirety. The Indonesian government has pledged to gradually widen the base of the carbon tax. If we assume that the carbon tax revenue cannot be fully collected and redistributed, the Indonesian government should prioritize the poorest households. This can be done by a targeted cash transfer program exclusively for low-income households.

We note that funding a cash transfer program by means of the revenues from carbon taxation could turn out to be problematic over time. As carbon emissions decline in response to the tax, the tax base shrinks, which may reduce government revenue depending on the sensitivity of emissions to the tax rate. While this funding problem may arise, it is not likely to happen soon, primarily because the price-elasticity of the demand for carbon-intensive goods and services is relatively low and also because carbon tax rates will most likely be ramped up more slowly than in some of our experiments. In addition, if the supply of renewable energy at lower cost is scaled up, households will reduce their consumption of carbon-intensive goods and services in favour of low- or zero-carbon goods and services. This will, in turn, reduce the need for the cash compensation for the real income losses due to carbon taxation.

This study uses a static model to measure the impacts of carbon tax and revenue recycling policy, under the assumption that the price elasticities of producer and consumer of demand functions are zero. This represents a limitation to this study. In reality, households are likely to adjust their behavior in response to the economy-wide price increase induced by carbon tax. For instance, households may shift their expenditure from products with high relative price increases to those with lower relative price increases. Future research could explore more comprehensive models that incorporate behavioral responses of households and producers. This could be done by 'closing' the input-output model (i.e., by endogenizing part of demand as a function of income) and by incorporating the responses of consumers and producers to the changes in relative prices. Additionally, future research could also explore more dynamic modeling approaches by capturing the effects of carbon taxation on technological progress, industrial restructuring, and capital accumulation over time.

While this study focuses on Indonesia, the methodology and findings could be extended to evaluate similar impacts in other developing countries with comparable socioeconomic and energy profiles. This would provide insights into how carbon taxation and revenue recycling schemes can be designed to fit into different national contexts to achieve both environmental and social objectives.

Data Availability

Global and country-specific Input-Output data are available free of charge from EXIOBASE (https://zenodo.org/records/5589597). Household survey data are available on request from the Indonesian statistical office (Badan Pusat Statistik), in which restrictions and fees apply to utilize the data (https://www.bps.go.id/en). Authors have been granted permission to use the Indonesian household survey data for research purposes.

Code Availability

For transparency and reproducibility, the code written for this study is made available here: https://github.com/gustinara/IDNCarbonTax.

Appendix

4.A Simulation Results

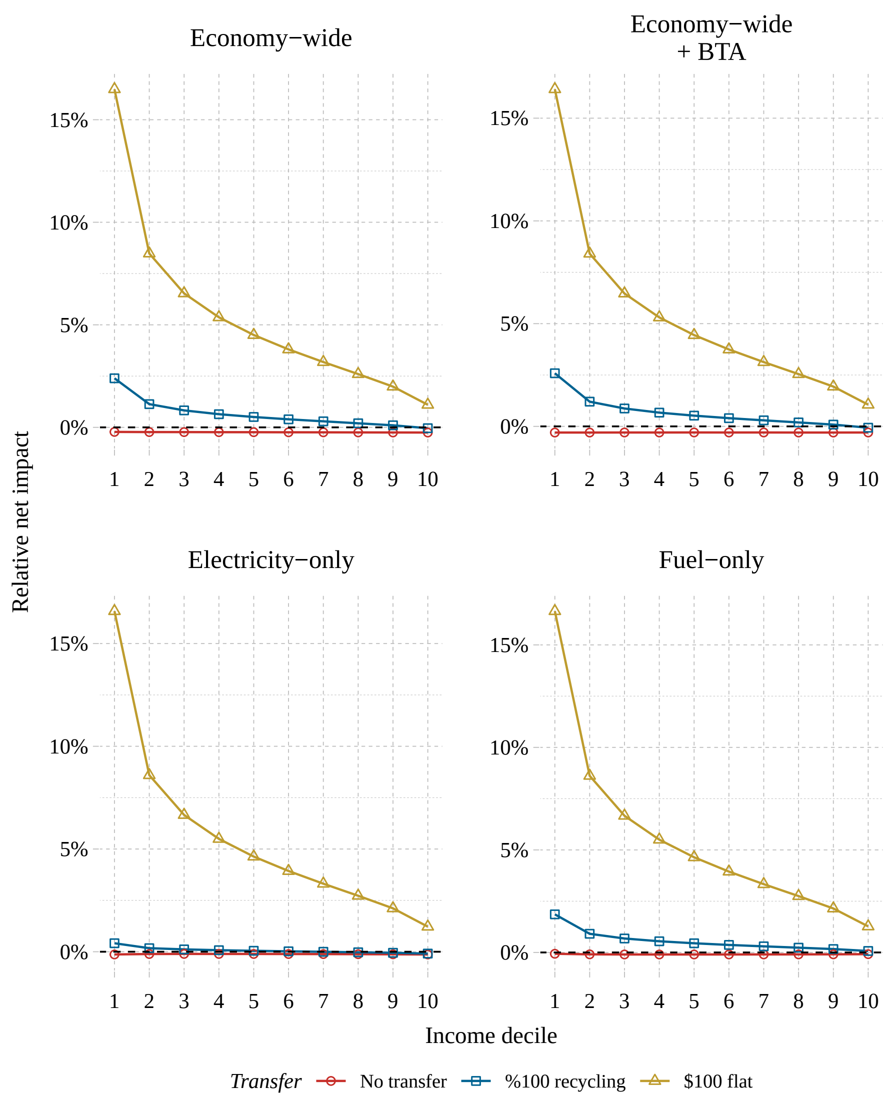


Figure 4.A.1: Relative net impact of a $2/tonne carbon tax in various pricing scenarios.

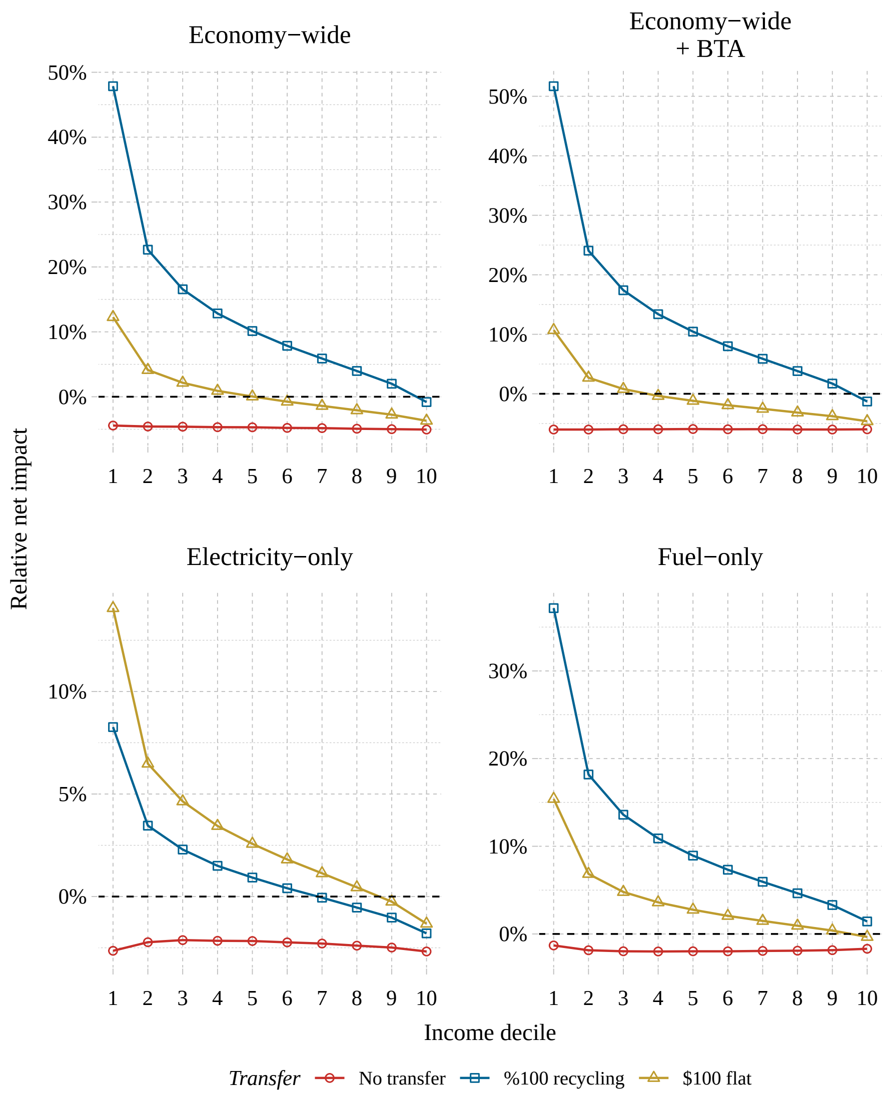


Figure 4.A.2: Relative net impact of a $40/tonne carbon tax in various taxation scenarios.

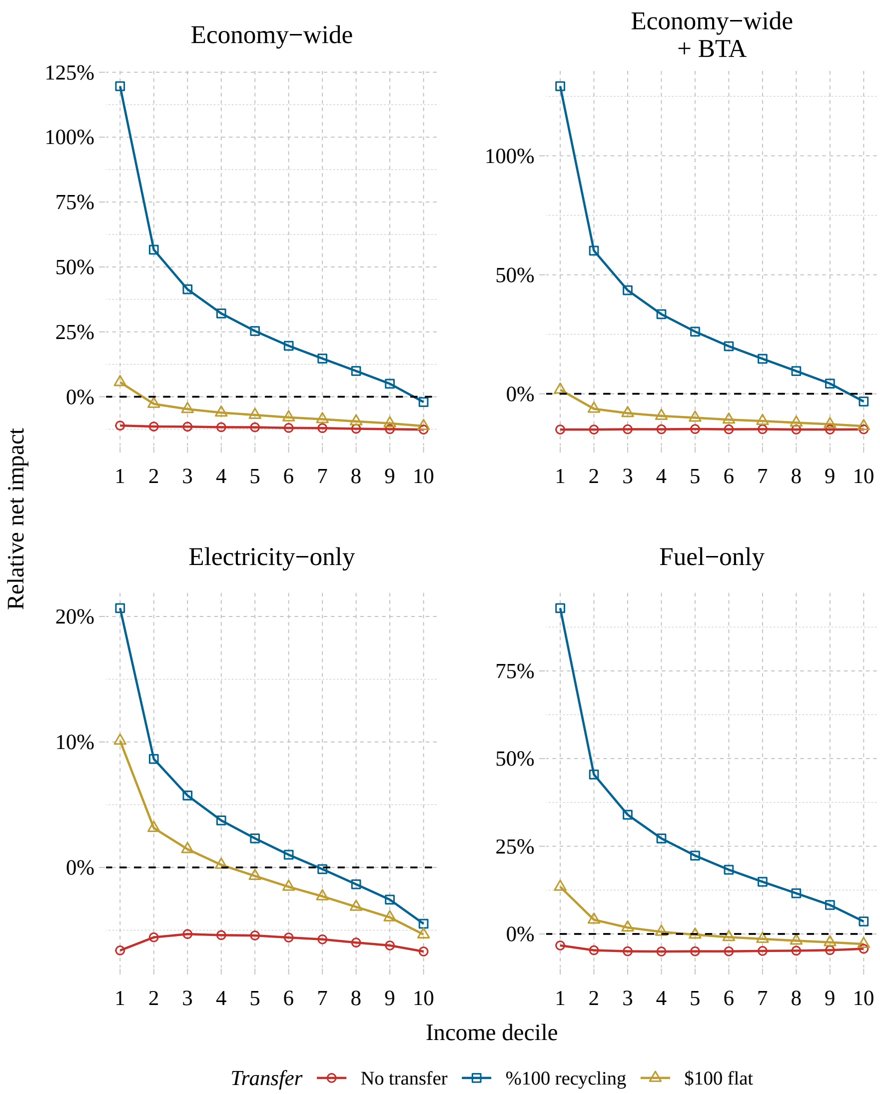


Figure 4.A.3: Relative net impact of a $100/tonne carbon tax in various pricing scenarios.

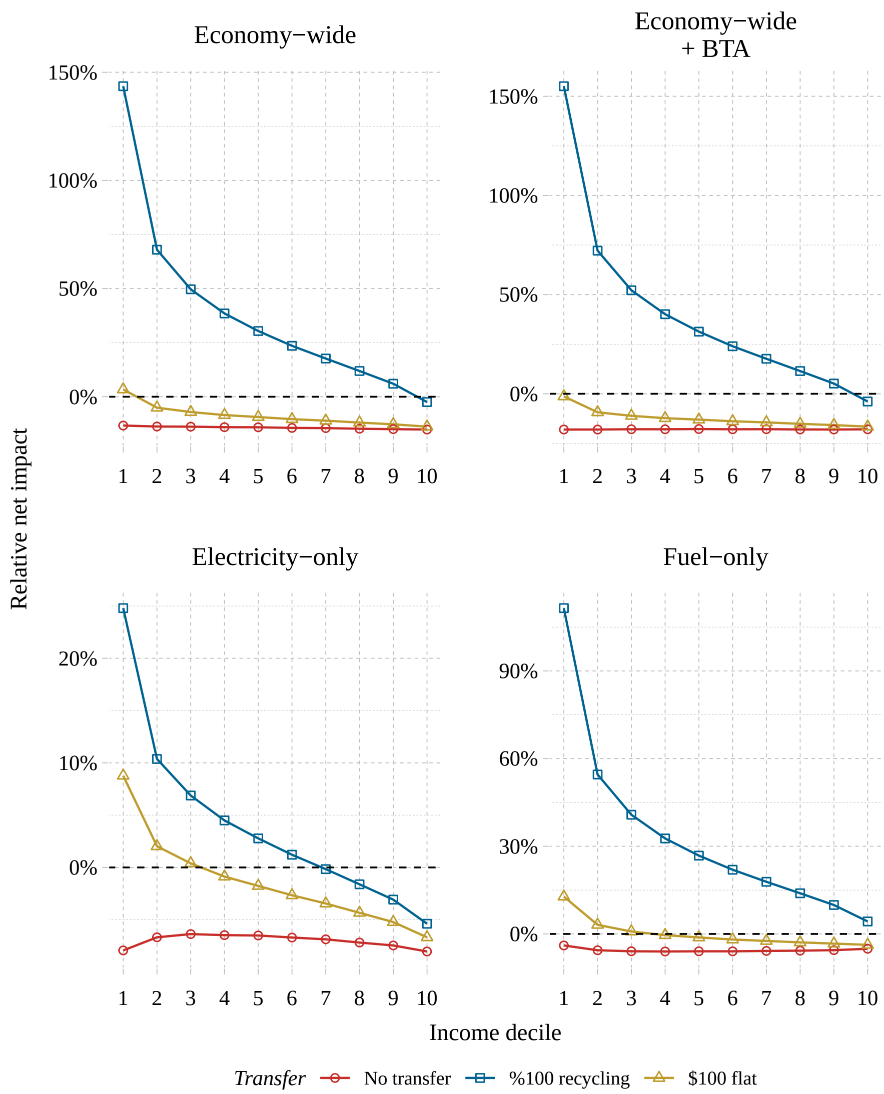


Figure 4.A.4: Relative net impact of a $120/tonne carbon tax in various pricing scenarios.

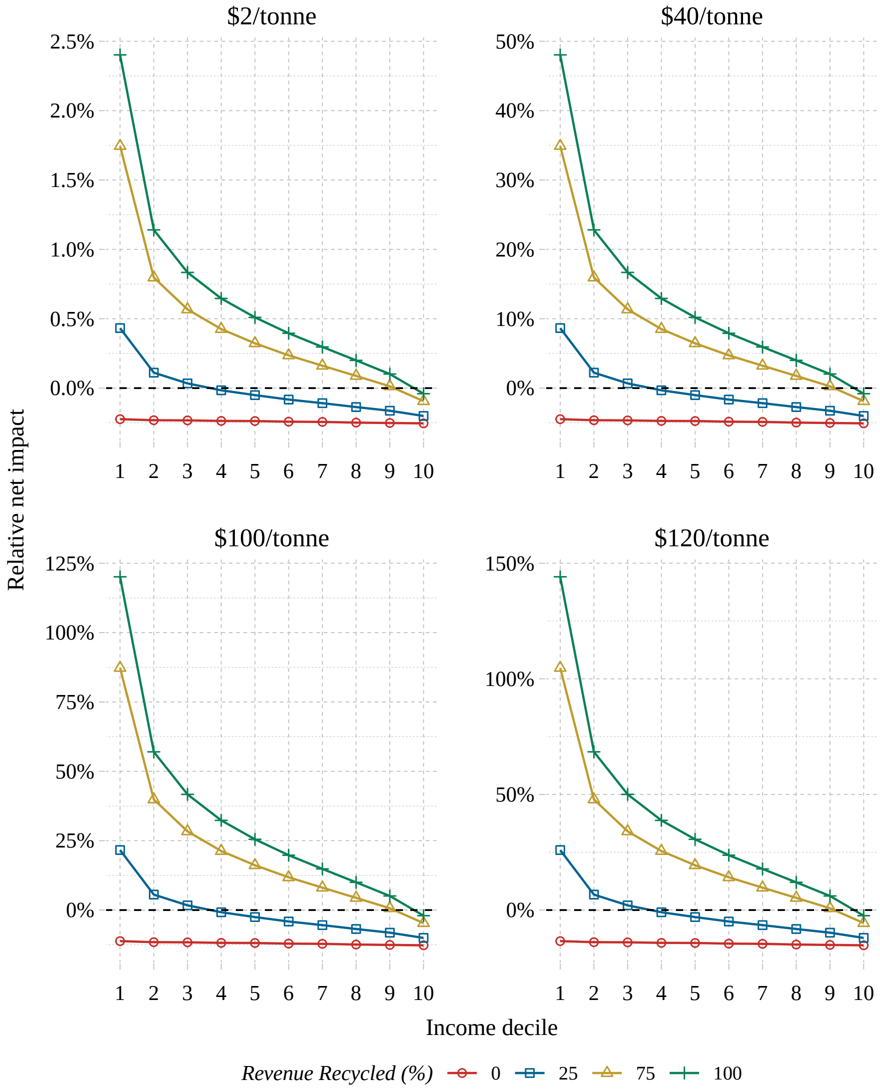


Figure 4.A.5: Relative net impact of various rates of national carbon tax under the uniform revenue recycling scenario.

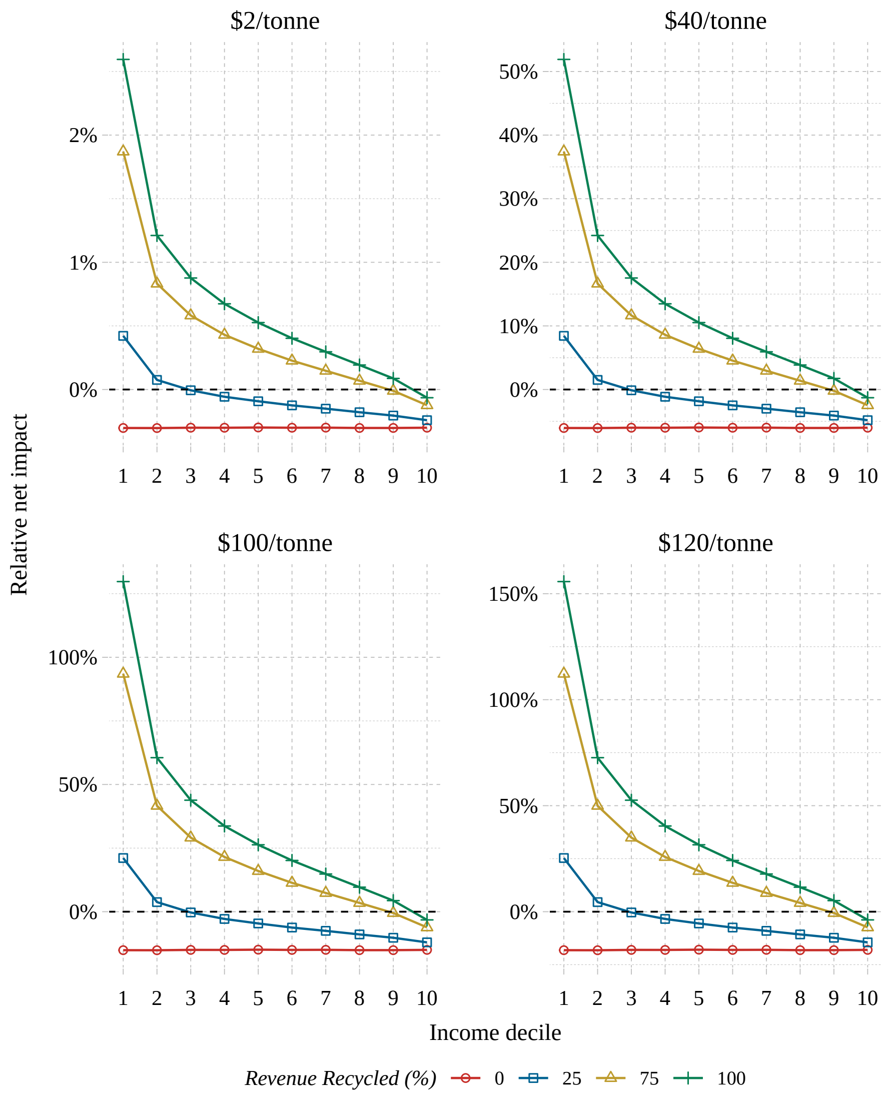


Figure 4.A.6: Relative net impact of various rates of national and imported carbon tax under the uniform revenue recycling scenario.

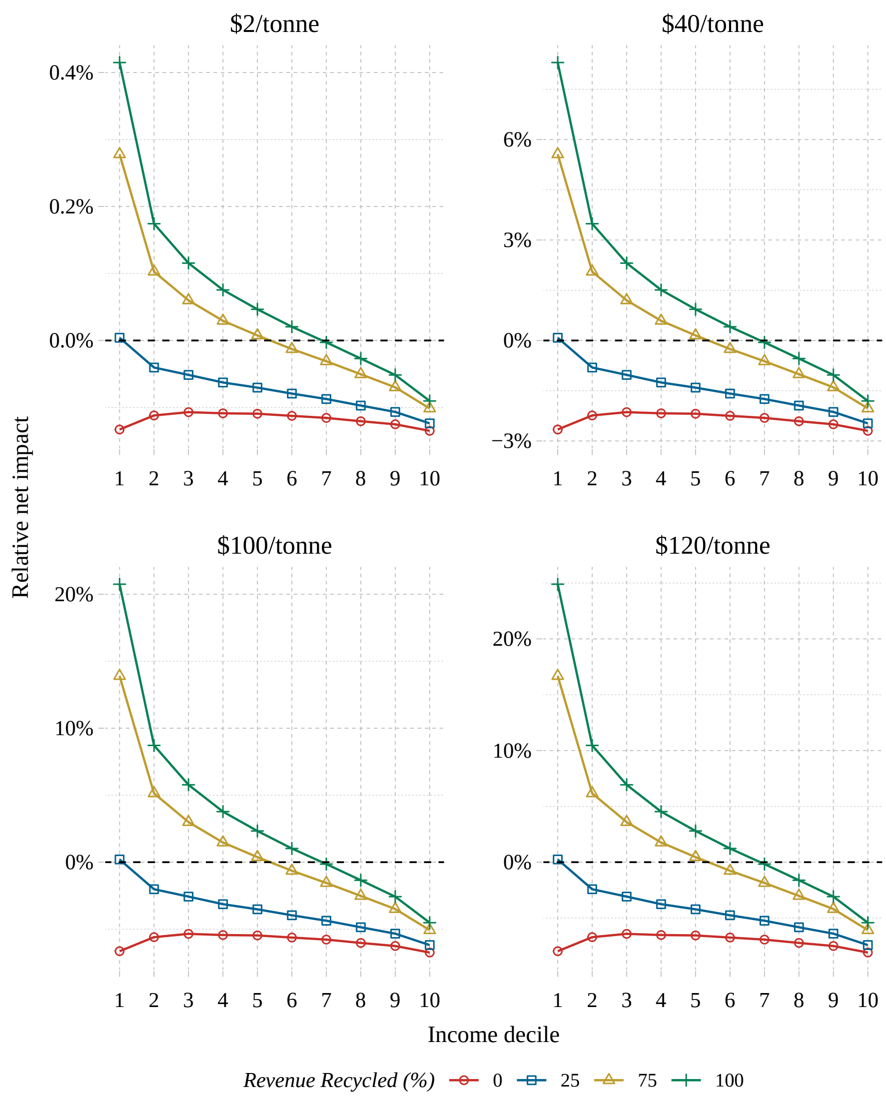


Figure 4.A.7: Relative net impact of various rates of national electricity carbon tax under the uniform revenue recycling scenario.

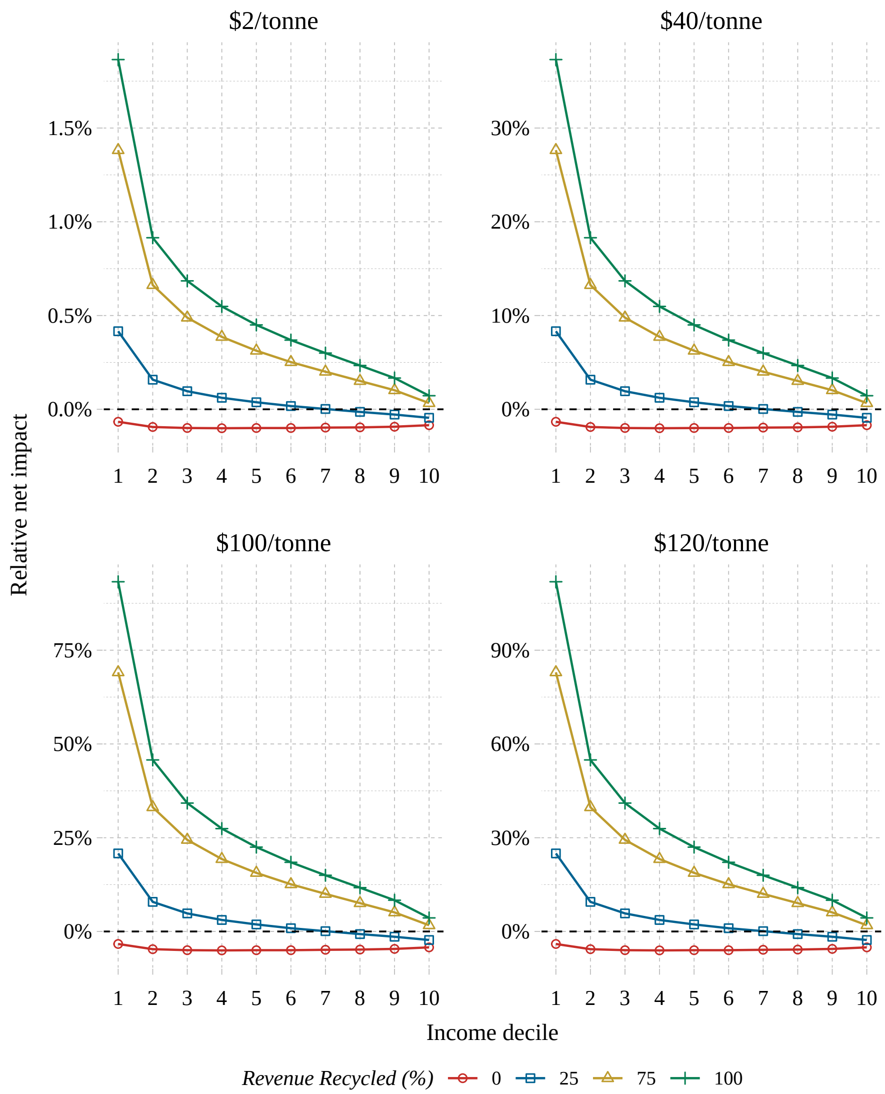


Figure 4.A.8: Relative net impact of various rates of national fuel carbon tax under the uniform revenue recycling scenario.

Table 4.A.1: Tax Scenarios and Impacts Across Quantiles

Tax Scenario	Tax Rate	Recycling (%)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
“Economy-wide”	$2	0	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
“Economy-wide”	$2	25	0.4	0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.2	-0.2
“Economy-wide”	$2	75	1.7	0.8	0.6	0.4	0.3	0.2	0.2	0.1	0.0	-0.1
“Economy-wide”	$2	100	2.4	1.1	0.8	0.6	0.5	0.4	0.3	0.2	0.1	0.0
“Economy-wide”	$40	0	-4.4	-4.6	-4.6	-4.7	-4.7	-4.8	-4.8	-4.9	-5.0	-5.1
“Economy-wide”	$40	25	8.6	2.2	0.7	-0.3	-1.0	-1.6	-2.2	-2.7	-3.2	-4.0
“Economy-wide”	$40	75	34.8	15.8	11.3	8.5	6.4	4.7	3.2	1.7	0.3	-1.9
“Economy-wide”	$40	100	47.9	22.7	16.6	12.8	10.1	7.8	5.9	4.0	2.0	-0.8
“Economy-wide”	$100	0	-11.1	-11.5	-11.5	-11.7	-11.8	-12.0	-12.1	-12.3	-12.5	-12.6
“Economy-wide”	$100	25	21.6	5.6	1.7	-0.8	-2.5	-4.1	-5.4	-6.8	-8.1	-10.0
“Economy-wide”	$100	75	87.0	39.6	28.2	21.1	16.0	11.7	8.0	4.4	0.6	-4.7
“Economy-wide”	$100	100	119.6	56.6	41.4	32.1	25.3	19.6	14.7	9.9	5.0	-2.0
“Economy-wide”	$120	0	-13.3	-13.8	-13.8	-14.1	-14.1	-14.4	-14.5	-14.8	-15.0	-15.2
“Economy-wide”	$120	25	25.9	6.7	2.0	-0.9	-3.0	-4.9	-6.5	-8.1	-9.7	-12.0
“Economy-wide”	$120	75	104.3	47.5	33.8	25.4	19.3	14.1	9.6	5.2	0.8	-5.6
“Economy-wide”	$120	100	143.6	68.0	49.7	38.5	30.4	23.5	17.7	11.9	6.0	-2.5
“Economy-wide+BTA”	$2	0	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
“Economy-wide+BTA”	$2	25	0.4	0.1	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2
“Economy-wide+BTA”	$2	75	1.9	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.0	-0.1
“Economy-wide+BTA”	$2	100	2.6	1.2	0.9	0.7	0.5	0.4	0.3	0.2	0.1	-0.1
“Economy-wide+BTA”	$40	0	-6.0	-6.0	-6.0	-6.0	-5.9	-6.0	-5.9	-6.0	-6.0	-6.0
“Economy-wide+BTA”	$40	25	8.4	1.5	-0.1	-1.1	-1.8	-2.5	-3.0	-3.5	-4.1	-4.8
“Economy-wide+BTA”	$40	75	37.3	16.5	11.6	8.5	6.4	4.5	2.9	1.4	-0.2	-2.5
“Economy-wide+BTA”	$40	100	51.7	24.1	17.4	13.4	10.4	8.0	5.9	3.8	1.7	-1.3
“Economy-wide+BTA”	$100	0	-15.0	-15.0	-14.9	-14.9	-14.8	-14.9	-14.9	-15.0	-15.0	-14.9
“Economy-wide+BTA”	$100	25	21.0	3.8	-0.3	-2.8	-4.6	-6.2	-7.5	-8.9	-10.2	-12.0
“Economy-wide+BTA”	$100	75	93.2	41.4	28.9	21.4	15.9	11.3	7.3	3.4	-0.5	-6.2
“Economy-wide+BTA”	$100	100	129.2	60.1	43.5	33.4	26.1	20.0	14.7	9.6	4.3	-3.2
“Economy-wide+BTA”	$120	0	-18.0	-18.0	-17.9	-17.9	-17.8	-17.9	-17.8	-18.0	-18.0	-17.9

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Tax Scenario	Tax Rate	Recycling (%)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
“Economy-wide+BTA”	$120	25	25.3	4.5	-0.4	-3.4	-5.5	-7.4	-9.0	-10.6	-12.2	-14.4
“Economy-wide+BTA”	$120	75	111.8	49.6	34.7	25.6	19.1	13.5	8.8	4.1	-0.6	-7.4
“Economy-wide+BTA”	$120	100	155.1	72.2	52.2	40.1	31.3	24.0	17.6	11.5	5.2	-3.9
“Electricity-only”	$2	0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
“Electricity-only”	$2	25	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
“Electricity-only”	$2	75	0.3	0.1	0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1
“Electricity-only”	$2	100	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.0	-0.1	-0.1
“Electricity-only”	$40	0	-2.6	-2.2	-2.1	-2.2	-2.2	-2.2	-2.3	-2.4	-2.5	-2.7
“Electricity-only”	$40	25	0.1	-0.8	-1.0	-1.2	-1.4	-1.6	-1.7	-1.9	-2.1	-2.5
“Electricity-only”	$40	75	5.5	2.0	1.2	0.6	0.2	-0.3	-0.6	-1.0	-1.4	-2.0
“Electricity-only”	$40	100	8.3	3.5	2.3	1.5	0.9	0.4	-0.1	-0.5	-1.0	-1.8
“Electricity-only”	$100	0	-6.6	-5.6	-5.3	-5.4	-5.4	-5.6	-5.7	-6.0	-6.2	-6.7
“Electricity-only”	$100	25	0.2	-2.0	-2.6	-3.1	-3.5	-3.9	-4.3	-4.8	-5.3	-6.1
“Electricity-only”	$100	75	13.8	5.1	3.0	1.5	0.4	-0.6	-1.5	-2.5	-3.5	-5.0
“Electricity-only”	$100	100	20.7	8.6	5.7	3.7	2.3	1.0	-0.1	-1.3	-2.6	-4.5
“Electricity-only”	$120	0	-7.9	-6.7	-6.4	-6.5	-6.5	-6.7	-6.9	-7.2	-7.5	-8.0
“Electricity-only”	$120	25	0.2	-2.4	-3.1	-3.7	-4.2	-4.7	-5.2	-5.8	-6.4	-7.4
“Electricity-only”	$120	75	16.6	6.1	3.6	1.8	0.5	-0.8	-1.8	-3.0	-4.2	-6.0
“Electricity-only”	$120	100	24.8	10.4	6.9	4.5	2.8	1.2	-0.2	-1.6	-3.1	-5.4
“Fuel-only”	$2	0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
“Fuel-only”	$2	25	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
“Fuel-only”	$2	75	1.4	0.7	0.5	0.4	0.3	0.2	0.2	0.2	0.1	0.0
“Fuel-only”	$2	100	1.9	0.9	0.7	0.5	0.4	0.4	0.3	0.2	0.2	0.1
“Fuel-only”	$40	0	-1.3	-1.9	-2.0	-2.0	-2.0	-2.0	-1.9	-1.9	-1.8	-1.7
“Fuel-only”	$40	25	8.3	3.2	1.9	1.2	0.8	0.3	0.0	-0.3	-0.6	-0.9
“Fuel-only”	$40	75	27.5	13.2	9.7	7.7	6.2	5.0	4.0	3.0	2.0	0.6
“Fuel-only”	$40	100	37.2	18.2	13.6	10.9	8.9	7.3	6.0	4.6	3.3	1.4
“Fuel-only”	$100	0	-3.3	-4.6	-4.9	-5.0	-4.9	-5.0	-4.8	-4.8	-4.6	-4.2
“Fuel-only”	$100	25	20.8	7.9	4.8	3.1	1.9	0.9	0.1	-0.7	-1.4	-2.3
“Fuel-only”	$100	75	68.9	32.9	24.3	19.2	15.5	12.5	9.9	7.5	5.0	1.6
“Fuel-only”	$100	100	92.9	45.5	34.0	27.2	22.3	18.3	14.9	11.6	8.3	3.6

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Tax Scenario	Tax Rate	Recycling (%)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
“Fuel-only”	$120	0	-3.9	-5.6	-5.9	-6.0	-5.9	-5.9	-5.8	-5.7	-5.5	-5.1
“Fuel-only”	$120	25	24.9	9.5	5.8	3.7	2.3	1.0	0.1	-0.8	-1.7	-2.7
“Fuel-only”	$120	75	82.6	39.5	29.1	23.0	18.6	15.0	11.9	9.0	6.0	1.9
“Fuel-only”	$120	100	111.5	54.6	40.8	32.7	26.8	22.0	17.9	13.9	9.9	4.3

Table 4.A.2: The amount of uniform cash transfer received by each household in various carbon tax rates and scenarios in Indonesia

	Tax base			
Carbon tax rate	"Economy-wide"	"Economy-wide + BTA"	"Electricity-only"	"Fuel-only"
$2	$16	$17	$3	$12
$40	$316	$349	$66	$232
$100	$790	$871	$165	$581
$120	$948	$1046	$198	$697

Table 4.A.3: Percentage of carbon tax revenue used for the BLT cash transfer program in various carbon tax rates and scenarios in Indonesia

	Scenario			
Carbon tax rate	"Economy-wide"	"Economy-wide + BTA"	"Electricity-only"	"Fuel-only"
2	100%	100%	100%	100%
40	32%	29%	100%	43%
100	13%	11%	61%	17%
120	11%	10%	51%	14%

Table 4.A.4: Relative Net Impact of a $2/tonne carbon tax in various pricing scenarios and cash transfer options (%)

Income decile	National			National + Import			Electricity			Fuel		
	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT
1	-0.224	2.402	16.558	-0.303	2.595	16.479	-0.133	0.415	16.649	-0.067	1.865	16.715
2	-0.231	1.140	8.537	-0.303	1.211	8.465	-0.112	0.174	8.656	-0.094	0.915	8.674
3	-0.233	0.834	6.584	-0.300	0.877	6.516	-0.107	0.116	6.709	-0.100	0.685	6.717
4	-0.237	0.646	5.406	-0.301	0.674	5.342	-0.109	0.075	5.534	-0.101	0.549	5.542
5	-0.237	0.510	4.539	-0.299	0.526	4.477	-0.109	0.047	4.667	-0.100	0.450	4.676
6	-0.242	0.395	3.831	-0.300	0.403	3.772	-0.113	0.020	3.960	-0.100	0.369	3.973
7	-0.244	0.297	3.209	-0.300	0.296	3.153	-0.116	-0.003	3.337	-0.098	0.300	3.355
8	-0.249	0.200	2.618	-0.302	0.193	2.564	-0.121	-0.027	2.746	-0.096	0.234	2.770
9	-0.251	0.102	2.004	-0.302	0.087	1.953	-0.125	-0.051	2.130	-0.093	0.167	2.162
10	-0.254	-0.040	1.111	-0.300	-0.064	1.065	-0.135	-0.090	1.230	-0.085	0.072	1.281

Notes: Own calculations. NT stands for no transfer where there is no accompanying cash transfer policy.

Table 4.A.5: Relative Net Impact of a $40/tonne carbon tax in various pricing scenarios and cash transfer options (%)

	National			National + Import			Electricity			Fuel		
Income decile	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT
1	-4.48	48.04	12.31	-6.05	51.90	10.73	-2.66	8.30	14.12	-1.33	37.30	15.45
2	-4.63	22.81	4.14	-6.06	24.22	2.71	-2.24	3.49	6.53	-1.89	18.30	6.88
3	-4.65	16.68	2.16	-6.01	17.53	0.81	-2.14	2.31	4.68	-1.99	13.70	4.82
4	-4.73	12.93	0.91	-6.01	13.47	-0.37	-2.17	1.51	3.47	-2.02	10.97	3.62
5	-4.75	10.20	0.03	-5.97	10.52	-1.20	-2.19	0.93	2.59	-2.00	9.00	2.78
6	-4.84	7.91	-0.76	-6.01	8.05	-1.94	-2.25	0.41	1.82	-2.00	7.38	2.08
7	-4.87	5.93	-1.42	-5.99	5.93	-2.54	-2.31	-0.06	1.14	-1.95	6.00	1.50
8	-4.97	4.00	-2.11	-6.05	3.85	-3.18	-2.41	-0.54	0.46	-1.93	4.67	0.94
9	-5.03	2.03	-2.77	-6.05	1.74	-3.79	-2.50	-1.03	-0.25	-1.86	3.33	0.40
10	-5.08	-0.81	-3.72	-6.00	-1.29	-4.64	-2.70	-1.81	-1.33	-1.69	1.45	-0.33

Notes: Own calculations. NT stands for no transfer where there is no accompanying cash transfer policy.

Table 4.A.6: Relative Net Impact of a $100/tonne carbon tax in various pricing scenarios and cash transfer options (%)

	National			National + Import			Electricity			Fuel		
Income decile	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT
1	-11.19	120.10	5.59	-15.13	129.75	1.65	-6.65	20.75	10.14	-3.33	93.25	13.45
2	-11.57	57.02	-2.81	-15.15	60.54	-6.38	-5.60	8.72	3.17	-4.72	45.74	4.05
3	-11.63	41.69	-4.81	-15.01	43.83	-8.20	-5.35	5.78	1.47	-4.98	34.24	1.83
4	-11.83	32.32	-6.18	-15.03	33.68	-9.39	-5.44	3.77	0.21	-5.04	27.43	0.60
5	-11.86	25.50	-7.09	-14.93	26.30	-10.15	-5.47	2.33	-0.69	-4.99	22.49	-0.22
6	-12.09	19.77	-8.02	-15.02	20.14	-10.95	-5.63	1.02	-1.55	-4.99	18.45	-0.92
7	-12.18	14.83	-8.73	-14.99	14.82	-11.53	-5.78	-0.14	-2.33	-4.88	14.99	-1.43
8	-12.43	9.99	-9.56	-15.12	9.63	-12.25	-6.03	-1.35	-3.16	-4.82	11.68	-1.95
9	-12.57	5.08	-10.31	-15.12	4.35	-12.86	-6.26	-2.57	-4.00	-4.65	8.33	-2.39
10	-12.71	-2.02	-11.34	-15.01	-3.22	-13.65	-6.74	-4.52	-5.38	-4.23	3.62	-2.87

Notes: Own calculations. NT stands for no transfer where there is no accompanying cash transfer policy.

Table 4.A.7: Relative Net Impact of a $120/tonne carbon tax in various pricing scenarios and cash transfer options (%)

Income decile	National			National + Import			Electricity			Fuel		
	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT	NT	Uniform	BLT
1	-13.43	144.12	3.35	-18.15	155.70	-1.37	-7.97	24.90	8.81	-4.00	111.90	12.78
2	-13.89	68.42	-5.12	-18.18	72.65	-9.42	-6.72	10.46	2.05	-5.66	54.89	3.11
3	-13.96	50.03	-7.14	-18.02	52.60	-11.20	-6.42	6.93	0.40	-5.98	41.09	0.84
4	-14.19	38.78	-8.55	-18.03	40.42	-12.39	-6.52	4.53	-0.88	-6.05	32.91	-0.41
5	-14.24	30.60	-9.46	-17.91	31.56	-13.14	-6.56	2.79	-1.78	-5.99	26.99	-1.21
6	-14.51	23.72	-10.44	-18.03	24.16	-13.96	-6.75	1.23	-2.68	-5.99	22.14	-1.92
7	-14.61	17.80	-11.16	-17.98	17.78	-14.53	-6.93	-0.17	-3.48	-5.86	17.99	-2.40
8	-14.92	11.99	-12.05	-18.14	11.55	-15.28	-7.23	-1.62	-4.37	-5.78	14.01	-2.92
9	-15.08	6.09	-12.83	-18.14	5.23	-15.88	-7.51	-3.09	-5.25	-5.57	10.00	-3.32
10	-15.25	-2.43	-13.88	-18.01	-3.87	-16.65	-8.09	-5.42	-6.73	-5.08	4.35	-3.72

Notes: Own calculations. NT stands for no transfer where there is no accompanying cash transfer policy.

Table 4.A.8: Carbon tax relative to expenditure (%)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Relative carbon tax (%)	**4.48**	**4.63**	**4.65**	**4.73**	**4.75**	**4.84**	**4.87**	**4.97**	**5.03**	**5.08**
Electricity	2.66	2.24	2.14	2.17	2.19	2.25	2.31	2.41	2.50	2.70
Motor Gasoline*	1.25	1.80	1.90	1.92	1.89	1.89	1.84	1.81	1.73	1.55
Collected and purified water, distribution services of water (41)	0.18	0.16	0.16	0.16	0.17	0.19	0.19	0.21	0.23	0.24
Financial intermediation services, except insurance and pension funding services (65)	0.04	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06
Wearing apparel; furs (18)	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06
Sea and coastal water transportation services	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Post and telecommunication services (64)	0.03	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.08
Beverages	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Inland water transportation services	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04
Air transport services (62)	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.05

Note: Own calculations. The table shows the average carbon tax relative to total expenditure on product level, calculated based on $40 ‘Economy-wide’ carbon tax. The table shows only the top 10 products.

Table 4.A.9: Carbon tax embodied in consumption products ($)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Electricity	17.7	25.9	31.8	39.0	46.3	55.9	67.8	85.3	113.0	226.0
Motor Gasoline	9.3	20.9	28.2	34.4	40.0	46.8	53.8	63.9	78.2	123.6
Collected and purified water, distribution services of water (41)	1.2	1.9	2.3	2.9	3.7	4.7	5.7	7.4	10.2	19.4
Financial intermediation services, except insurance and pension funding services (65)	0.3	0.6	0.7	0.9	1.1	1.4	1.6	2.0	2.6	5.2
Wearing apparel; furs (18)	0.3	0.5	0.7	0.8	1.0	1.3	1.5	1.9	2.5	4.8
Post and telecommunication services (64)	0.2	0.5	0.8	1.0	1.2	1.5	1.9	2.5	3.3	6.3
Sea and coastal water transportation services	0.2	0.4	0.6	0.7	0.9	1.1	1.3	1.6	2.0	3.8
Beverages	0.2	0.3	0.4	0.6	0.7	0.8	1.0	1.2	1.6	2.7
Inland water transportation services	0.2	0.3	0.4	0.5	0.6	0.8	0.9	1.1	1.5	3.1
Air transport services (62)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	1.0	1.4	5.1

Note: Own calculations. The table shows the average carbon tax embodied in consumption products, calculated based on $40 ‘Economy-wide’ carbon tax and only shows the top 10 products.

Table 4.A.10: Contribution of consumption products to carbon tax (%)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Electricity	57.2	48.2	46.0	46.0	46.1	46.5	47.5	48.5	49.8	53.7
Motor Gasoline	30.1	38.9	40.8	40.5	39.8	39.0	37.7	36.4	34.4	29.4
Collected and purified water, distribution services of water (41)	4.0	3.5	3.4	3.4	3.7	3.9	4.0	4.2	4.5	4.6
Financial intermediation services, except insurance and pension funding services (65)	1.0	1.0	1.1	1.1	1.1	1.1	1.2	1.1	1.2	1.2
Wearing apparel; furs (18)	0.9	0.9	1.0	1.0	1.0	1.1	1.1	1.1	1.1	1.1
Post and telecommunication services (64)	0.7	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.5	1.5
Sea and coastal water transportation services	0.7	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Beverages	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6
Inland water transportation services	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7
Air transport services (62)	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	1.2

Note: Own calculations. The table shows the contribution of consumption products to carbon tax, calculated based on $40 ‘Economy-wide’ carbon tax and only shows the top 10 products.

Table 4.A.11: Contribution of electricity sub-sectors to carbon tax (%)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Electricity total	**57.2**	**48.2**	**46.0**	**46.0**	**46.1**	**46.5**	**47.5**	**48.5**	**49.8**	**53.7**
Electricity by gas	38.8	32.3	30.6	30.6	30.6	30.9	31.5	32.2	33.1	35.6
Electricity by petroleum and other oil derivatives	15.5	12.9	12.2	12.2	12.2	12.3	12.5	12.8	13.2	14.2
Electricity by coal	2.9	3.0	3.1	3.2	3.3	3.4	3.4	3.5	3.6	3.9
Electricity by Geothermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by biomass and waste	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by hydro	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by nuclear	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by wind	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by solar photovoltaic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by solar thermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity by tide, wave, ocean	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity nec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: Own calculations. Note: Own calculations. The table shows the average carbon tax relative to total expenditure of the electricity sub-products, calculated based on $40 ‘Economy-wide’ carbon tax.

Table 4.A.12: Expenditure of households across income deciles ($)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Food products nec	127.1	209.8	271.3	333.4	396.4	469.3	556.5	659.4	831.2	1284.2
Processed rice	100.5	146.6	166.9	178.0	188.9	197.0	206.5	216.9	228.8	240.7
Vegetables, fruit, nuts	98.3	140.0	167.5	191.5	216.6	240.5	270.6	311.5	364.4	499.1
Fish and other fishing products; services incidental of fishing (05)	36.9	58.1	73.6	89.8	106.5	124.7	145.2	173.6	213.1	307.9
Motor Gasoline	34.0	75.9	102.4	121.8	140.3	160.2	182.6	217.8	272.6	506.8
Tobacco products (16)	33.2	85.9	124.3	157.6	188.8	221.1	256.2	303.2	348.0	382.0
Beverages	32.8	63.9	87.4	108.9	132.8	159.8	194.1	236.0	310.2	522.5
Chemicals nec	31.1	48.1	60.3	73.0	87.0	104.1	123.4	149.0	190.2	341.3
Electricity	25.5	36.6	44.4	54.4	64.4	77.6	94.0	118.5	156.9	313.1
Wearing apparel; furs (18)	17.9	31.3	42.1	52.8	65.1	79.6	96.5	119.9	159.0	302.6
Insurance and pension funding services, except compulsory social security services (66)	14.2	22.2	27.1	32.2	39.0	45.1	54.2	65.2	90.3	207.8
Health and social work services (85)	12.5	21.7	27.2	34.7	42.0	53.3	66.2	87.0	121.6	283.3
Products of meat poultry	9.8	19.4	26.3	33.3	41.2	48.1	57.7	68.2	83.7	120.5
Post and telecommunication services (64)	9.7	24.5	35.9	46.8	59.0	73.8	92.3	119.9	160.5	298.4
Other services (93)	6.7	15.0	23.4	33.4	44.6	55.4	70.7	86.4	119.0	223.9
Education services (80)	6.1	19.8	30.2	40.3	50.9	64.8	79.6	103.9	143.2	371.6
Other land transportation services	5.7	8.8	10.7	13.5	16.6	20.2	24.9	30.9	41.8	78.5
Recreational, cultural and sporting services (92)	5.3	8.8	11.6	16.1	20.5	30.1	41.8	56.3	100.8	450.6
Motor vehicles, trailers and semi-trailers (34)	0.3	1.4	2.7	5.5	9.4	17.3	31.9	61.5	102.3	664.1
Private households with employed persons (95)	0.2	0.3	0.6	1.0	2.1	2.9	5.4	9.7	26.4	248.2

Note: Own calculations. The value shows the average expenditure on product level and only shows the top 20 products.

Table 4.A.13: Expenditure of households in 4 sectors economy ($)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
electricity	25.8	37.0	45.0	55.0	65.1	78.5	95.1	119.9	158.9	317.0
fuel	42.0	88.7	118.3	141.8	165.6	191.8	222.0	268.0	346.2	706.7
foods	435.9	677.6	834.0	973.3	1119.5	1271.8	1461.0	1690.4	2049.8	2996.6
other	190.3	371.4	507.2	645.3	793.7	972.0	1189.0	1498.6	2007.8	4618.5

Note: Own calculations. The value shows the average expenditure aggregated into 4 sectors.

Table 4.A.14: The share of expenditure in 4 sectors economy (%)

Product	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
electricity	3.7	3.2	3.0	3.0	3.0	3.1	3.2	3.4	3.5	3.7
fuel	6.1	7.6	7.9	7.8	7.7	7.6	7.5	7.5	7.6	8.2
foods	62.8	57.7	55.4	53.6	52.2	50.6	49.2	47.3	44.9	34.7
other	27.4	31.6	33.7	35.5	37.0	38.7	40.1	41.9	44.0	53.5

Note: Own calculations. The value shows the share of expenditure aggregated into 4 sectors.

Table 4.A.15: Relative net impact of various rates of 'Economy-wide' carbon tax and percentage of revenue recycling under the uniform revenue recycling scenario (%)

	$2				$40				$100				$120			
Income decile	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%
1	-0.22	1.42	4.70	6.34	-4.48	28.35	93.99	126.81	-11.19	70.86	234.97	317.03	-13.43	85.04	281.97	380.44
2	-0.23	0.63	2.34	3.20	-4.63	12.52	46.82	63.96	-11.57	31.30	117.04	159.91	-13.89	37.56	140.45	191.89
3	-0.23	0.43	1.77	2.43	-4.65	8.68	35.34	48.67	-11.63	21.70	88.35	121.68	-13.96	26.04	106.02	146.02
4	-0.24	0.32	1.42	1.97	-4.73	6.31	28.38	39.41	-11.83	15.76	70.94	98.53	-14.19	18.92	85.13	118.24
5	-0.24	-0.24	-0.24	-0.24	-4.75	-4.75	-4.75	-4.75	-11.86	-11.86	-11.86	-11.86	-14.24	-14.24	-14.24	-14.24
6	-0.24	-0.24	-0.24	-0.24	-4.84	-4.84	-4.84	-4.84	-12.09	-12.09	-12.09	-12.09	-14.51	-14.51	-14.51	-14.51
7	-0.24	-0.24	-0.24	-0.24	-4.87	-4.87	-4.87	-4.87	-12.18	-12.18	-12.18	-12.18	-14.61	-14.61	-14.61	-14.61
8	-0.25	-0.25	-0.25	-0.25	-4.97	-4.97	-4.97	-4.97	-12.43	-12.43	-12.43	-12.43	-14.92	-14.92	-14.92	-14.92
9	-0.25	-0.25	-0.25	-0.25	-5.03	-5.03	-5.03	-5.03	-12.57	-12.57	-12.57	-12.57	-15.08	-15.08	-15.08	-15.08
10	-0.25	-0.25	-0.25	-0.25	-5.08	-5.08	-5.08	-5.08	-12.71	-12.71	-12.71	-12.71	-15.25	-15.25	-15.25	-15.25

Table 4.A.16: Relative net impact of various rates of 'Economy-wide+BTA' carbon tax and percentage of revenue recycling under the uniform revenue recycling scenario (%)

	$2				$40				$100				$120			
Income decile	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%
1	-0.3	0.42	1.87	2.59	-6.05	8.44	37.41	51.90	-15.13	21.09	93.53	129.75	-18.15	25.31	112.24	155.70
2	-0.3	0.08	0.83	1.21	-6.06	1.51	16.65	24.22	-15.15	3.77	41.62	60.54	-18.18	4.52	49.94	72.65
3	-0.3	-0.01	0.58	0.88	-6.01	-0.12	11.65	17.53	-15.01	-0.30	29.12	43.83	-18.02	-0.36	34.94	52.60
4	-0.3	-0.06	0.43	0.67	-6.01	-1.14	8.60	13.47	-15.03	-2.85	21.51	33.68	-18.03	-3.42	25.81	40.42
5	-0.3	-0.09	0.32	0.53	-5.97	-1.85	6.40	10.52	-14.93	-4.62	15.99	26.30	-17.91	-5.55	19.19	31.56
6	-0.3	-0.12	0.23	0.40	-6.01	-2.49	4.54	8.05	-15.02	-6.23	11.35	20.14	-18.03	-7.48	13.62	24.16
7	-0.3	-0.15	0.15	0.30	-5.99	-3.01	2.95	5.93	-14.99	-7.54	7.37	14.82	-17.98	-9.04	8.84	17.78
8	-0.3	-0.18	0.07	0.19	-6.05	-3.57	1.38	3.85	-15.12	-8.93	3.44	9.63	-18.14	-10.72	4.13	11.55
9	-0.3	-0.20	-0.01	0.09	-6.05	-4.10	-0.21	1.74	-15.12	-10.25	-0.51	4.35	-18.14	-12.30	-0.62	5.23
10	-0.3	-0.24	-0.12	-0.06	-6.00	-4.83	-2.47	-1.29	-15.01	-12.06	-6.17	-3.22	-18.01	-14.48	-7.41	-3.87

Table 4.A.17: Relative net impact of various rates of 'Electricity-only' carbon tax and percentage of revenue recycling under the uniform revenue recycling scenario (%)

	$2				$40				$100				$120			
Income decile	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%
1	-0.13	0.00	0.28	0.41	-2.66	0.08	5.56	8.30	-6.65	0.20	13.90	20.75	-7.97	0.24	16.68	24.90
2	-0.11	-0.04	0.10	0.17	-2.24	-0.81	2.06	3.49	-5.60	-2.02	5.14	8.72	-6.72	-2.42	6.17	10.46
3	-0.11	-0.05	0.06	0.12	-2.14	-1.03	1.20	2.31	-5.35	-2.57	2.99	5.78	-6.42	-3.08	3.59	6.93
4	-0.11	-0.06	0.03	0.08	-2.17	-1.25	0.59	1.51	-5.44	-3.13	1.47	3.77	-6.52	-3.76	1.77	4.53
5	-0.11	-0.07	0.01	0.05	-2.19	-1.41	0.15	0.93	-5.47	-3.52	0.38	2.33	-6.56	-4.22	0.46	2.79
6	-0.11	-0.08	-0.01	0.02	-2.25	-1.59	-0.26	0.41	-5.63	-3.96	-0.64	1.02	-6.75	-4.76	-0.77	1.23
7	-0.12	-0.09	-0.03	0.00	-2.31	-1.75	-0.62	-0.06	-5.78	-4.37	-1.55	-0.14	-6.93	-5.24	-1.86	-0.17
8	-0.12	-0.10	-0.05	-0.03	-2.41	-1.94	-1.01	-0.54	-6.03	-4.86	-2.52	-1.35	-7.23	-5.83	-3.02	-1.62
9	-0.13	-0.11	-0.07	-0.05	-2.50	-2.13	-1.40	-1.03	-6.26	-5.34	-3.49	-2.57	-7.51	-6.40	-4.19	-3.09
10	-0.13	-0.12	-0.10	-0.09	-2.70	-2.47	-2.03	-1.81	-6.74	-6.19	-5.07	-4.52	-8.09	-7.42	-6.09	-5.42

Table 4.A.18: Relative net impact of various rates of national 'Fuel-only' carbon tax and percentage of revenue recycling under the uniform revenue recycling scenario (%)

	$2				$40				$100				$120			
Income decile	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%	0%	25%	75%	100%
1	-0.07	0.42	1.38	1.86	-1.33	8.33	27.64	37.30	-3.33	20.81	69.10	93.25	-4.00	24.98	82.92	111.90
2	-0.09	0.16	0.66	0.91	-1.89	3.16	13.25	18.30	-4.72	7.90	33.13	45.74	-5.66	9.48	39.75	54.89
3	-0.10	0.10	0.49	0.68	-1.99	1.93	9.77	13.70	-4.98	4.82	24.44	34.24	-5.98	5.79	29.32	41.09
4	-0.10	0.06	0.39	0.55	-2.02	1.23	7.72	10.97	-5.04	3.07	19.31	27.43	-6.05	3.69	23.17	32.91
5	-0.10	0.04	0.31	0.45	-2.00	0.75	6.25	9.00	-4.99	1.88	15.62	22.49	-5.99	2.26	18.75	26.99
6	-0.10	0.02	0.25	0.37	-2.00	0.35	5.04	7.38	-4.99	0.87	12.59	18.45	-5.99	1.04	15.11	22.14
7	-0.10	0.00	0.20	0.30	-1.95	0.04	4.01	6.00	-4.88	0.09	10.02	14.99	-5.86	0.11	12.03	17.99
8	-0.10	-0.01	0.15	0.23	-1.93	-0.28	3.02	4.67	-4.82	-0.69	7.55	11.68	-5.78	-0.83	9.07	14.01
9	-0.09	-0.03	0.10	0.17	-1.86	-0.56	2.04	3.33	-4.65	-1.40	5.09	8.33	-5.57	-1.68	6.11	10.00
10	-0.08	-0.05	0.03	0.07	-1.69	-0.91	0.66	1.45	-4.23	-2.27	1.66	3.62	-5.08	-2.72	1.99	4.35

4.B Supplementary Information

Table 4.B.1: Products in EXIOBASE3

Product	Code
Paddy rice	p01.a
Wheat	p01.b
Cereal grains nec	p01.c
Vegetables, fruit, nuts	p01.d
Oil seeds	p01.e
Sugar cane, sugar beet	p01.f
Plant-based fibers	p01.g
Crops nec	p01.h
Cattle	p01.i
Pigs	p01.j
Poultry	p01.k
Meat animals nec	p01.l
Animal products nec	p01.m
Raw milk	p01.n
Wool, silk-worm cocoons	p01.o
Manure (conventional treatment)	p01.w.1
Manure (biogas treatment)	p01.w.2
Products of forestry, logging and related services (02)	p02
Fish and other fishing products; services incidental of fishing (05)	p05
Anthracite	p10.a
Coking Coal	p10.b
Other Bituminous Coal	p10.c
Sub-Bituminous Coal	p10.d
Patent Fuel	p10.e
Lignite/Brown Coal	p10.f
BKB/Peat Briquettes	p10.g
Peat	p10.h
Crude petroleum and services related to crude oil extraction, excluding surveying	p11.a
Natural gas and services related to natural gas extraction, excluding surveying	p11.b
Natural Gas Liquids	p11.b.1
Other Hydrocarbons	p11.c
Uranium and thorium ores (12)	p12
Iron ores	p13.1
Copper ores and concentrates	p13.20.11
Nickel ores and concentrates	p13.20.12

Table 4.B.1: *(continued)*

Product	Code
Aluminium ores and concentrates	p13.20.13
Precious metal ores and concentrates	p13.20.14
Lead, zinc and tin ores and concentrates	p13.20.15
Other non-ferrous metal ores and concentrates	p13.20.16
Stone	p14.1
Sand and clay	p14.2
Chemical and fertilizer minerals, salt and other mining and quarrying products n.e.c.	p14.3
Products of meat cattle	p15.a
Products of meat pigs	p15.b
Products of meat poultry	p15.c
Meat products nec	p15.d
products of Vegetable oils and fats	p15.e
Dairy products	p15.f
Processed rice	p15.g
Sugar	p15.h
Food products nec	p15.i
Beverages	p15.j
Fish products	p15.k
Tobacco products (16)	p16
Textiles (17)	p17
Wearing apparel; furs (18)	p18
Leather and leather products (19)	p19
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials (20)	p20
Wood material for treatment, Re-processing of secondary wood material into new wood material	p20.w
Pulp	p21.1
Secondary paper for treatment, Re-processing of secondary paper into new pulp	p21.w.1
Paper and paper products	p21.2
Printed matter and recorded media (22)	p22
Coke Oven Coke	p23.1.a
Gas Coke	p23.1.b
Coal Tar	p23.1.c
Motor Gasoline	p23.20.a
Aviation Gasoline	p23.20.b
Gasoline Type Jet Fuel	p23.20.c
Kerosene Type Jet Fuel	p23.20.d
Kerosene	p23.20.e

Table 4.B.1: *(continued)*

Product	Code
Gas/Diesel Oil	p23.20.f
Heavy Fuel Oil	p23.20.g
Refinery Gas	p23.20.h
Liquefied Petroleum Gases (LPG)	p23.20.i
Refinery Feedstocks	p23.20.j
Ethane	p23.20.k
Naphtha	p23.20.l
White Spirit & SBP	p23.20.m
Lubricants	p23.20.n
Bitumen	p23.20.o
Paraffin Waxes	p23.20.p
Petroleum Coke	p23.20.q
Non-specified Petroleum Products	p23.20.r
Nuclear fuel	p23.3
Plastics, basic	p24.a
Secondary plastic for treatment, Re-processing of secondary plastic into new plastic	p24.a.w
N-fertiliser	p24.b
P- and other fertiliser	p24.c
Chemicals nec	p24.d
Charcoal	p24.e
Additives/Blending Components	p24.f
Biogasoline	p24.g
Biodiesels	p24.h
Other Liquid Biofuels	p24.i
Rubber and plastic products (25)	p25
Glass and glass products	p26.a
Secondary glass for treatment, Re-processing of secondary glass into new glass	p26.a.w
Ceramic goods	p26.b
Bricks, tiles and construction products, in baked clay	p26.c
Cement, lime and plaster	p26.d
Ash for treatment, Re-processing of ash into clinker	p26.d.w
Other non-metallic mineral products	p26.e
Basic iron and steel and of ferro-alloys and first products thereof	p27.a
Secondary steel for treatment, Re-processing of secondary steel into new steel	p27.a.w
Precious metals	p27.41
Secondary preciuos metals for treatment, Re-processing of secondary preciuos metals into new preciuos metals	p27.41.w
Aluminium and aluminium products	p27.42

Table 4.B.1: *(continued)*

Product	Code
Secondary aluminium for treatment, Re-processing of secondary aluminium into new aluminium	p27.42.w
Lead, zinc and tin and products thereof	p27.43
Secondary lead for treatment, Re-processing of secondary lead into new lead	p27.43.w
Copper products	p27.44
Secondary copper for treatment, Re-processing of secondary copper into new copper	p27.44.w
Other non-ferrous metal products	p27.45
Secondary other non-ferrous metals for treatment, Re-processing of secondary other non-ferrous metals into new other non-ferrous metals	p27.45.w
Foundry work services	p27.5
Fabricated metal products, except machinery and equipment (28)	p28
Machinery and equipment n.e.c. (29)	p29
Office machinery and computers (30)	p30
Electrical machinery and apparatus n.e.c. (31)	p31
Radio, television and communication equipment and apparatus (32)	p32
Medical, precision and optical instruments, watches and clocks (33)	p33
Motor vehicles, trailers and semi-trailers (34)	p34
Other transport equipment (35)	p35
Furniture; other manufactured goods n.e.c. (36)	p36
Secondary raw materials	p37
Bottles for treatment, Recycling of bottles by direct reuse	p37.w.1
Electricity by coal	p40.11.a
Electricity by gas	p40.11.b
Electricity by nuclear	p40.11.c
Electricity by hydro	p40.11.d
Electricity by wind	p40.11.e
Electricity by petroleum and other oil derivatives	p40.11.f
Electricity by biomass and waste	p40.11.g
Electricity by solar photovoltaic	p40.11.h
Electricity by solar thermal	p40.11.i
Electricity by tide, wave, ocean	p40.11.j
Electricity by Geothermal	p40.11.k
Electricity nec	p40.11.l
Transmission services of electricity	p40.12
Distribution and trade services of electricity	p40.13
Coke oven gas	p40.2.a
Blast Furnace Gas	p40.2.b
Oxygen Steel Furnace Gas	p40.2.c

Table 4.B.1: *(continued)*

Product	Code
Gas Works Gas	p40.2.d
Biogas	p40.2.e
Distribution services of gaseous fuels through mains	p40.2.1
Steam and hot water supply services	p40.3
Collected and purified water, distribution services of water (41)	p41
Construction work (45)	p45
Secondary construction material for treatment, Re-processing of secondary construction material into aggregates	p45.w
Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries	p50.a
Retail trade services of motor fuel	p50.b
Wholesale trade and commission trade services, except of motor vehicles and motorcycles (51)	p51
Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)	p52
Hotel and restaurant services (55)	p55
Railway transportation services	p60.1
Other land transportation services	p60.2
Transportation services via pipelines	p60.3
Sea and coastal water transportation services	p61.1
Inland water transportation services	p61.2
Air transport services (62)	p62
Supporting and auxiliary transport services; travel agency services (63)	p63
Post and telecommunication services (64)	p64
Financial intermediation services, except insurance and pension funding services (65)	p65
Insurance and pension funding services, except compulsory social security services (66)	p66
Services auxiliary to financial intermediation (67)	p67
Real estate services (70)	p70
Renting services of machinery and equipment without operator and of personal and household goods (71)	p71
Computer and related services (72)	p72
Research and development services (73)	p73
Other business services (74)	p74
Public administration and defence services; compulsory social security services (75)	p75
Education services (80)	p80
Health and social work services (85)	p85
Food waste for treatment: incineration	p90.1.a
Paper waste for treatment: incineration	p90.1.b

Table 4.B.1: *(continued)*

Product	Code
Plastic waste for treatment: incineration	p90.1.c
Intert/metal waste for treatment: incineration	p90.1.d
Textiles waste for treatment: incineration	p90.1.e
Wood waste for treatment: incineration	p90.1.f
Oil/hazardous waste for treatment: incineration	p90.1.g
Food waste for treatment: biogasification and land application	p90.2.a
Paper waste for treatment: biogasification and land application	p90.2.b
Sewage sludge for treatment: biogasification and land application	p90.2.c
Food waste for treatment: composting and land application	p90.3.a
Paper and wood waste for treatment: composting and land application	p90.3.b
Food waste for treatment: waste water treatment	p90.4.a
Other waste for treatment: waste water treatment	p90.4.b
Food waste for treatment: landfill	p90.5.a
Paper for treatment: landfill	p90.5.b
Plastic waste for treatment: landfill	p90.5.c
Inert/metal/hazardous waste for treatment: landfill	p90.5.d
Textiles waste for treatment: landfill	p90.5.e
Wood waste for treatment: landfill	p90.5.f
Membership organisation services n.e.c. (91)	p91
Recreational, cultural and sporting services (92)	p92
Other services (93)	p93
Private households with employed persons (95)	p95
Extra-territorial organizations and bodies	p99

Chapter 5

Conclusions

5.1 Overview

This dissertation explores the effect of a country's participation in international trade on domestic and foreign CO_2 emissions, and investigates how the emissions associated with such participation influence households across income levels in the context of carbon taxation policy. In doing so, three primary studies are carried out in **Chapter 2**, **3**, and **4**. **Chapter 2** empirically assesses the claim that trade enables developed countries to outsource emissions to developing countries. Specifically, it evaluates the extent to which developed-country PBE trends are driven by international trade. In doing so, this dissertation offers a new technology-adjusted emission accounting concept to measure the net effect of a country's participation in international trade on foreign emissions and develop interpretations for the resulting emission concepts.

Chapter 3 empirically evaluates the claim that a number of high income countries have significantly reduced domestic CO_2 emissions while maintaining meaningful economic growth. To evaluate if the 'decoupling' between economic growth and domestic CO_2 emissions in these economies is indeed true, we evaluate the net effect of trade participation on domestic CO_2 emissions. We interpret this as the 'net onshoring' of CO_2 emissions. In this chapter, we differ from the established EEBT approach and propose a measurement that is based on the MRIO approach.

In **Chapter 4**, this dissertation combines the EE MRIO analysis with a microsimulation analysis to measure the distributional implications of a carbon policy reform (carbon taxation and revenue recycling program) on households across the income spectrum in Indonesia. Indonesia, while facing the challenges of maintaining its development objectives, has planned to gradually introduce carbon taxation on its economy. The consequences of such a plan on household's consumption – given the recent policy contexts in Indonesia – remain relatively unexplored. Moreover, it is also essential to understand how the Indonesia government should be prepared to counteract the potential implications of carbon tax. By taking into account domestic as well as foreign emissions associated with domestic consumption, this chapter investigates how the combination of carbon taxation and revenue recycling scenarios will affect the welfare of Indonesian households belonging to different income groups.

This final chapter synthesizes the findings of **Chapter 2**, **3**, and **4**, attempts to answer the research questions of this thesis, critically reflects on the methods and the findings obtained, and suggests recommendations for future research and climate policy.

5.2 Research outcomes

The overarching research question this dissertation seeks to answer is

To what extent does a country's participation in international trade affect domestic and foreign CO_2 emissions, and how does the carbon taxation policy – as an instrument to stimulate carbon emissions reduction – affects the income of households in developing countries?

To answer the overarching research question, This dissertation addresses the following three sub-questions.

Subquestion 1: How does a country's participation in international trade affect carbon emissions in the rest of the world?

Many developed countries have managed to reduce their domestic PB CO_2 emissions while maintaining an adequate rate of economic growth. However, most developed countries also import more than they export emissions, while most developing countries export more than they import emissions. An interpretation derived from the conventional emission transfer analysis suggests that international trade have enabled developed countries to 'outsource' production to developing countries, which then increases the domestic emission emissions in the latter. However, Jakob and Marschinski (2013) argue that the emission imbalances recorded by the developed countries could partially (if not mostly) be driven by the international technology differences, that is, cross-country differences in the carbon intensity of energy and the energy intensity of production. Kander et al. (2015), Jiborn et al. (2018), Baumert et al. (2019) and Jiborn et al. (2020) propose a method to standardize technology at the world average level to evaluate the claim whether international, yet the 'technology-adjustment' implemented thus far only standardizes emission intensity. In this study, to adjust technology, we propose to also adjust 'input intensity; the same industries in two different countries may require different (monetary) inputs to produce the same level of (monetary) outputs. The same demand would result in higher environmental footprints, *ceteris paribus*, if more inputs are needed.

Assessing the impact of a country's participation in international trade on foreign emissions requires taking into account the foreign emissions generated by imports and the emissions avoided by the focus country's exports. The emissions avoided by exports is a concept that is derived from asking a hypothetical question, that is, what would the CO_2 emissions be if a certain commodity had not been exported by the country in question? The most plausible and least demanding assumption to answer this question is to assume that a similar good would be produced at world average emission intensities and input intensities on the world market for the corresponding sectors in the economy. The emissions hypothetically generated by using this 'world average' technology would imply the emissions *avoided* by the focus country's exports. Measuring the net impact of a country's participation in international trade on foreign emissions, thus, requires comparing the foreign emissions generated by imports (EEM) with the foreign emissions *avoided* by exports (TEEX). The technology-adjusted emissions balance (TBEET = TEEX − EEM) measures this. A country with positive TBEET, on balance, avoids foreign emissions, meaning by its participation in international trade it avoids the outcome in which the world has to release more CO_2 emissions than the foreign emissions generated for its imports. A country with negative TBEET on balance net-generates foreign emissions, meaning it generates more foreign emissions than the emissions it avoids by exports.

How does a country's trade affect CO_2 emissions in the rest of the world? The analysis in **Chapter 2** documents the cross-country dynamics of the technology-adjusted emission balance (TBEET). A large trade-deficit country like the USA records a negative TBEET, that is, the USA on balance generates foreign emissions. This means that the USA's trade avoids less emissions in the rest of the world (ROW) than the emissions it generates in the ROW to produce its imports. China mirrors the USA's trend as it records a positive TBEET. China's participation in trade avoids more emissions in the ROW than the emissions it generates in the ROW to produce its imports. The adage that states 'China is the factory of the world' might hold true; the country might also help its trade partners achieve their climate targets. The magnitude of the net-avoidance and net-generation varies across countries, yet a general pattern can be inferred from the findings. Most developed countries (except the USA) on balance avoid foreign emissions, while most large developing countries on balance generate foreign emissions. In general, there exists a positive cross-country correlation between TBEET and per-capita income. However, the strength of the statistical relationship between TBEET and per-capita should not be overestimated.

What factors drive the TBEET? Emissions embodied in exports (EEX) reflect the focus country's production technology, EEM reflect the rest of the world's technology. TEEX replace EEX in the TBEET, reducing the effect of the cross-country technological differences. The TBEET now depends on the scale and composition of trade balances. Hence, some patterns can be deduced from the global TBEET patterns. First, for countries like China, Germany, and the USA, the monetary trade balance is likely the primary driver of TBEET. Prominent trade-surplus countries (e.g. China, Germany, and the Netherlands) display positive TBEETs, while a large trade-deficit country like the USA displays negative TBEETs.

Second, for resource-abundant countries exporting mining products (e.g. Canada, Middle East, Norway, and Russia), the trade composition may partially explain why their TBEETs tend to be positive. These countries export mining products which cleaning and processing can be emission intensive. Third, the BEET is significantly driven by the cross-country differences in input intensities. This can be inferred by observing the differences between TEEX, EIEEX, and EEX. For most countries, the differences between TEEX and EEX is larger than the differences between EIEEX and EEX (Appendix, Table 2.B.6).

The technology-adjusted consumption-based emissions (TCBE) represent the territorial emissions (PBE) plus the emissions net generated in the rest of the world (TBEET). The decoupling between economic growth and CO_2 emissions is indeed true if, assuming that the economy is growing, the PBE and TCBE are decreasing. However, there is no such delinking if the TCBE increased over the same period as PBE decreased. The analysis in **Chapter 2** discovers that the PBE and TCBE are decreasing in many developed countries, suggesting that the PBE decreases in developed countries are not accompanied by the emission increases in the ROW. The Kaya decomposition of CO_2 emissions indicates that the decreases in both accounts in the developed countries are driven more by the energy intensity improvements than the decarbonization (Quéré et al., 2019). All the developing countries in the sample, however, record increasing PBE and TCBE: income and population drive emissions up more than the decarbonization and energy intensity improvements drive them down. The surge in domestic demand in the developing world has driven the emission increases more than the increased participation in global production chains (de Vries and Ferrarini, 2017; Jiborn et al., 2020).

In summary, the analysis in **Chapter 2** reveals that a country's participation in international trade affects the CO_2 in the ROW. The technology-adjusted emission balance (TBEET) reveals that large trade-deficit countries like the USA tend to generate more emissions abroad than they avoid, resulting in a negative TBEET. Conversely, trade-surplus countries like China avoid more emissions abroad than they generate, leading to a positive TBEET. This pattern extends to most developed countries, which generally avoid foreign emissions, while many large developing countries generate foreign emissions. The TBEET is influenced by trade balances and the composition of exports, with resource-abundant countries exporting emission-intensive mining products often showing positive TBEETs. Additionally, the TBEET is driven by differences in production technology and input intensities across countries. The technology-adjusted consumption-based emissions (TCBE) include both territorial emissions and net foreign emissions. In developed countries, both TCBE and territorial emissions are decreasing due to improvements in energy intensity, indicating a decoupling of economic growth from carbon emissions. However, in developing countries, both TCBE and territorial emissions are increasing, driven by rising income and population, which outweigh improvements in energy efficiency and decarbonization efforts.

Subquestion 2: How does the participation in international trade affect a country's domestic carbon emissions?

By participating in international trade, a country releases domestic CO_2 emissions to produce exports and at the same time generates foreign emissions which are associated with the production of goods and services which it imports. A country is said to 'onshore' emissions by producing exports and 'offshore' emissions by its imports. When a country 'onshores' more emissions to produce exports (EEX) than it 'offshores' emissions to produce imports (EEM), its participation in trade results in a net increase in its territorial CO_2 emissions (PBE). In contrast, when a country's trade generates EEM more than it generates EEX, its trade implies a net reduction in its PBE. Studies implementing the MRIO document that in general many developed countries 'net offshore' emissions while most large developing countries 'net onshore' emissions. The trade is said to have allowed the developed countries to meet the domestic CO_2 emission reduction targets while maintaining an acceptable rate of economic growth. However, this 'decoupling' comes with the cost of domestic emission increases in the developing countries. **Chapter 3** is carried out to appraise whether the absolute 'decoupling' reported by the developed countries is indeed valid.

As demonstrated in **Chapter 3**, the conventional emission transfer parameter BEET cannot evaluate the 'decoupling' because it is partially driven by the existence of the international differences in production technology. To evaluate the effect of a country's participation in trade on domestic emissions, one should consider not only the emissions it onshores to produce exports but also the domestic emissions it avoids by importing from the rest of the world. The former imply the EEX and the latter imply the domestic emissions avoided by imports (EAM). The EAM assumes the imports were produced domestically, its measurement is done by replacing the worldwide production technology with the domestic production technology of the focus country. The net effect of a country's participation in trade on domestic emissions are then determined by the *net onshoring* of emissions (NetOn), calculated by comparing the emission onshoring for exports (EEX) with the EAM, giving NetOn = EEX − EAM. A country with positive NetOn net onshores emissions, meaning by trade participation it onshores more emissions than it avoids domestic emissions by imports. A country with negative NetOn net offshores emissions, meaning it avoids more domestic emissions than it onshores emissions by exports.

How does the participation in international trade affect a country's domestic carbon emissions? The USA and China once again exercise a contrasting emission trends. The USA is net offshoring CO_2 emissions, that is, the country offshores more than it onshores emissions. Put differently, the USA's trade avoids more domestic emissions by imports than it generates domestic emissions for exports. China, on the other hand, is net onshoring emissions. This means that throughout the study period China's trade generates more domestic CO_2 emissions for exports than it avoids domestic emissions by imports. This once again stresses that China is the world's 'emission haven', in that China's participation in international trade generates more domestic emissions to produce exports than the emissions avoided by its imports. The size of net onshoring for both countries are small compared to scale of their BEETs. For the large trade-surpluses countries like China and Germany, the change in net onshoring during the period of analysis roughly tracks the change in trade balance. The increase in net onshoring in the early 2000s reflects the emergence of the trade surpluses recorded by these two countries. At the end of the period of analysis, the size of emissions net onshored by China and Germany shrinks relative to the earlier period. For Japan, the net onshoring is almost negligible before 2003, becomes increasingly negative between 2003-2012, and increases after that. These trends are likely driven by the influx of foreign fuels which peaks in 2008 and 2012 when global oil prices were 2-3 times the level of the previous decades. India is net offshoring emissions throughout the analysis period because it exports services with low emission intensity and imports high-intensity manufactured goods. There is no negative cross-country correlation between BEET and per-capita income, while there is a positive cross-country correlation between net onshoring and per-capita income. This correlation, however, needs to be interpreted contextually.

Appraising the decoupling success requires a domestic emission metric that takes into account the net onshoring of emission. In **Chapter 3**, this is done by calculating the domestic-technology consumption-based emissions (CBE). The analysis on the cross-country domestic-technology CBE reveals that these trends closely follow production-based emissions (PBE). In China and India, both PBE and domestic-technology CBE are increasing, whereas in Germany, both measures are decreasing. The USA and the UK show an initial increase followed by a decrease in both metrics. This similarity in trends occurs because the scale of net onshoring is minor relative to PBE. However, Japan, a country that is scarce in natural resources, is an anomaly. Its case illustrates the limitations of the domestic technology assumption. Japan does not produce the imported energy products in significant quantities; its economy cannot replicate the imported energy products' domestically, resulting in significant discrepancies between PBE and domestic-technology CBE. Generally, the domestic-technology CBE provides insights into what emissions would look like if countries produced their imports domestically.

The cross-country analysis of net onshoring of emissions indicates a weak positive association with per-capita income, whereas the BEET shows a negative association. Richer countries tend to have lower BEETs due to their cleaner energy systems and more efficient production technologies. However, this pattern does not hold as strongly for net onshoring, which can be influenced by various factors, including trade balances and the composition of imports and exports. Empirical evidence contradicts the Pollution Haven Hypothesis (PHH), which suggests that stricter environmental regulations in richer countries would lead them to offshore dirty production. Instead, the Heckscher-Ohlin theory of comparative advantage and the composition of economic activity provide better explanations for the observed patterns. The analysis underscores the complex dynamics influencing net onshoring and offshoring of emissions across different countries and economic contexts.

Subquestion 3: How are the households across income levels affected by the implementation of carbon taxation policy?

Carbon tax is seen as a viable mitigation policy to reduce CO_2 emissions. As a Pigouvian-style tax, a carbon tax holds polluters accountable by internalizing the social cost of carbon in their production costs and prices. A carbon tax can also generate revenue to finance investments in the transition to a cleaner energy system. A carbon tax works by creating a direct financial incentive for both producers and consumers to, over the longer period of time, reduce the carbon footprints associated with their economic activities. However, the primary challenge of carbon tax might lie in its public acceptance due to its short-run (distributionally-regressive) economic consequences. In the short run, a carbon tax results in an increase in the prices of fossil fuels. This leads to the increases in the prices of other energy products, which trigger an economy-wide price hike. In a country where low income households are highly reliant on the use of affordable fossil fuel, levying carbon tax will disproportionally affect poor households. In Indonesia, the public has frequently demonstrated opposition after the government's decision to eliminate fossil fuel subsidies in 2008 (Mourougane, 2010; Renner et al., 2019) or in 2022 (Jones and Cardinale, 2023). **Chapter 4** studies to what extent the implementation of a carbon policy reform (that is, a carbon taxation policy and the accompanying cash transfer strategy) affects households across income levels. In this dissertation, Indonesia is selected as a case study of carbon policy reform because the country has planned to implement it in the near future. In the past, the public in Indonesia has expressed oppositions to the reduction or removal of fossil-fuel subsidies, which makes studying the distributional implications of carbon policy reform in the country even more relevant in practice.

By measuring the net impact on Indonesian household expenditure of a carbon policy reform in relative terms (i.e., estimating the net expenditure after carbon tax and cash transfer relative to initial expenditure), this study finds that carbon policy reforms in Indonesia has a tendency to be progressive. In particular, when the carbon tax revenue is uniformly distributed, the relative net impacts in absolute terms is higher for low-income households. In other words, the (positive) relative net impact on household expenditure of carbon policy reform becomes smaller as household income increases. However, the degree of progressiveness (or regressiveness) of carbon policy reform is not indicative of expenditure recovery, that is, whether the post-reform net expenditure levels of all households have recovered to the initial expenditure levels. Without an accompanying cash transfer policy, carbon tax in Indonesia is neither progressive nor regressive, as it reduces the consumption of households in all income deciles by circa 10% all households in Indonesia almost equally in proportional terms, irrespective of the carbon tax rates. This highlights the nature of a carbon tax in Indonesia: all households, regardless of income, bear the tax burden proportionally to their expenditure of taxed consumption goods.

In the national 'Economy-wide' carbon taxation scenario, and when the entire tax revenue is uniformly recycled to all households, the bottom the bottom 90% of households would recover and net benefit from the carbon policy reform. However, under the same tax scenario with a '\$100 flat' cash transfer program, only the bottom 50% of households recover and net benefit from the carbon policy reform. Furthermore, introducing BTA mechanism on imports alongside a national carbon tax does not significantly alter the relative net impacts of all households. The BTA mechanism marginally increases the relative net impacts on the bottom 50% of households. The overall impact of a BTA implementation is fairly limited.

Which consumption items contribute to carbon tax burden? By aggregating consumption items into four categories (electricity, fuel, foods, and others), this study finds that a carbon tax in Indonesia mainly affects households from the price increase of two consumption items: electricity and fuel. For the bottom 10% of households, electricity and fuel together are responsible for 89% of the carbon tax burden these households have to bear in order to maintain their initial consumption levels, while food and other consumption items only contribute 1% and 10% respectively. We observe a consistent pattern across the income spectrum, with the fuel and electricity consumption contributing between 86% and 89% to the carbon tax for households in the middle- and high-income deciles as well.

We find that household expenditure in Indonesia is composed mainly on food and other consumption items. Electricity and fuel, on the other hand, only constitutes a small portion of households' expenditures. This pattern is observable across the income spectrum. This consistent pattern indicates that the share of total consumer spending on electricity and fuel consumption is less likely to be the primary driver of the incidence of carbon taxation in Indonesia. Instead, the main driver is the high carbon intensity of these products. Indonesia's electricity mix is dominated by fossil-based energy sources, which account for around 80% of total electricity generation (International Energy Agency, 2022). Consequently, the emissions embodied in one unit of electricity or fuel consumption are relatively higher, leading to a greater carbon tax incidence. This reliance on fossil fuels for electricity generation amplifies the impact of the carbon tax on households, as the carbon tax directly targets these high-emission sources.

A carbon tax on fuel products affects households in multiple ways. Producing fuel becomes more expensive due to the tax on emissions generated during production, and this increase in production costs is passed on to consumers as higher prices. This price increase impacts various aspects of household expenditure, particularly in areas heavily reliant on fuel. For the transportation sectors, emissions generated by air, land, and water transportation services, which heavily depend on fossil fuels, are also subject to taxation. These increased costs are transferred to consumers through higher prices for transportation services, affecting both direct travel expenses and the cost of goods that rely on transportation.

We find that the rates of carbon taxation rates influence the magnitude of the relative net impacts more than their distribution. Regardless of the tax rates applied, the distribution of the relative net impacts does not change as the carbon tax rates change. Our results show that in all carbon taxation scenarios, uniform revenue recycling would allow households in the 1st-6th to recover and, on balance, benefit from the carbon policy reform, irrespective of the carbon tax rate.

Answering the main research question

Thus, the main research question,

To what extent does a country's participation in international trade affect domestic and foreign CO_2 emissions, and how does the carbon taxation policy – as an instrument to stimulate carbon emissions reduction – affects the income of households in developing countries?

is answered by the following. To what extent does a country's participation in international trade influence foreign CO_2 emissions? A country's participation in international trade significantly influences foreign CO_2 emissions and are measured by the emissions net-avoided by the focus country, that is, the difference between the foreign emissions avoided by a country's exports and the foreign emissions generated by its imports. Many developed countries generally avoid more emissions by exports than they generate by imports (except e.g. the USA which net generates emissions in the ROW). In other words, many developed countries net avoid foreign emissions. In contrast, most large developing countries on balance generate foreign emissions (except e.g. China which net avoids foreign emissions). There exists a positive cross-country correlation between the foreign emissions net-avoided (TBEET) and per-capita income.

To what extent does a country's participation in international trade influence domestic CO_2 emissions? Measuring a country's participation in international trade on domestic CO_2 emissions requires taking into measurement the domestic emissions generated by exports and the domestic emissions avoided by imports. This net effect on domestic emissions is the net onshoring of emissions (NetOn). Positive NetOn implies net onshoring of emissions, while negative NetOn implies net offshoring of emissions. The USA net offshores CO_2 emissions, that is, the USA avoids more domestic emissions by imports more than generating domestic emissions by exports. China, in contrast, net onshores CO_2 emissions, meaning China generates more than it avoids domestic emissions. There is a positive cross-country correlation between NetOn and per-capita income.

How does the carbon taxation policy affects the income of households in developing countries? The carbon taxation policy affects the income of households through the increases in commodity prices. A carbon tax increases the prices of fossil fuels and other commodities, leading to an economy-wide price hikes. The extent in which households will be affected depends on the production and consumption structure of the economy. In Indonesia, a carbon tax will affect households across income levels almost equally in proportional terms, irrespective of the carbon tax rates. This means that a carbon tax is neither progressive nor regressive. However, when it is accompanied by a cash transfer policy, the combination of them has a tendency to be progressive, although the degree of progressiveness does not mean all households recover from the impact of the carbon tax. In Indonesia, a carbon tax affects households mostly through the price increases in electricity and fuel, although both commodities comprise a small portion of households' expenditures. The proportional impact of carbon tax remains consistent regardless of the carbon tax rate applied. The carbon tax rate only influences magnitude (not distribution) of impacts.

5.3 Reflections and Limitations

5.3.1 On the Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model

In this dissertation, the EE MRIO framework serves as the primary method to measure the emissions embodied in monetary final demand. The MRIO model is based on Leontief's

(1941) Input-Output (IO) analysis that is expanded to include inter-region and inter-industry flows of products and services in a single analysis module. The EE MRIO model extends the original IO analysis by introducing the vector of environmental stressors to the MRIO system. The EE MRIO is constructed following the critiques on the UNFCCC CO_2 emission accounting frameworks, which define the system boundary of emissions' responsibilities by national territories and offshore areas over which the country has jurisdiction. By this definition, countries are only responsible for territorial emissions and are not responsible for the carbon leakage through imports. The EE MRIO solves this issues by allowing to account not only the emissions based on the territorial emission concept but also for the concept of emission footprints, that is, the direct and indirect emissions associated with a country's domestic consumption.

There exist two IO-based approaches to account for CO_2 emissions: the CO_2 emissions embodied in bilateral trade (EEBT) and the MRIO. Both approaches disagree on how the carbon emissions embodied in exports and imports are accounted. This disagreement stems from the differences in the way the CO_2 emissions embodied in intermediate imports are allocated. The EEBT does not split the bilateral trade flows into components of intermediate and final products, while the MRIO distinguishes between trade that goes into intermediate and final products. Hence, the EEBT allocates the emissions embodied in intermediate imports to the importer countries, even if these products will be re-exported (i.e. not consumed as final products by the importer countries). The MRIO, on the other hand, passes on the intermediate imports until it is eventually embodied in the final consumption. With this, to account for the emissions embodied in imports, the EEBT accounts only the emissions embodied in the *direct* imports and does not account for the multi-layer intermediate uses in the previous stages of intermediate productions. To account for the emissions embodied in exports, the EEBT does not make a distinction between the emissions embodied in the exported intermediates that return home, while the MRIO separates the emissions embodied in the products that return home. While both accounts agree on the global level, these distinctive features potentially lead to both accounts reporting different quantities and directions of CO_2 emissions embodied in trade for every country. For this reason, this dissertation uses the MRIO model to account for the emissions embodied in final demand.

The EE MRIO is a tractable mathematical model to analyze not only how resources are flowing within and between countries but also how and where the emissions are discharged along the production and consumption activities. However, the EE MRIO model, which is built upon the basic IO model, incorporates a number of underlying assumptions and limitations. Acknowledging these assumptions and limitations is necessary when interpreting the results generated by the model. The most fundamental assumption is that production in a Leontief IO system operates under *constant returns to scale*. That is, the intermediate inputs are constant proportions of the output of the purchasing industry (the ratio between an input and output of production is called a technical coefficient). For instance, in a monetary IO system, the iron ore purchases are a constant fraction of the value of primary steel output. If the output of primary steel doubles, the inputs of iron ore will double. This proportional input-output relation is not realistic in the longer run. This is because over time, as firms or industries expand, firms and industries might experience economies of scales, that is, the increase in efficiency due to larger scale in production, or diseconomies of scale, that is, the reduction in efficiency due to over-expansion or production complexity. Besides, in longer run, technological advancement can lead to more outputs with the same or even fewer inputs.

Attention also needs to be given to the data-related aspects of the IO Model. At the very heart of the EE MRIO model is an algebraic relation between an international vector of environmental stressors, a global Leontief inverse matrix, and a global final demand matrix. The inter-country and inter-industry transactions data are documented in either monetary, which is used in the monetary MRIO model, or in physical terms, which is utilized to construct the physical MRIO model. To measure the direct and indirect emissions embodied in final demand, this study uses the monetary MRIO model because it intends to analyze how the magnitude and direction of international emission transfers are related to the monetary trade flows across countries. However, the use of monetary transactions data is without any shortcomings. In monetary units, a price change might or might not be related to the change in the use of physical units. The physical transactions data (as used in the physical MRIO model) is deemed to have higher accuracy to measure the environmental impacts compared to monetary transactions data (as used in the monetary MRIO model). This is because physical transactions data directly quantifies the actual material uses (Hubacek and Giljum, 2003). However, it is important to note that in reality, products can be non-homogeneous: Toyota Prius and a Ford Focus will fall within the category of 'car products' in the physical transactions data even if both cars require different material uses to produce and are sold at different market prices. This categorization approach is not of fundamental issue in the MRIO analysis, and would increasingly be less of an issue when the sector resolution of the MRIO data increases, yet it implies that the physical transactions data would not fully reflect the actual material flows (and hence the environmental footprints) (Suh, 2004). In the physical MRIO model, an actual issue might occur when one seeks to quantify the physical unit of (various) service sectors. This is because services do not have a straightforward physical manifestation that can easily be measured. Measuring the monetary unit of services sectors, on the other hand, is not of a particular issue in the monetary MRIO model.

5.3.2 On the Role of Technology in Determining the Cross-Country Emission Patterns

In the EE MRIO model, the balance of emissions embodied in trade is ultimately driven by the technological and final demand factors. Technological factors – emission intensity of output and input intensity of output – to some extent influence the cross-country emission patterns. Emission intensity reflects the amount of emissions produced per one unit of monetary output, while input intensity denotes the amount of monetary inputs required per one unit of monetary output. These technological features vary across countries due to the differences in production processes, energy mixes, and technological advancements. Some countries can produce a category of product with lower emissions and lesser inputs compared to other countries. The exchange of one unit of this product between two countries, assuming this product is identical, leads to one country generating more emissions than the other.

Technological progress and advancements have the potential to significantly alter the dynamics of the balance of emissions embodied in trade. As countries adopt cleaner and more efficient technologies, their emission intensity (the amount of CO_2 emissions per unit of output) and input intensity (the amount of inputs required per unit of output) are likely to decrease. This leads to lower emissions per unit of production and greater resource efficiency. Such technological improvements can change the dynamics of the emission balances, particularly for countries that have historically relied on carbon-intensive production methods.

For example, a country that transitions from coal-based energy production to renewable energy sources like wind, solar, or hydroelectric power will experience a substantial reduction in emission intensity. This shift not only lowers the overall emissions associated with domestic production but also affects the emissions embodied in goods exported to other countries. Moreover, the technological advancement in industrial process can lead to more efficient use of resources, and further lead to lower emissions per unit of output. For instance, the use of advanced irrigation systems in modern agriculture can lead to more efficient use of resources, meaning lower emissions per unit of agricultural outputs. For countries which export agricultural products, this technological progress will lower their emissions embodied in exports.

5.3.3 On the Short-Term Carbon Tax Assessment Model

This dissertation uses a static model to assess the short-term impacts of carbon policy reform (carbon taxation policy and cash transfer program) on households across income level (**Chapter 4**). This model consists of two modules working sequentially. First, the EE

MRIO produces the account of emissions embodied in households final demand aggregated by products. Dividing this account with the aggregate final demand gives the emission intensity of final demand, which is then required as a input for the second module, the microsimulation module. The microsimulation module is based on the household survey data containing the expenditure data for sample households, that is, how much each sample household spends on consumption products annually. Multiplying the emission intensity of final demand with a household's expenditure for the corresponding consumption category yields the emissions embodied in consumption category for that household. Furthermore, multiplying the emissions embodied in consumption categories with carbon tax gives the embodied carbon tax in each consumption product.

In this study, Indonesia is selected as a case study for various reasons. Indonesia is a large economy by GDP and population measures and a prominent global CO_2 emitter. The country has faced the challenges of reducing the growth and the current level of its emissions while maintaining the goal of increasing the living standard of its people. Apart from that, Indonesia has still pledged to deploy carbon policy measures, among which is the carbon taxation policy. In the near future, the country plans to levy a low $2 per tonne CO_2 carbon tax on a narrow scope of coal-electricity sector. Later, Indonesia intends to rise the taxation rate and expand the scope to cover the entire economy. In light of this scenario, this study considers various carbon taxation rates and scenarios that are relevant in the case of Indonesia. To determine the taxation rates, this study considers the rates suggested by various sources such as Tol (2019), Kaufman et al. (2020), Stern and Stiglitz (2021), and (World Bank, 2023). The scenarios are determined based on the government's plan to gradually introduce the carbon tax to the entire sectors in the economy. This study also anticipates a scenario where the government deploys a countermeasure policy to shield the low-income households from the negative impact of carbon tax. Hence, Three possible cash transfer programs are considered: the hypothetical Uniform cash transfer, the existing BLT cash transfer, and the partial cash transfer for low-income households. There might possibly exist a similar future scenario in other (developing) countries facing the dual challenge of reducing carbon emissions while achieving development targets, on which a similar carbon policy reform assessment model can be tested.

As a static model, it analyzes the first-order distributional impacts of carbon policy reform on households. However, there are underlying assumptions and limitations in this model. In the short term, it assumes that both producers and consumers have limited room to respond to the change brought about by carbon policy reform. In this scenario, the demands of both producers and consumers remain unaffected by changes in prices. This means that both producers and consumers continue to buy and sell the same quantity of goods and services, irrespective of changes in commodity prices. As such, the model defines the price elasticity of demand for both producers and consumers as zero. While this assumption might be useful to predict the immediate impact, it might not accurately reflect real-world economic behavior where demand and supply often respond to price changes. Households might react to the economywide price increase induced by carbon tax either by reducing the consumption of carbon-intensive products (e.g. because they are more expensive due to the carbon tax), or by substituting with 'cleaner' products. Producers might react by efficiency improvements or by substitutions. A multi-order model that captures the changes in producers' and consumers' behavior might better represent the real-world scenario.

The model also assumes that upon receiving the cash from the revenue recycling program, households would spend it entirely for consumption. This leads to further assumptions on savings and how the cash is spent in regards to the previous expenditure pattern. First, since it is assumed that the cash is spent entirely, there will be no savings made by households regardless of their initial income levels (additional cash might not matter much for high-income households to maintain their pre-tax consumption levels). Second, households are assumed to spend the received cash in the same proportion as the previous structure of consumption. For instance, if 20% of a household's expenditure comprises of electricity payment, 20% of the received cash transfer would then be spent as an electricity payment. This assumption is related to the short-term nature of the model, in that in the near future households might have limited time for behavior changes so that they tend to adopt the previous pattern of consumption. In reality, households might or might not follow the initial consumption pattern upon receiving the additional cash.

Other assumptions and limitations in the model are also worth to mention. The study (e.g. Piketty and Saez (2007)) this dissertation is referring to argues that the tax is deemed 'progressive' if the negative impact of carbon tax is lower on low-income households than on high-income households. However, this definition says nothing about the state of households post-reform expenditures, that is, whether the households' expenditures have really recovered after the carbon tax and cash transfer. Another assumption in the model pertains the efficiency of tax administration. The implementation of carbon tax is assumed to be administratively efficient; the available tax revenue for cash transfer is equal to the 'on-paper' estimation generated by the model. Besides, the model also does not provide a mechanism to measure the policy's acceptability (for instance, whether the lower impact on low-income households means the policy is accepted by the public). Next, the model only takes into account the distributional impact of carbon policy reform. In reality, the implications of carbon policy reform might be intertwined with the impacts exerted by other policies. Lastly, constructing the final demand matrix of an IO model with a disaggregated electricity sector requires assumption that is based on the countries' energy mix, that is, the electricity final demand is segregated into electricity sub-sectors in proportion of their corresponding energy mixes (Stadler et al., 2018). In the case of Indonesia, a country with highly-centralized electricity system, power producers transmit the electricity they generate to the the main grids, making it impossible to differentiate which sources of electricity households are consuming.

5.4 Recommendations

5.4.1 Recommendations for future research

There has been a confirmed negative cross-country correlation between the conventional balance of emissions embodied in trade (BEET) and per-capita income. The international emission transfer (BEET) is driven largely by cross-country technology differences, as producers tend to generate less emissions per unit of output in developed countries than in developing countries (see the decomposition study by Jakob and Marschinski (2013)). However, as argued in **Chapter 2**, BEET cannot be used to measure the net impact of a country's trade on foreign carbon emissions, defined as the net weak carbon leakage. **Chapter 2** tries to solve this by proposing the technology-adjusted BEET (TBEET) to measure the net weak carbon leakage. TBEET compares the foreign emissions generated by imports (EEM) and foreign emissions avoided by exports (TEEX). It turns out that there is a positive cross-country correlation between TBEET and per-capita income. Structural decomposition methods could numerically reveal what might drive the differences between the TBEET and BEET. This type of analysis is beyond the scope of this dissertation but could be a worthwhile area of exploration for future research. Besides, it might also be a worthwhile enterprise to carry out analysis that separates CO_2 emissions from consumption and investments. In the case of China, it is possible that the surge of domestic consumption in the past decades has been spurred partially by foreign investments. The Input-Output model uses certain fixed technologies and consumer demands. It does not consider how the influx of foreign investments can change these technologies and demands.

Chapter 4 uses a static, short-term model to appraise the distributional impacts of carbon policy reform in Indonesia. The model assumes that the producer and consumer price elasticity of demand functions to be zero. This is certainly not the case in real world where both actors might respond to the price changes in various ways. It might be possible that households react by consuming less or by substituting the emission-intensive products they initially consume. Future studies could consider introducing more realistic price elasticities of demand, even if this means the model would run through more than one order of analysis (hence, it transforms into a dynamic model). For example, the first order of analysis reveals the immediate impact of carbon tax and cash transfer. The next orders of analysis might include introducing the price elasticity of demand, or income elasticity of demand after receiving the cash transfer. This scheme, however, would significantly increase the complexities and uncertainties of the model. Should the model run through more than one order of analysis, future research might also want to consider the producer's price elasticity of demand of intermediate products. Producers would react to the price changes in energy inputs and the changes in households' demands after the tax and cash transfers. This triggers changes in the input composition of the production. This new system will be reflected by a new input coefficient matrix representing the post-reform production structure.

5.4.2 Policy implications and recommendations

Deriving an accurate policy measure to reduce CO_2 emissions requires a CO_2 emission accounting scheme that reflects how countries' policies affect global emissions. This emission accounting scheme should enable policy makers to credit efforts in reducing emissions and otherwise penalize the actions that increase them (Kander et al., 2015). The conventional production-based emission accounting (PBA), even if it is still a relevant emission accounting approach for policy making, disregards the emission leakage, that is, the emissions embodied in imports. The consumption-based emissions accounting (CBA) is constructed to solve this leakage issue by attributing emissions to final consumer. However, CBA disregards the aspects of emissions the focus country can actually influence, in that it is not responsive to the changes in domestic technology used to produce exports. The conventional net CO_2 emission transfers, measured by the gap between PBA and CBA, also cannot be used to measure the contribution of international trade on both domestic and foreign emissions.

In this dissertation, **Chapter 2** and **Chapter 3** seek to solve this issue and complement the existing CO_2 emission accounting methods. These chapters propose alternative emission accounting schemes to appraise what cannot be interpreted by the conventional emission accounting approach. **Chapter 2** proposes the technology-adjusted accounting method and implements it to appraise the net impact of trade on foreign emissions and the existence of decoupling. **Chapter 3** proposes the MRIO-based technology-adjustment to appraise the net impact of trade on domestic emissions and the existence of decoupling. The outcomes of both chapters provide policy makers with useful information on how the state of international differences in production technology could influence the global CO_2 emission patterns. The new interpretation of international emission dynamics presented by the *new weak leakage* and *net onshoring of emissions* could serve as a useful complement to other emission monitoring instruments for policy makers.

Perhaps the most apparent policy implications arise from **Chapter 4**, as this chapter directly assesses the design options of carbon policy reform in Indonesia. In that chapter, various combinations of carbon taxation scenarios (national, national plus imported, electricity, and lpg carbon taxes), tax rates, and revenue recycling options are explored. In practice, one of the setbacks of implementing a carbon tax, or other climate policies in general, is the consideration that the policy might be regressive for low-income households. In the case where reducing emissions is detrimental, the Indonesian government might want to design a carbon taxation policy while shielding low-income households from the subsequent impacts. That way the Indonesian government should properly design a relief policy for low-income households. The assessment requires a careful analysis not only of the subsequent impacts of taxation but also of the net expenditure after revenue recycling program. The traditional definition of tax progressiveness cannot serve as a single-standing parameter, it should be coupled with the post-cash-transfer expenditure analysis to evaluate whether the vulnerable households net benefit from the reform. **Chapter 4** finds that carbon policy reform in Indonesia, if designed accordingly, has a progressive tendency and might net benefit low-income households.

If the objective of carbon policy reform is to give incentives to reduce CO_2 emissions while protecting the low-income households from falling into persistent poverty, a universal tax rebate could be an interesting option. Besides, a universal tax rebate could also net benefit the majority of the consumers, which would ensure the political and societal acceptability of the reform (Olson Jr, 1971; Trebilcock, 2014). However, the implementation of such a strategy might be administratively demanding. By considering the administrative inefficiency along the tax collection and redistribution processes, the revenue available for cash transfer might not be enough to execute a universal revenue redistribution plan. Improving the existing cash transfer program in Indonesia (for instance, by increasing its coverage) might be a more viable option than establishing a new scheme of universal tax rebate. At the time of writing (January, 2024), the Indonesian government is about to arrange a cash transfer (the BLT) program to relief the low-income households from the impact exerted by the *El Niño*. Additionally, a progressive universal cash transfer could also be an option, in that cash transfer is distributed according to the initial income levels.

The government's initial plan to levy a carbon tax on electricity sectors could be effective to reduce carbon emissions because both electricity sectors, and also fuel use, are intensive in carbon emissions. However, the government should be cautious with respect to the potential implications for the vulnerable households that could emerge from that plan. The study in **Chapter 4** finds that carbon taxation mostly affects households in Indonesia through the price increase in electricity and fuel products. This is reflected in the contribution of consumption items to the carbon tax embodied in households' consumption. Thereby, the carbon taxation should be paired with a cash transfer program which at the very least is targeted to the vulnerable households.

References

Ackerman, F., Ishikawa, M., and Suga, M. (2007). The Carbon Content of Japan–US Trade. *Energy Policy*, 35(9):4455–4462.

Aden, N. (2018). Necessary but not sufficient: The Role of Energy Efficiency in Industrial Sector Low-carbon Transformation. *Energy Efficiency*, 11(5):1083–1101.

Afionis, S., Sakai, M., Scott, K., Barrett, J., and Gouldson, A. (2017). Consumption-based Carbon Accounting: Does It Have a Future? *WIREs Climate Change*, 8(1):e438.

Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is Free Trade Good for the Environment? *American Economic Review*, 91(4):877–908.

Araar, A., Dissou, Y., and Duclos, J.-Y. (2011). Household Incidence Of Pollution Control Policies: A Robust Welfare Analysis Using General Equilibrium Effects. *Journal of Environmental Economics and Management*, 61(2):227–243.

Arndt, C., Chinowsky, P., Fant, C., Paltsev, S., Schlosser, C. A., Strzepek, K., Tarp, F., and Thurlow, J. (2019). Climate Change and Developing Country Growth: The Cases Of Malawi, Mozambique, and Zambia. *Climatic Change*, 154:335–349.

Arto, I., Roca, J., and Serrano, M. (2014). Measuring Emissions Avoided by International Trade: Accounting for Price Differences. *Ecological Economics*, 97:93–100.

Asian Development Bank (2023). *Basic Statistics 2023*. Asian Development Bank.

Atkinson, G., Dietz, S., Neumayer, E., and Agarwala, M. (2014). *Handbook of Sustainable Development: Second Edition*. Edward Elgar Publishing.

Baranzini, A., Goldemberg, J., and Speck, S. (2000). A Future for Carbon Taxes. *Ecological economics*, 32(3):395–412.

Basri, M. C. and Rahardja, S. (2010a). Mild Crisis, Half Hearted Fiscal Stimulus: Indonesia During the GFC. *Assessment on the Impact of Stimulus, Fiscal Transparency and Fiscal Risk. ERIA Research Project Report*, 1:169–211.

Basri, M. C. and Rahardja, S. (2010b). The Indonesian Economy Amidst the Global Crisis: Good Policy and Good Luck. *ASEAN Economic Bulletin*, pages 77–97.

Basri, M. C. and Riefky, T. (2023). Ensuring an Inclusive, Affordable, and Smooth Climate Transition in Indonesia. *Keys to Climate Action*, 127.

Baumert, N., Kander, A., Jiborn, M., Kulionis, V., and Nielsen, T. (2019). Global Outsourcing of Carbon Emissions 1995–2009: A Reassessment. *Environmental Science & Policy*, 92:228–236.

Baumol, W. J., Baumol, W. J., Oates, W. E., Bawa, V. S., Bawa, W., Bradford, D. F., et al. (1988). *The Theory Of Environmental Policy*. Cambridge University Press.

Blundell, R. and Preston, I. (1998). Consumption Inequality and Income Uncertainty. *The Quarterly Journal of Economics*, 113(2):603–640.

Brännlund, R. and Nordström, J. (2004). Carbon Tax Simulations Using a Household Demand Model. *European Economic Review*, 48(1):211–233.

Brenner, M., Riddle, M., and Boyce, J. K. (2007). A Chinese Sky Trust?: Distributional Impacts of Carbon Charges and Revenue Recycling in China. *Energy Policy*, 35(3):1771–1784.

Bureau, B. (2011). Distributional Effects of a Carbon Tax on Car Fuels in France. *Energy Economics*, 33(1):121–130.

Burke, P. J. (2013). The National-Level Energy Ladder and Its Carbon Implications. *Environment and Development Economics*, 18(4):484–503.

Burtraw, D., Sweeney, R., and Walls, M. (2009). The Incidence of US Climate Policy: Alternative Uses of Revenues from a Cap-and-trade Auction. *National Tax Journal*, 62(3):497–518.

Cahyadi, N., Hanna, R., Olken, B. A., Prima, R. A., Satriawan, E., and Syamsulhakim, E. (2020). Cumulative Impacts of Conditional Cash Transfer Programs: Experimental Evidence from Indonesia. *American Economic Journal: Economic Policy*, 12(4):88–110.

Carattini, S., Baranzini, A., Thalmann, P., Varone, F., and Vöhringer, F. (2017). Green Taxes in a Post-paris World: Are Millions of Nays Inevitable? *Environmental and Resource Economics*, 68:97–128.

Chen, Z. M. and Chen, G. Q. (2011). Embodied Carbon Dioxide Emission at Supra-National Scale: A Coalition Analysis for G7, BRIC, and the Rest of the World. *Energy Policy*, 39(5):2899–2909.

Cherniwchan, J., Copeland, B. R., and Taylor, M. S. (2017). Trade and the Environment: New Methods, Measurements, and Results. *Annual Review of Economics*, 9(1):59–85.

Copeland, B. R., Shapiro, J. S., and Taylor, M. S. (2022). Globalization and the Environment. *Handbook of International Economics*, page 575.

Copeland, B. R. and Taylor, M. S. (1994). North-South Trade and the Environment. *The Quarterly Journal of Economics*, 109(3):755–787.

Cornwell, A. and Creedy, J. (1996). Carbon Taxation, Prices and Inequality in Australia. *Fiscal Studies*, 17(3):21–38.

Cramton, P., MacKay, D. J., Ockenfels, A., and Stoft, S. (2017). *Global Carbon Pricing: The Path to Climate Cooperation*. The MIT Press.

Darwili, A. and Schröder, E. (2022). On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade. *Environmental and Resource Economics*.

Datta, A. (2010). The Incidence of Fuel Taxation in India. *Energy Economics*, 32:S26–S33.

Davis, S. J. and Caldeira, K. (2010). Consumption-Based Accounting of CO2 Emissions. *Proceedings of the National Academy of Sciences*, 107(12):5687–5692.

de Vries, G. J. and Ferrarini, B. (2017). What Accounts for the Growth of Carbon Dioxide Emissions in Advanced and Emerging Economies? The Role of Consumption, Technology and Global Supply Chain Participation. *Ecological Economics*, 132:213–223.

Dechezleprêtre, A., Koźluk, T., Kruse, T., Nachtigall, D., and Serres, A. d. (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. Publisher: Now Publishers, Inc.

Dechezleprêtre, A. and Sato, M. (2017). The Impacts of Environmental Regulations on Competitiveness. *Review of Environmental Economics and Policy*, 11(2):183–206. Publisher: The University of Chicago Press.

Dietzenbacher, E., Cazcarro, I., and Arto, I. (2020). Towards a More Effective Climate Policy on International Trade. *Nature Communications*, 11(1):1130.

Dietzenbacher, E. and Mukhopadhyay, K. (2007). An Empirical Examination of the Pollution Haven Hypothesis for India: Towards a Green Leontief Paradox? *Environmental and Resource Economics*, 36(4):427–449.

Domingos, T., Zafrilla, J. E., and López, L. A. (2016). Consistency of Technology-Adjusted Consumption-Based Accounting. *Nature Climate Change*, 6(8):729–730.

Dorband, I. I., Jakob, M., Kalkuhl, M., and Steckel, J. C. (2019). Poverty and Distributional Effects Of Carbon Pricing in Low-and Middle-income Countries–a Global Comparative Analysis. *World Development*, 115:246–257.

Douenne, T. (2020). The Vertical and Horizontal Distributive Effects of Energy Taxes: A Case Study of a French Policy. *The Energy Journal*, 41(3):231–254.

Drews, S. and Van den Bergh, J. C. (2016). What Explains Public Support for Climate Policies? A Review Of Empirical and Experimental Studies. *Climate policy*, 16(7):855–876.

Dyarto, R. and Setyawan, D. (2021). Understanding the Political Challenges of Introducing a Carbon Tax in Indonesia. *International Journal of Environmental Science and Technology*, 18:1479–1488.

Feenstra, R. C., Inklaar, R., and Timmer, M. P. (2015). The Next Generation of the Penn World Table. *American Economic Review*, 105(10):3150–3182.

Feindt, S., Kornek, U., Labeaga, J. M., Sterner, T., and Ward, H. (2021). Understanding Regressivity: Challenges and Opportunities Of European Carbon Pricing. *Energy Economics*, 103:105550.

Feng, K., Hubacek, K., Guan, D., Contestabile, M., Minx, J., and Barrett, J. (2010). Distributional Effects Of Climate Change Taxation: The Case of the UK.

Ferng, J.-J. (2003). Allocating the Responsibility of CO2 Over-emissions from the Perspectives of Benefit Principle and Ecological Deficit. *Ecological economics*, 46(1):121–141.

Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., et al. (2022). Global Carbon Budget 2022. *Earth System Science Data Discussions*, 2022:1–159.

Gaulier, G. and Zignago, S. (2010). BACI: International Trade Database at the Product-Level. The 1994-2007 Version. Technical Report 2010-23, CEPII Research Center.

Goulder, L. H. and Schein, A. R. (2013). Carbon Taxes Versus Cap and Trade: A Critical Review. *Climate Change Economics*, 4(03):1350010.

Hassett, K. A., Mathur, A., and Metcalf, G. E. (2009). The Incidence of a US Carbon Tax: A Lifetime and Regional Analysis. *The Energy Journal*, 30(2).

Hertwich, E. G. and Peters, G. P. (2009). Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environmental Science & Technology*, 43(16):6414–6420.

Hubacek, K. and Giljum, S. (2003). Applying Physical Input–Output Analysis to Estimate Land Appropriation (Ecological Footprints) of International Trade Activities. *Ecological Economics*, 44(1):137–151.

IEA (2018). CO2 Emissions from Fuel Combustion, International Energy Agency.

International Energy Agency (2022). *An Energy Sector Roadmap to Net Zero Emissions in Indonesia*. OECD.

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 [Core Writing Team, H. Lee and J. Romero (eds.)]*.

Jakob, M. and Marschinski, R. (2013). Interpreting Trade-Related CO2 Emission Transfers. *Nature Climate Change*, 3(1):19–23.

Jakob, M., Steckel, J. C., and Edenhofer, O. (2014). Consumption- Versus Production-Based Emission Policies. *Annual Review of Resource Economics*, 6(1):297–318.

Jakob, M., Ward, H., and Steckel, J. C. (2021). Sharing Responsibility for Trade-Related Emissions Based on Economic Benefits. *Global Environmental Change*, 66:102207.

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., and Moran, D. D. (2018). Decoupling or Delusion? Measuring Emissions Displacement in Foreign Trade. *Global Environmental Change*, 49:27–34.

Jiborn, M., Kulionis, V., and Kander, A. (2020). Consumption versus Technology: Drivers of Global Carbon Emissions 2000–2014. *Energies*, 13(2):339. Number: 2 Publisher: Multidisciplinary Digital Publishing Institute.

Jones, B. and Cardinale, R. (2023). Social and Political Opposition to Energy Pricing Reforms. *Climate and Development*, pages 1–12.

Kander, A., Jiborn, M., Moran, D. D., and Wiedmann, T. O. (2015). National Greenhouse-Gas Accounting for Effective Climate Policy on International Trade. *Nature Climate Change*, 5(5):431–435.

Kanemoto, K., Moran, D., Lenzen, M., and Geschke, A. (2014). International Trade Undermines National Emission Reduction Targets: New Evidence from Air Pollution. *Global Environmental Change*, 24:52–59.

Karstensen, J., Peters, G. P., and Andrew, R. M. (2018). Trends of the EU's Territorial and Consumption-Based Emissions from 1990 to 2016. *Climatic Change*, 151(2):131–142.

Kaufman, N., Barron, A. R., Krawczyk, W., Marsters, P., and McJeon, H. (2020). A Near-term to Net Zero Alternative to the Social Cost of Carbon for Setting Carbon Prices. *Nature Climate Change*, 10(11):1010–1014.

Kerkhof, A. C., Moll, H. C., Drissen, E., and Wilting, H. C. (2008). Taxation of Multiple Greenhouse Gases and the Effects on Income Distribution: A Case Study of the Netherlands. *Ecological Economics*, 67(2):318–326.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018). Making Carbon Pricing Work for Citizens. *Nature Climate Change*, 8(8):669–677.

Labandeira, X. and Labeaga, J. (1999). Combining Input-output Analysis and Micro-simulation to Assess the Effects of Carbon Taxation on Spanish Households. *Fiscal studies*, 20(3):305–320.

Leontief, W. (1970). Environmental Repercussions and the Economic Structure: An Input-Output Approach. *The Review of Economics and Statistics*, 52(3):262–271.

Leontief, W. (1986). *Input-Output Economics*. Oxford University Press, New York.

Leontief, W. W. (1941). *The Structure of American Economy, 1919-1929: An Empirical Application of Equilibrium Analysis*. Harvard University Press.

Li, J. and O'Donoghue, C. (2013). A Survey of Dynamic Microsimulation Models: Uses, Model Structure and Methodology. *International Journal of microsimulation*, 6(2):3–55.

Liang, Q.-M., Wang, Q., and Wei, Y.-M. (2013). Assessing the Distributional Impacts of Carbon Tax Among Households Across Different Income Groups: The Case of China. *Energy & environment*, 24(7-8):1323–1346.

Liu, L. (2015). A critical examination of the consumption-based accounting approach: Has the blaming of consumers gone too far? *WIREs Climate Change*, 6(1):1–8.

López, L. A., Arce, G., Kronenberg, T., and Rodrigues, J. F. D. (2018). Trade from Resource-Rich Countries Avoids the Existence of a Global Pollution Haven Hypothesis. *Journal of Cleaner Production*, 175:599–611.

López, L. A., Arce, G., and Zafrilla, J. E. (2013). Parcelling Virtual Carbon in the Pollution Haven Hypothesis. *Energy Economics*, 39:177–186.

Malerba, D., Gaentzsch, A., and Ward, H. (2021). Mitigating Poverty: The Patterns of Multiple Carbon Tax and Recycling Regimes for Peru. *Energy Policy*, 149:111961.

Miller, R. E. and Blair, P. D. (2009). *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press.

Mourougane, A. (2010). Phasing Out Energy Subsidies in Indonesia. OECD Publishing.

Nurdianto, D. A. and Resosudarmo, B. P. (2016). The Economy-wide Impact of a Uniform Carbon Tax in ASEAN. *Journal of Southeast Asian Economies*, pages 1–22.

OECD (2021). OECD Inter-Country Input-Output Database.

OECD (2022). Trade in Embodied CO2 Database (TECO2) Database.

Ohlendorf, N., Jakob, M., Minx, J. C., Schröder, C., and Steckel, J. C. (2021). Distributional Impacts of Carbon Pricing: A Meta-analysis. *Environmental and Resource Economics*, 78:1–42.

Olson Jr, M. (1971). *The Logic Of Collective Action: Public Goods and the Theory of Groups, with a New Preface and Appendix*, volume 124. Harvard University Press.

Pearce, D. (1991). The Role of Carbon Taxes in Adjusting to Global Warming. *The Economic Journal*, 101(407):938–948.

Peters, G. (2008a). Reassessing Carbon Leakage. Eleventh Annual Conference on Global Economic Analysis, "Future of Global Economy", Helsinki, Finland, June 12-14, 2008.

Peters, G. P. (2007). Opportunities and Challenges for Environmental MRIO Modeling: Illustrations with the GTAP Database. In *16th International Input-Output Conference*, volume 30.

Peters, G. P. (2008b). From Production-Based to Consumption-Based National Emission Inventories. *Ecological Economics*, 65(1):13–23.

Peters, G. P. (2010). Policy Update: Managing Carbon Leakage. *Carbon Management*, 1(1):35–37.

Peters, G. P. and Hertwich, E. G. (2008a). CO2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science & Technology*, 42(5):1401–1407.

Peters, G. P. and Hertwich, E. G. (2008b). Post-Kyoto Greenhouse Gas Inventories: Production Versus Consumption. *Climatic Change*, 86(1):51–66.

Peters, G. P., Minx, J. C., Weber, C. L., and Edenhofer, O. (2011). Growth in Emission Transfers Via International Trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the United States of America*, 108(21):8903–8908.

Peters, G. P., Weber, C. L., Guan, D., and Hubacek, K. (2007). China's Growing CO2 Emissions: A Race between Increasing Consumption and Efficiency Gains. *Environmental Science & Technology*, 41(17):5939–5944. Publisher: American Chemical Society.

Pigou, A. C. (1924). *The Economics Of Welfare*. Macmillan.

Piketty, T. and Saez, E. (2007). How Progressive is the US Federal Tax System? A Historical and International Perspective. *Journal of Economic perspectives*, 21(1):3–24.

Quéré, C. L., Korsbakken, J. I., Wilson, C., Tosun, J., Andrew, R., Andres, R. J., Canadell, J. G., Jordan, A., Peters, G. P., and Vuuren, D. P. v. (2019). Drivers of Declining CO2 Emissions in 18 Developed Economies. *Nature Climate Change*, 9(3):213.

Renner, S., Lay, J., and Schleicher, M. (2019). The Effects of Energy Price Changes: Heterogeneous Welfare Impacts and Energy Poverty in Indonesia. *Environment and Development Economics*, 24(2):180–200.

Rodrigues, J. F. D., Domingos, T. M. D., and Marques, A. P. S. (2010). *Carbon Responsibility and Embodied Emissions: Theory and Measurement*. Routledge.

Sajeewani, D., Siriwardana, M., and Mcneill, J. (2015). Household Distributional and Revenue Recycling Effects of the Carbon Price in Australia. *Climate Change Economics*, 6(03):1550012.

Setyowati, A. B. and Quist, J. (2022). Contested Transition? Exploring the Politics and Process of Regional Energy Planning in Indonesia. *Energy Policy*, 165:112980.

Songwe, V., Stern, N., and Bhattacharya, A. (2022). Finance for Climate Action: Scaling Up Investment for Climate and Development. *Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science*.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Koning, A. d., and Tukker, A. (2018). EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology*, 22(3):502–515.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J. H., Theurl, M. C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., Koning, A., and Tukker, A. (2021). Exiobase 3.

Steckel, J. C., Dorband, I. I., Montrone, L., Ward, H., Missbach, L., Hafner, F., Jakob, M., and Renner, S. (2021). Distributional Impacts Of Carbon Pricing in Developing Asia. *Nature Sustainability*, 4(11):1005–1014.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33):8252–8259.

Stern, N. and Stiglitz, J. E. (2021). *The Social Cost Of Carbon, Risk, Distribution, Market Failures: an Alternative Approach*, volume 15. National Bureau of Economic Research Cambridge, MA, USA.

Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., La Rovere, E. L., Morris, A., Moyer, E., Pangestu, M., et al. (2017). Report Of the High-level Commission On Carbon Prices.

Suh, S. (2004). A Note on the Calculus for Physical Input–Output Analysis and Its Application to Land Appropriation of International Trade Activities. *Ecological Economics*, 48(1):9–17.

Symons, E., Speck, S., Proops, J. L., et al. (2000). *The Effects of Pollution and Energy Taxes Across the European Income Distribution*, volume 5. Department of Economics, Keele University Keele, UK.

Taylor, M. S. (2005). Unbundling the Pollution Haven Hypothesis. *Advances in Economic Analysis & Policy*, 4(2).

Tiezzi, S. (2005). The Welfare Effects and the Distributive Impact of Carbon Taxation on Italian Households. *Energy Policy*, 33(12):1597–1612.

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production. *Review of International Economics*, 23(3):575–605.

Tol, R. S. J. (2019). *Climate Economics: Economic Analysis of Climate, Climate Change and Climate Policy*. Edward Elgar Publishing, 2nd edition.

Trebilcock, M. J. (2014). *Dealing With Losers: The Political Economy Of Policy Transitions*. Oxford University Press, USA.

Vogt-Schilb, A., Walsh, B., Feng, K., Di Capua, L., Liu, Y., Zuluaga, D., Robles, M., and Hubaceck, K. (2019). Cash Transfers for Pro-poor Carbon Taxes in Latin America and the Caribbean. *Nature Sustainability*, 2(10):941–948.

Wang, Q., Hubacek, K., Feng, K., Wei, Y.-M., and Liang, Q.-M. (2016). Distributional Effects Of Carbon Taxation. *Applied energy*, 184:1123–1131.

Weitzman, M. L. (2007). A Review of the Stern Review on the Economics of Climate Change. *Journal of economic literature*, 45(3):703–724.

Wood, R., Neuhoff, K., Moran, D., Simas, M., Grubb, M., and Stadler, K. (2019). The Structure, Drivers and Policy Implications of the European Carbon Footprint. *Climate Policy*, 0(0):1–19.

World Bank (2023). *State and Trends of Carbon Pricing 2023*.

Wu, R., Ma, T., and Schröder, E. (2022). The Contribution of Trade to Production-Based Carbon Dioxide Emissions. *Structural Change and Economic Dynamics*, 60:391–406.

Xia, Q., Wang, H., Liu, X., and Pan, X. (2020). Drivers of Global and National CO2 Emissions Changes 2000–2017. *Climate Policy*, 0(0):1–12.

Xu, Y. and Dietzenbacher, E. (2014). A Structural Decomposition Analysis of the Emissions Embodied in Trade. *Ecological Economics*, 101:10–20.

Yamano, N. and Guilhoto, J. (2020). CO2 Emissions Embodied in International Trade and Domestic Final Demand: Methodology and Results Using the OECD Inter-Country Input-Output Database.

Yusuf, A. A. and Resosudarmo, B. P. (2015). On the Distributional Impact of a Carbon Tax in Developing Countries: The Case of Indonesia. *Environmental Economics and Policy Studies*, 17:131–156.

Zhang, Y. (2012). Scale, Technique and Composition Effects in Trade-Related Carbon Emissions in China. *Environmental and Resource Economics*, 51(3):371–389.

Zhang, Z. (2018). Technology-Adjusted National Carbon Accounting for a Greener Trade Pattern. *Energy Economics*, 73:274–285.

Zhang, Z., Zhu, K., and Hewings, G. J. D. (2017). A Multi-Regional Input–Output Analysis of the Pollution Haven Hypothesis from the Perspective of Global Production Fragmentation. *Energy Economics*, 64:13–23.

Acknowledgements

Some PhD candidates may have *grandiose* intentions for pursuing their PhDs. While I, too, hope to use the knowledge I have gathered to address society’s current and future challenges, the motivation for doing a PhD is, for me, deeply personal. It has been an intellectual journey—one that began when I made the life-changing decision to resign from my job and pursue a master’s degree.

I realized then that, like many engineers, I was technically prepared to excel in the job market but lacked a deeper understanding of why and for whom we create technology. Technology, we were often told, is vital for human progress, but the questions of why, for whom, and with what consequences were left unanswered. I chose to step off the engineering bandwagon and pursue a master‘s degree with the intention of exploring the interplay between technology and society—how they shape and influence one another. It was a leap into uncharted territory, filled with unfamiliar terms and concepts. Even the usual learning approach of finding patterns didn’t always apply. Yet, I am forever grateful for that decision, as it eventually led me to pursue a PhD at TPM Faculty, TU Delft.

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Curriculum Vitae

Aldy Gustinara Darwili was born on the 14th of December 1990 in Jakarta, Indonesia. He graduated from Civil and Environmental Engineering Department, Universitas Indonesia in 2013. After completing his undergraduate studies, Aldy worked as a structure engineer in Saipem Indonesia's Offshore Engineering Division for two years under a graduate development program.

In 2017, Aldy earned his Master of Science degree in Management of Technology from Delft University of Technology, specializing in economics and finance. His thesis, titled "Secular Stagnation of Total Factor Productivity Growth: Evidence from the Italian Economy", used macro analysis to investigate the persistent stagnation of total factor productivity growth that has happened in the Italian Economy.

Aldy further pursue a PhD at Delft University of Technology, focusing on multi-regional input-output models, climate policy analysis, and the implications of international trade on global carbon emissions. His dissertation, "Emissions Embodied in Trade: Magnitudes, Directions, and Policy Implications", contributes to the understanding of carbon emissions and trade dynamics.

Professionally, Aldy has amassed over four years of combined research and consultancy experience at multiple organizations such as The World Bank and Global Efficiency Intelligence. His work spans developing multi-regional input-output models, assessing carbon pricing policies, analyzing emissions embodied in trade, and exploring the intersection of climate change, and economic development.

List of Publications and Conference Appearances

Publications

Hasanbeigi, A., & Darwili, A. (2022). *Embodied Carbon in Trade: Carbon Loophole*. Global Efficiency Intelligence. Florida, United States.

Darwili, A., & Schröder, E. (2023). *On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade*. Environmental and Resource Economics, 84(1), 65-98.

Darwili, A., & Schröder, E. (2024). *Which Countries Have Offshored Carbon Dioxide Emissions in Net Terms?* Under review in Ecological Economics.

Darwili, A., Storm, S., & Schröder, E. (2025). *Distributional Implications of Carbon Taxation Policy in Indonesia*. Under review in Energy and Climate Change.

Conferences

2021, March, 16th Input-Output Workshop, Bochum, Germany, “On the Interpretation and Measurement of Technology-Adjusted Emissions Embodied in Trade”. (Oral; virtual)