

Hübler, Michael; Braun, Marius; Keimes, Nils

Article

Regional climate policy analysis in the EU member country Germany

German Economic Review (GER)

Provided in Cooperation with:

Verein für Socialpolitik / German Economic Association

Suggested Citation: Hübler, Michael; Braun, Marius; Keimes, Nils (2026) : Regional climate policy analysis in the EU member country Germany, German Economic Review (GER), ISSN 1468-0475, De Gruyter, Berlin, Vol. 27, Iss. 3, pp. 195-229, <https://doi.org/10.1515/ger-2024-0102>

This Version is available at:

<https://hdl.handle.net/10419/343395>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by/4.0/>

Michael Hübler*, Marius Braun and Nils Keimes

Regional Climate Policy Analysis in the EU Member Country Germany

<https://doi.org/10.1515/ger-2024-0102>

Received September 27, 2024; accepted July 8, 2025; published online August 6, 2025

Abstract: This article studies the heterogeneity of European climate policy effects within Germany (Lower Saxony and the rest of Germany) and between other member states of the European Union (EU). It uses a global Eaton and Kortum trade model to examine the EU emissions trading system (EU ETS) with the carbon border adjustment mechanism (CBAM) and reveals significant differences in policy effects across EU countries and within Germany. Under a medium CO₂ target, CBAM has a negligible average welfare effect on the entire EU while it can eliminate the carbon leakage caused by the EU ETS. Assuming a less stringent CO₂ target, CBAM creates a welfare gain of the EU, whereas, assuming a more stringent target, it creates a welfare loss compared with the EU ETS alone. More stringent CO₂ targets in the EU ETS increase the effectiveness of CBAM in reducing carbon leakage and hence global emissions. Because official and constructed regional data sets are often incomplete, outdated or not publicly available and their compilation and resolution are not standardized, the official public provision of a comprehensive, harmonized, up-to-date regional data set, at least with federal state level resolution, is advisable.

Keywords: regional data; advanced trade model; climate policy; EU ETS; CBAM; Germany

JEL classifications: C68; F18; Q52; Q54; R50

***Corresponding author: Michael Hübler**, Agricultural, Food and Environmental Policy, Institute for Agricultural Policy and Market Research, Center for International Development and Environmental Research (ZEU), Justus Liebig University Giessen, Senckenbergstr. 3, 35390 Gießen, Germany, E-mail: michael.huebler@agrar.uni-giessen.de. <https://orcid.org/0000-0002-7119-7934>

Marius Braun and Nils Keimes, Faculty of Business Studies and Economics, Justus Liebig University Giessen, Gießen, Germany

 Open Access. © 2025 the author(s), published by De Gruyter.  This work is licensed under the Creative Commons Attribution 4.0 International License.

1 Introduction

Input-output tables are an important basis for model-based assessments of climate, trade or other economic policies and economic shocks, such as energy or food price changes. Although national input-output tables are widely available, within-country data (regional input-output tables, RIOTs, and multi-regional input-output, MRIO, tables) are scarce, especially for countries with relatively small geographic areas, in particular, Germany. Within-country disaggregation of data and models is more elaborated for large countries, structured in federal states or provinces, i.e., the United States, China and India (see, for example, Caliendo et al. 2018; Zhang et al. 2020; Leimbach et al. 2024). In Europe, within-country data are available for Germany, the United Kingdom, Belgium and Spain and have been applied to assess regional carbon footprints (Lenzen et al. 2010; Towa et al. 2022) and the impact of trade relationships on water resources (Cazcarro et al. 2013). Therefore, in this article, we provide guidance for researchers (modellers) who want to carry out a regional policy analysis of Germany (or other countries) based on the literature and our own policy analysis of the current European climate and trade policy. From our analysis, we derive policy recommendations considering regional specificity.

Within-country data are necessary to assess the regional effects of policies or shocks within countries in a precise way. This relevance especially stems from the differential economic impacts of policies or shocks across regions due to differences in the economic importance of active sectors, their interconnections and their contribution to the overall output of a region. Future impacts of climate change, such as floods, and resulting policy reactions are a crucial example for socially and politically highly relevant regional challenges,¹ and they depend on local geographic and climatic conditions. In addition to adaptation to climate change, mitigation of greenhouse gas emissions, especially the transformation of the energy system with the expansion of renewable energies, is a major challenge that is in the spotlight of this article while climate change impacts cannot be evaluated due to missing data at the region and country level. It is subject to regional potentials and obstacles because different regions within countries often exhibit heterogeneity with regard to their renewable energy potentials, sectoral structures, focal points of production and natural resource endowments, particularly with fossil fuels.

In our policy analysis, we investigate Germany and the European Union (EU) because they are climate and energy policy front-runners and subject to economic and renewable-energy related heterogeneity. Since the EU “is currently

¹ See, for example, Adeel et al. (2020) regarding regional effects of floods in the United States, Canada and Mexico.

undergoing a digital and green transition” that affects the heterogeneous European regions in different ways and may hinder regional coherence (Maucorps et al. 2023), it is important to study the regional heterogeneity of EU policy effects. In particular, we compare the effects of the EU’s climate policy across EU countries and within Germany, the biggest economy within the EU. Our analysis includes the established EU Emissions Trading System (ETS) and the new EU Carbon Border Adjustment Mechanism (CBAM). Understanding the economic incentives and effects of such carbon-based tariffs can be an important step towards a global climate policy solution, possibly via a climate policy club (coalition) as an intermediate step. Because Germany is heavily involved in international trade, it can be significantly affected by these policies. Because Germany is regionally heterogeneous regarding its economic structure, trade policy effects can significantly differ across German regions (federal states).

Whereas German regions with strong dependence on fossil fuel-based sectors and regions with in-situ coal reserves are presumably negatively affected by stricter climate/energy policy regimes and may therefore receive adequate financial support, other regions are more robust to stricter climate/energy policy settings or even benefit from them. Lower Saxony is a prominent expected beneficiary (cf. Pothén and Hübler 2018; Pothén and Hübler 2021) among the German federal states. Although wind power plants are common across Germany, the northern coastal federal states, particularly Lower Saxony, exhibit a large on-shore and off-shore wind power potential and a high economic dependency on the wind power industry compared to the rest of Germany. Consequently, power generators in Lower Saxony can provide renewable energy (electricity) and sell CO₂ emission permits to earn revenues. Lower Saxony has less industrial and more rural areas with significant agricultural production compared to other German regions. Since agriculture is not included in the considered CO₂ emissions trading scheme, Lower Saxony is not severely affected by CO₂ pricing, which predominantly places a cost burden on energy-/CO₂-intensive industries. Against this background, the regional focus of our policy simulations is on Lower Saxony. In contrast, southern federal states have a large solar power potential and host important industries, such as automotive manufacturers and suppliers. Thus, climate policies striving for an increasing share of renewable energies will presumably result in (negative or positive) region-dependent economic effects that we explore leaving aside (reduced) climate change damages.

In particular, we ask the following research questions: How far do the economic effects of the current EU ETS and CBAM differ within the EU and within Germany? What are the conclusions for climate policy design and for improvements of regional data (especially from Germany) and the deployment of modelling methods (especially regional and advanced trade models)?

To address these questions, we review the relevant literature and data sources focusing on Germany to clarify the availability of regional data and their use in policy analysis. Furthermore, we compare the regional effects of the current European climate policy across EU countries and across regions within Germany as a prominent EU member country. Based on that, we derive research priorities and data requirements. The insights obtained can be relevant for modelers, data providers, funders and policy makers.

Different to the literature that mostly uses input-output methods or standard computable general equilibrium (CGE) models, for our policy analysis, we deploy a global CGE model with an advanced trade module and regional disaggregation to identify regional differences of policy impacts. In particular, we use a new quantitative trade model introduced by Pothén and Hübler (2018), building on the Ricardian trade theory of Eaton and Kortum (2002) and quantitatively implemented by Caliendo et al. (2018, 2023). Unlike conventional input-output methods, this allows us to compare policy scenarios to a benchmark scenario taking endogenous policy-induced general equilibrium effects into account. In recent contributions, Sogalla (2023) and Sogalla et al. (2024) find that in models with heterogeneous firms (cf. Melitz 2003; Kreckemeier and Richter 2014), sufficiently strong reductions in firms' emission intensities or reallocation of production between firms with different productivities and emission intensities can reduce overall emissions. Arkolakis et al. (2012) compare different types of (advanced) trade models to identify similarities and differences (also see Costinot and Rodríguez-Clare 2014, including numerical evaluations of policy responses). Accordingly, our scrutinized Eaton and Kortum (2002) type trade model generates results that are similar to those derived from a corresponding Armington (1969) type model (cf. Hübler et al. 2024) while differences in regional (within-country) effects are detected.

As a contribution to the economic policy modeling literature, we simulate the *regional* effects of CBAM on Germany based on the EU ETS. In the related literature, Hübler et al. (2024) study the effects of the EU ETS, CBAM and so-called "climate clubs" on German household income groups at the German-wide level. They find significant differences between the policy effects, e.g., a positive effect on poor households but a negative effect on rich households. Other studies find regional differences of climate and trade policy on German regions (Pothén and Hübler 2018, 2021; Hübler and Herdecke 2020). However, they do not study the effects of CBAM. Korpar et al. (2023) set up a multi-region, multi-sector structural gravity model to study the effects of CBAM and find small policy effects. So far, however, the model-based literature on carbon border adjustment policies (for example, Böhringer et al. 2012; Mattoo et al. 2013) has to our knowledge not examined *regional* policy effects within countries which we address in Section 3.

In general, our review of the literature and policy analysis reveal significant, policy-relevant regional differences in economic (policy) effects. According to our model simulations assuming a 44 % reduction of CO₂ emissions in (vis-à-vis) 2014 mimicking a 55 % by 2030 compared to 1990 as envisaged by the EU, the effect of the EU ETS on Lower Saxony in the North of Germany is positive (due to its large wind power potential) whereas the effect on the Rest of Germany is on average negative. (Note that benefits of reduced climate change impacts are not modeled in this cost effectiveness analysis). CBAM has small positive effects on both regions, but the effect is considerably larger in Lower Saxony than in the Rest of Germany. Accordingly, regional policy advice based on results from aggregate regions (here, Germany or the EU) can be misleading.

While the small policy effects that we find are in accordance with Korpar et al. (2023), a sensitivity check provides additional new insights: Because the import tariff rates of CBAM are proportional to the current CO₂ price in the EU ETS, we obtain a typical “optimal tariff” relationship in which the terms-of-trade and hence welfare are improved in an inverted U-shaped manner (compare Weitzel et al. 2012). Under the 44 % CO₂ target, any welfare effect of CBAM on the entire EU is hardly measurable. A less stringent CO₂ target results in a lower CO₂ price and therefore lower tariff rates which creates a minor average welfare gain of the EU from CBAM compared with the EU ETS alone in accordance with Korpar et al. (2023). A more stringent CO₂ target results in a substantially higher CO₂ price and therefore higher tariff rates which creates an additional average welfare loss of the EU. A more stringent target, however, increases the effectiveness of CBAM in reducing carbon leakage and hence global emissions. According to a decomposition analysis of the CO₂ reductions in our model, the technique effect via Ricardian specialization of the Eaton and Kortum theory, reduces CO₂ emissions to a minor extent in Lower Saxony and a small extent in the Rest of Germany.

In contrast to the regionally different policy results, our review of data sources and the related literature reveals a lack of available regional data from Germany. Although researchers have constructed and compiled RIOTs of mainly Western German federal states and some comprehensive MRIO tables (Többen 2017a, 2017b; Krebs 2020) (see Table 1 and Appendix Figure A1) covering all federal states, current official and publicly available data (from statistical offices) are largely missing. Consequently, we identify and discuss priorities of future research and data requirements aiming at providing a unified, official and publicly available country-wide regional data set of Germany and similarly of other countries.

This article proceeds as follows. Section 2 explores the availability of regional input-output data from Germany and reviews the literature on policy effects in German regions. Section 3 provides a model-based regional policy analysis of the current EU ETS and CBAM policies focusing on Lower Saxony compared with the

rest of Germany and the EU with selected separated member countries. Section 4 discusses research challenges, research priorities and data requirements for regional policy analysis. Section 5 concludes.

2 Review of Regional Data and Policy Assessments

Considering the importance of regional economic (policy) analyses, this section reviews available regional data from Germany and policy studies using these data.

2.1 Availability and Construction of Regional Datasets from Germany

This section summarizes the availability of regional data considering Germany at the federal state level as a prominent example. The availability of such data defines the technical boundaries of policy analyses (as summarized in Section 2.2) and identifies gaps that can be filled by statistical agencies and researchers. An example for an input-output table of a German federal state officially provided by a statistical agency is Baden-Wuerttemberg in the year 1990 (Pothen and Hübler 2018). Although approaches have been developed to create subnational time series data (Wang et al. 2017), regional input-output data remain scant. Therefore, researchers have constructed recent input-output tables of further German federal states.

Table 1 summarizes the regional input-output tables of German federal states that have been constructed by scholars. As a notable contribution, using shipment data, Krebs (2020) constructs an interregional input-output table (IRIOT) containing 402 German counties, 26 foreign trading partners and 17 sectors.² In addition to Table 1, Schröder and Zimmermann (2014) construct regional output multipliers for the Baltic Sea region for different regionalization methods.

Regarding regionalization, the literature generally relies on non-survey methods with two common approaches being the Commodity Balance (CB) approach (also known as Supply-Demand Pool, SDP, approach) and the Location Quotient (LQ) approach. The CB method presupposes that regional intermediary transactions, along with interregional trade, can be inferred from national data by assessing the balance between regional supply and demand (Jin 1991). The LQ method, together with the more recent Flegg Location Quotient (FLQ) method developed by Flegg and Webber (2000) and Flegg and Tohmo (2013), estimates regional multipliers using

² The data and code used to construct the IRIOT are available via the author's website: <https://sites.google.com/view/oliver-krebs/research?authuser=0>.

Table 1: Regional input-output tables of German federal states (based on Kronenberg and Wolter 2017, and an own survey of the literature). CHARM: Cross-Hauling Adjusted Regionalization Method, CB: commodity balance, SDP: supply-demand pool, LQ: location quotient, FLQ: flegg location quotient.

State	Author(s)	Year	Num. of sectors	Method	Publicly available
Baden-Wuerttemberg	Haigner et al. (2015)	2010	51	CHARM	No
Baden-Wuerttemberg	Heindl and Voigt (2012)	2006	72	CB/SDP	Yes
Baden-Wuerttemberg	Koch et al. (2019)	2014	38	CHARM	No
Hamburg	Prognos (2009)	2005	12	?	No
Hamburg	Kronenberg (2011)	2003	71	CHARM	No
Hessen	Penzkofer (2002)	1995	?	?	No
Hessen	Koschel et al. (2006)	2000	18	LQ	No
Lower Saxony	Schröder (2012)	2007	71	CHARM	Yes
Lower Saxony	Stöver (2018)	2013	20	CHARM	Yes
Mecklenburg-Western Pomerania	Kronenberg (2010)	2003	16	CHARM	Yes
North Rhine-Westphalia	Kronenberg and Többen (2011)	2007	59	CHARM	Yes
North Rhine-Westphalia	Prognos (2007)	2000	12	?	No
Saxony	Lehr et al. (2013)	2006	16	CHARM	No
Thuringia	Dettmer and Sauer (2014)	2010	73	FLQ	No
All German federal states	Többen (2017a, 2017b)	2011	41	CHARM	No
All German federal states	Krebs (2020)	2010	17	Krebs (2020)	Yes

national and regional employment data to derive regional input-output coefficients (Flegg et al. 1995).

However, as pointed out by Tohmo (2004) and Kronenberg (2009), both methods tend to produce tables that are systematically biased, primarily because they do not account for cross-hauling, i.e., intra-industry trade (the simultaneous exporting and importing of the same type of product). To address this shortcoming, Kronenberg (2009) has developed the Cross-Hauling Adjusted Regionalization Method (CHARM). In addition, some authors (e.g., Koch et al. 2019) adopt a hybrid approach that includes the use of original federal state-specific data. Based on a modified version of the CHARM method developed by Többen and Kronenberg (2015), Többen (2017a) creates a multi-regional input-output (MRIO) table of the year 2011 connecting single regional tables and covering all 16 German federal states (see Többen 2017b). The modified CHARM method addresses two limitations of the original approach: the assumption that cross-hauling in *interregional* trade is zero, and the outcome that estimates of interregional trade flows potentially violate accounting balances.

As summarized in Table 2, relevant data sources for these approaches include the Scientific Use Files of the Household Budget Survey (“Einkommens- und Verbrauchsstichprobe”, EVS, microeconomic household survey data from

Table 2: Data sources for the construction of regional input-output tables (based on Stöver 2018; Koch et al. 2019). NIOT: national input-output table, Destatis: German Statistical Office, EVS: Household Budget Survey, VGRdL: Regional Accounts of the Federal States, CHARM: cross-hauling adjusted regionalization method, BfA: Federal Employment Agency.

Variable	Data source	Provider	Publication frequency	Publicly available
Intermediate demand	NIOT	Destatis	Annual	Yes
Private consumption	EVS	Destatis	Quinquennial	No
Government final consumption expenditure	VGRdL	Federal states	Annual	Yes
Gross fixed capital formation	VGRdL	Federal states	Annual	Yes
Change in inventories	NIOT	Destatis	Annual	Yes
Exports and imports	CHARM/NIOT	–	–	–
Compensation of employees	VGRdL	Federal states	Annual	Yes
Employment by sectors	Labor data	BfA	Monthly	Yes

“Forschungsdatenzentren”, FDZ 2024) provided by the Research Data Centre (RDC) of the German Statistical Office, the German Statistical Office (“Statistisches Bundesamt”, Destatis 2022, macroeconomic German-wide non-survey data), the Regional Accounts of the Federal States (“Volkswirtschaftliche Gesamtrechnung der Länder”, VGRdL 2022b, macroeconomic non-survey data from the German federal states) as well as labor market statistics provided by the Federal Employment Agency (“Bundesagentur für Arbeit”, BfA 2022).

In summary, as illustrated in Appendix Figure A1, the availability of RIOTs differs at the German federal state level. While Baden-Wuerttemberg, Hamburg, Hessen, North Rhine-Westphalia and Lower Saxony provide multiple RIOTs, less RIOTs are available for the eastern than for the western federal states.³

2.2 Assessments of Policy Effects in German Regions

In the previous subsection, we have identified a scarcity of regional data from Germany. Correspondingly, only a relatively small number of studies attempt to quantify regional policy impacts in Germany. Focusing on the German energy transition, our literature survey has identified only a few studies analyzing sub-national climate policy effects in Germany.

Töbбен (2017a) analyzes the regional and distributional effects of the German Renewable Energy Sources Act (EEG) in all 16 German federal states. He finds that

³ We have counted two RIOTs for each federal state to account for the multi-regional input-output tables developed by Töbбен (2017a) and Krebs (2020).

most federal states benefit from an extended operation of renewable energies in terms of value added, particularly those states with large capacities for renewable energy generation. In addition, North Rhine-Westphalia and Baden-Wuerttemberg benefit from the production of renewable energy power plants and their components. Regarding distributional effects, the EEG has a negative impact on disposable income due to higher consumer prices, which is primarily challenging for low-income households.

Pothen and Hübler (2018) study the impacts of CO₂ pricing and renewable energy subsidies in Lower Saxony using a new quantitative trade model, i.e., a global CGE model including an elaborated trade module, with renewable energies in the electricity sector (see Section 3.1). In summary, they identify differences in the economic effects between Lower Saxony and the Rest of Germany induced by climate and/or trade policy, in particular, a welfare gain of 0.40 % in Lower Saxony compared with 0.18 % in the Rest of Germany. Pothen and Hübler (2021) calibrate the model introduced by Pothen and Hübler (2018) dynamically to future development scenarios until the year 2050. Their results confirm regional differences between Northwest Germany and the Rest of Germany caused by climate policy, for instance, a welfare loss of 0.11 % in Northwest Germany compared with 0.59 % in the Rest of Germany in 2040.

Hübler and Herdecke (2020) study the economic effects of US import tariffs against China and, as a reaction, increased Chinese import tariffs. They compare the Eaton and Kortum (2002) CGE model of Pothen and Hübler (2018) with an Armington (1969) CGE model for comparison. They find very small welfare effects on Germany. Depending on the targeted goods/sectors and tariff rates, regional differences of policy effects between Lower Saxony and the Rest of Germany are detected that can have opposite signs.

Bröcker et al. (2016) carry out an input-output analysis of the regional impacts of offshore wind energy expansion in Northern Germany on value added and employment. Assuming an additional offshore wind energy capacity of 15 gigawatts until 2030, the authors project an additional annual production value of 688 million Euros in 2029 and additional employment of 9,093 persons in Northern Germany.

Schröder (2010) investigates the production and employment effects of wind energy deployment in the Hanover region by using a RIOT for an input-output analysis of the Hanover region in the year 2009. He finds that wind energy use has small positive effects on regional employment and value added (1.6 million Euros via wind turbine construction and 2.3 million Euros via wind turbine operation). Likewise, Schröder (2012) estimates that offshore wind energy use is associated with a 0.007 % increase in Lower Saxony's total production value and raises employment.

Due to the German coal phase-out, North Rhine-Westphalia is a hot spot area with regard to socio-economic repercussions (for related policy recommendations,

see Göke et al. 2018; Kittel et al. 2020). González-Eguino et al. (2012) use a CGE model to investigate the effects of climate policy in North Rhine-Westphalia. They assume a 15 % relocation of the iron and steel sector away from North Rhine-Westphalia and find that this relocation results in a decrease in regional GDP of 0.37 % and a reduction in regional CO₂ emissions of approximately 2 %. In a different study, Kronenberg et al. (2018) evaluate the economic impacts of increased investments in energy efficiency in North Rhine-Westphalia by using a biregional input-output table. They consider a target scenario, in which the investment ratio is increased to 18 % of the regional GDP resulting in a 0.3 % point increase in the growth rate of gross value added and additional employment of about 98,000 people. Using a partial-equilibrium investment and dispatch model, Sgarciu et al. (2023) project an annual loss of 900 jobs in Lusatia due to the coal phase-out and an increase in CO₂ prices accelerated by the phase-out of Lusatian lignite-fired power generation.

Heindl and Voigt (2012) conduct an input-output analysis of the turnover and employment effects of the EEG in Baden-Wuerttemberg. With internal funding, the authors estimate net turnover and employment effects of approximately 2.4 billion Euros and –34,000 jobs until 2020, respectively, whereas investments from external funding are associated with turnover and employment effects of approximately 6.5 billion Euros and +24,000 jobs, respectively.

3 Simulation of Regional Climate Policy Effects

This section presents an exemplary regional policy analysis of Germany. It provides an overview of the model and its regional disaggregation, it defines climate policy scenarios and presents the simulation results. After the discussion of the regional results, it provides sectoral, decomposition and sensitivity analysis results.

3.1 Overview of the Model

In our comparative static policy analysis, we apply the static global new quantitative trade model presented in Pothen and Hübler (2018) with an updated calibration to Global Trade Analysis Project (GTAP) version 10 data with the base year 2014.⁴ The trade model follows the Ricardian new trade theory of Eaton and Kortum (2002) (see Caliendo and Parro 2015; Caliendo et al. 2018, for a numerical implementation). Within Germany, it goes beyond GTAP by explicitly representing the federal state Lower Saxony separated from the Rest of Germany (ROG, for an overview of the regional disaggregation, see Section 3.2; for details, see Pothen and Hübler 2018).

⁴ <https://www.gtap.agecon.purdue.edu/>.

Table 3: Sectors (goods and services) of Pothén and Hübler (2018).

Sector	Description
AGRI	Agriculture
COAL	Coal
CRUD	Crude oil
NGAS	Natural gas
PETR	Refined petroleum
FOOD	Food production
MINE	Mining
PAPR	Paper and pulp
CHEM	Chemicals, rubber and plastic
NMMS	Mineral products nec.
IRST	Iron and steel
NFMS	Non-ferrous metals
MANU	Manufacturing
ELEC	Electricity
TRNS	Transport
CONS	Construction
SERV	Services
INVS	Investment

Additionally, it goes beyond standard (GTAP) data and models by disaggregating the electricity sector of the regions Lower Saxony (LSX), Rest of Germany (ROG), France (FRA), United Kingdom (GBR) and Italy (ITA).

The deployed aggregation of the global data set GTAP features 18 production sectors (various goods, services and investment, see Table 3) in each of the 19 model countries/regions (see Table 4).⁵ Prices adjust so that all markets clear. The numéraire price is given by the USA. Production (output) is sold domestically or exported. Investments (INVS) are equal to savings and produced like other goods but not traded internationally (for details, see Pothén and Hübler 2018, Appendix D). Each model country/region features a representative consumer who absorbs domestic production and imports. Savings are a region-specific fixed fraction of the consumer's income. The consumer's expenditures are financed via income from providing the production factors labor, capital and natural resources and from receiving net transfers (tax revenues minus subsidies) in a lump-sum way. The production factors are perfectly mobile across sectors within countries/regions but internationally immobile. They enter the production sectors as inputs together

⁵ *EU27* (European Union) and *WRLD* (World) aggregate the results of the included countries but do not appear in the model.

Table 4: Policy effects of the European Emissions Trading System (EUETS) and the European Carbon Border Adjustment Mechanism (CBAM) on the model regions. The reported welfare effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario referring to the year 2014 (defined by GTAP 10) in percent. CBAM – EUETS reports the difference between CBAM and EUETS in percentage points.

Region	Description	EUETS	CBAM	CBAM – EUETS
LSX	Lower Saxony	0.17	0.42	0.25
ROG	Rest of Germany	−0.19	−0.05	0.14
FRA	France	0.10	0.19	0.08
GBR	United Kingdom	−0.21	−0.18	0.04
ITA	Italy	−0.23	−0.22	0.01
EUR	Rest of EU-27	−0.56	−0.69	−0.12
ROE	Rest of ETS (non-EU)	0.02	0.13	0.12
<i>EU27</i>	EU-27 (aggregate result)	−0.30	−0.31	0.00
FSU	Former Soviet Union	0.06	−0.14	−0.20
BRA	Brazil	0.00	−0.01	−0.01
CAN	Canada	0.02	−0.03	−0.05
USA	United States of America	−0.01	−0.02	−0.01
MEX	Mexico	0.01	−0.03	−0.04
CHN	China	0.00	0.00	0.00
IND	India	−0.01	−0.03	−0.02
JPN	Japan	0.01	0.02	0.02
KOR	South Korea	0.00	0.04	0.04
ROA	Rest of Asia	−0.03	−0.07	−0.04
OCE	Australia & Oceania	−0.05	−0.07	−0.02
ROW	Rest of the World	0.02	−0.12	−0.14
<i>WRLD</i>	World (aggregate result)	−0.08	−0.10	−0.02

with intermediate goods inputs that can be imported or produced domestically. Each country's/region's current account deficit or surplus is given by the data and always stays constant.

Consumption, production and trade are represented by constant elasticity of substitution (CES) functions. Details can be found in Pothén and Hübler (2018) (Figures 1, 2 and 3 and Appendix Table C1). In consumption, first, energy goods and non-energy goods are combined separately in a complementary way (CES elasticities of 0.4 and 0.25). Then, these two bundles are combined in a complementary fashion (CES elasticity of 0.25).

In the non-electricity sectors, fossil fuel inputs are combined in a Cobb-Douglas fashion (CES elasticity of 1). The fossil fuel bundle is combined with electricity in a complementary way (CES elasticity of 0.5). The resulting energy composite is combined with a capital-labor bundle in a complementary way (CES elasticity of 0.4), while capital and labor are combined in a Cobb-Douglas fashion.

Thereafter, non-energy intermediate goods inputs are attached in a Leontief fashion (CES elasticity of 0), and finally natural resources are added in a complementary way (CES elasticity of 0.6). Similarly, the electricity sector first combines fossil fuels (CES elasticity of 0.3) as well as capital and labor (CES elasticity of 1) separately and then puts these two bundles together (CES elasticity of 0.4). The main difference to other sectors is that (in the regions LSX, ROG, FRA, GBR and ITA) the following energy sources/technologies are combined as substitutes (CES elasticity of 3): coal, oil, gas, nuclear, hydro, wind, solar, geothermal and biomass. Furthermore, inputs in overhead, energy transmission and distribution (CES elasticity of 0) and a technology-specific fixed factor (CES elasticities of 0.1–0.6) are attached.

The use of fossil fuels (coal, gas, crude and refined oil) releases CO₂ emissions according to their fossil-fuel-specific CO₂ contents (given by the benchmark year data). In sectors subject to carbon pricing, the cost of these emissions must be paid by purchasing emission allowances at their current market price; that is, CO₂ is proportionally (via a Leontief function, CES elasticity of 0) connected to fossil fuel inputs and then treated as any other production input; in particular, allowances are traded on the CO₂ market established by the emission trading system.

The reaction of trade flows to changes in tariffs or trade costs is based on a structural estimation of the parameter values of the trade module including iceberg trade costs and gravity model parameters, such as a common border, common language or free trade agreement (see Pothén and Hübler 2018). The GTAP data incorporate existing taxes/tariffs and subsidies. Hence, the model represents a sub-optimal second-best world.

The solution of the resulting set of optimality conditions yields a global general equilibrium of all goods and factor markets in all model regions assuming perfect competition without modeling externalities.

3.2 Regional Disaggregation of the Model

For the following policy analysis, the data underlying the model have been updated to GTAP 10. Within Germany, the model calibration separates Lower Saxony (LSX) from the Rest of Germany (ROG). To this end, following the literature summarized in Sections 2.1 and 2.2, Pothén and Hübler (2018) derive a regional disaggregation procedure which is detailed in Appendix E of their article.

First, using consumption/investment data from VGRdL (2022b) and assuming that consumer preferences are identical across German federal states, Lower Saxony's consumption and investment shares are calculated and applied to the GTAP data.

Second, using employment and energy data from BfA (2016a, 2016b), LAE (2016a, 2016b), and WVEE (2012), Lower Saxony's sectoral gross output shares are calculated.

Third, assuming that the pattern of intermediate goods inputs in production is the same across German federal states, Lower Saxony's input shares are computed.

Fourth, the Cross-Hauling Adjusted Regionalization Method (CHARM, Kronenberg 2009), extended by Többen and Kronenberg (2015), is applied to approximate trade flows between Lower Saxony and the Rest of Germany as well as other countries and world regions.

3.3 Definition of the Policy Scenarios

For our exemplary regional policy analysis of German, we define two policy scenarios. As a reference point, we define a benchmark scenario that captures EU policies implemented in 2014 given by the data (see Pothen and Hübler 2018) including so-called “grandfathering” (a free allocation of 90 % of the CO₂ allowances to firms) and a CO₂ price of approximately US-\$19 per ton of CO₂. We do not model any climate change impacts throughout the policy analysis.

Definition of EUETS:

To set the emission target of the European Emissions Trading System (EU ETS) for both policy scenarios, we follow the greenhouse gas emission target for the year 2030 envisaged by the European Commission (Climate Action) and translate it into a 44 % reduction of CO₂ emissions within (vis-à-vis) the year 2014 (provided by the benchmark data) in the EU ETS sectors (see Pothen and Hübler 2018).⁶ This means, the total amount of CO₂ emissions in the EU ETS is given by the total amount of CO₂ allowances (which is lower in the policy scenario than in the benchmark scenario and fixed) while the CO₂ price adjusts endogenously and is determined by the market equilibrium of the market for CO₂ allowances. We do not explicitly model other climate or energy policies (such as carbon taxes) in non-ETS sectors or final consumption. The EU ETS includes the model regions Lower Saxony (LSX), Rest of Germany (ROG), France (FRA), United Kingdom (GBR), Italy (ITA), Rest of EU-27 (EUR) and Rest of ETS (non-EU, ROE) and the model sectors refined petroleum (PETR), paper and pulp (PAPR), chemical products (CHEM), mineral products nec (NMMS), iron and steel (IRST), non-ferrous metals (NFMS) and electricity (ELEC) (see Pothen and Hübler 2018, Appendix Tables A1 and A2). The initial regional endowments

⁶ “Our ambition for 2030: Under the European Climate Law, EU Member States will work collectively to become climate neutral by 2050. As a first milestone, the EU is aiming to reduce net emissions by at least 55 % by 2030 compared to 1990. The revised EU ETS will contribute to achieving this target. To achieve the necessary emission reductions cost-effectively, the EU ETS has been strengthened, and its scope expanded to maritime transport. Altogether, the cap is tightened to bring emissions down by 62 % by 2030 compared to 2005 levels,” https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/our-ambition-2030_en (accessed 03/2024).

with CO₂ allowances are allocated according to the regional benchmark year CO₂ emissions (shares). Carbon pricing is not assumed in other model regions.

Definition of CBAM:

A novelty of our analysis is the examination of regional effects induced by the Carbon Border Adjustment Mechanism (CBAM) announced by the European Commission (Taxation and Customs Union).⁷ CBAM aims at leveling the carbon playing field between producers within the EU (subject to EU ETS carbon pricing) and those producing outside the EU (without or with lower carbon pricing) and exporting into the EU. In this way, fairer competition and reduced carbon leakage⁸ shall be achieved. Therefore, this scenario includes the EU ETS policy defined above and adds import taxation according to the carbon contents of goods imported into the EU. The carbon contents of goods are taken from Hübler et al. (2024) and valued at the endogenous CO₂ price derived from the general equilibrium model solution. When the CO₂ price in the EU ETS rises endogenously, especially due to tighter emission targets, the import tax rates of CBAM will increase proportionally.

3.4 Regional Results of the Policy Scenario Simulations

Table 4 reports the policy scenario simulation results focusing on the welfare effects of each policy scenario relative to the benchmark scenario. Welfare effects are measured as relative changes in consumption expenditures divided by the true-cost-of-living index (see Pothen and Hübler 2018) to obtain real effects (excluding monetary effects). Figure 1 summarizes the policy effects on Lower Saxony and the Rest of Germany; it shows the difference between the welfare effects of CBAM and EU ETS in the middle.

7 “CBAM: The EU’s Carbon Border Adjustment Mechanism (CBAM) is the EU’s tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries. By confirming that a price has been paid for the embedded carbon emissions generated in the production of certain goods imported into the EU, the CBAM will ensure the carbon price of imports is equivalent to the carbon price of domestic production, and that the EU’s climate objectives are not undermined. The CBAM is designed to be compatible with WTO-rules. CBAM will apply in its definitive regime from 2026, while the current transitional phase lasts between 2023 and 2026. This gradual introduction of the CBAM is aligned with the phase-out of the allocation of free allowances under the EU Emissions Trading System (ETS) to support the decarbonisation of EU industry,” https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en (accessed 03/2024).

8 Theoretically, emission reductions in the EU can partly be compensated by emission increases abroad via reductions of fossil fuel prices on international markets, relocation of EU producers to abroad or climate policy relaxation abroad.

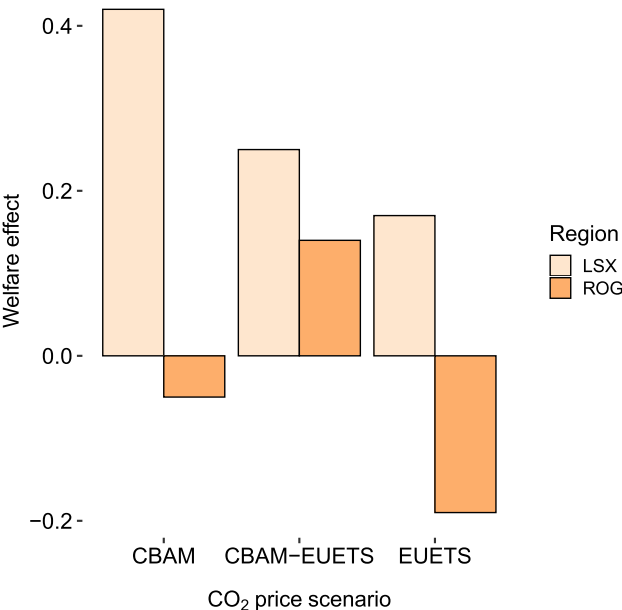


Figure 1: Policy effects of the European Emissions Trading System (EUETS) and the European Carbon Border Adjustment Mechanism (CBAM) on Lower Saxony (LSX) and the Rest of Germany (ROG). The welfare effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario in percent. CBAM–EUETS illustrates the difference between the welfare effects of CBAM and EUETS in percentage points.

Effects of EUETS:

The endogenous CO₂ price in the EU ETS reaches approximately US-\$190 per ton of CO₂. The renewable energy share in power generation (ELEC) increases to almost 46 % compared with 30 % in the benchmark in Lower Saxony (LSX) and to 42 % compared with almost 21 % in the benchmark in the Rest of Germany (ROG). In the production sectors of LSX and ROG, CO₂ emissions decline by approximately 55 % and 41 % compared to the benchmark. The leakage rate (endogenous increase in emissions abroad divided by the exogenous emission reduction in the EU ETS) increases from 26 % in the benchmark to 45 %. EUETS reduces global CO₂ emissions by more than 1.1 %. Changes in the price level (true-cost-of-living index) are minor and point in different directions across the model regions. Whereas total income increases to a minor extent in LSX, it decreases to a minor extent in ROG compared with the benchmark scenario.

While all resulting welfare losses across model regions are smaller than 0.6 %, all welfare gains are smaller than 0.2 % (see Table 4). Lower Saxony (LSX, 0.17 %)

and France (FRA, 0.10 %) benefit most from EUETS due to their large wind or nuclear potential, respectively. The Rest of Germany (ROG), the United Kingdom (GBR) and Italy (ITA) become worse off (by 0.19 %, 0.21 % and 0.23 %, respectively). The remaining EU ETS countries that are not EU members (ROE) benefit slightly (0.02 %). The remaining EU countries that are EU members (EUR) lose significantly (by 0.56 %): while the model features renewable energies explicitly in the separate model regions/countries LSX, ROG, FRA, GBR and ITA, this feature is not available in the aggregate EU ETS regions EUR and ROE which renders decarbonization more difficult and costly. The aggregate EU (EU27) region suffers a moderate welfare loss (by 0.30 %) because we do not model reduced climate change damages and climate policy creates a distortion.

The former Soviet Union (FSU) countries benefit slightly from EUETS (by 0.06 %); although fossil fuel imports into the EU are hindered, carbon-intensive production may be relocated from the EU to neighbour countries, such as FSU. Effects on the Rest of the World (ROW, a 0.02 % gain) and the entire world (WRLD, a 0.08 % loss) are small. Similar to the entire EU, the entire World loses due to carbon pricing because the benefits of less CO₂ in the atmosphere and hence reduced climate change are not taken into account and carbon pricing creates an economic distortion (inefficiency). The large open economies USA and India (IND, both a 0.01 % loss), Japan (JPN), Mexico (MEX, both a 0.01 % gain) and Canada (CAN, a 0.02 % gain) are affected to a minor extent, while Korea (KOR), China (CHN) and Brazil (BRA) are insignificantly affected.

Overall, EUETS has smaller effects than in the study by Hübler et al. (2024), because the model examined here in this article provides more flexibility to reduce CO₂ emissions, especially to decarbonize power supply in the EU countries where energy sources/technologies are modelled explicitly. Particularly, France (FRA) benefits from its large nuclear power potential. The policy effect on the Rest of the EU-27 (EUR), however, is very similar in both models (approximately, −0.5 %) despite different climate policy targets (a 10 % reduction in 2014 in Hübler et al. 2024). The EU climate policy spillovers on other countries/regions in the world are smaller than in Hübler et al. (2024) and the qualitative pattern of the climate policy spillovers on other countries/regions in the world shows differences.⁹

In summary, the EUETS results presented in Table 4 and illustrated in Figure 1 underline that regional disaggregation matters: the climate policy effects of the EUETS scenario on Lower Saxony and the Rest of Germany have similar magnitudes but opposite signs. Lower Saxony benefits from climate policy with emissions trading due to its large wind power potential. Further disaggregation of the Rest of

⁹ The model scrutinized here, uses functional (fossil fuel) input structures (and elasticities of substitution) that differ from Hübler et al. (2024), it models renewable energies explicitly in selected EU countries and analyses other CO₂ emission targets.

Germany, e.g., in south, east and west, could reveal further differences between regions regarding their potential to expand renewable energies and hence to reduce emissions with relatively low marginal abatement costs. Furthermore, the policy effects differ significantly across European countries/regions.

Effects of CBAM:

In this policy scenario, the endogenous CO₂ price increases to approximately US-\$240 per ton of CO₂. Intuitively, due to the reduced imports, EU production expands which increases demand for CO₂ allowances putting upward pressure on the CO₂ price. The renewable energy share in power generation (ELEC) increases to more than 47 % compared with 46 % under EUETS in Lower Saxony (LSX) and to 46 % compared with almost 42 % under EUETS in the Rest of Germany (ROG). The leakage rate declines from 45 % under EUETS to 25 % under CBAM which is slightly below the benchmark rate; this means that CBAM is an effective instrument to reduce carbon leakage. CBAM reduces global CO₂ emissions by more than 1.8 %, i.e., 0.7 % points more than EUETS alone. These effects are somewhat lower than those found by Sogalla (2023).

While EUETS reduces the average domestic supply of Lower Saxony (LSX) by almost 3 %, CBAM slightly mitigates this decline. While EUETS slightly reduces the average domestic supply in the Rest of Germany (ROG) and the entire EU (EU27), CBAM eliminates this effect in the Rest of Germany and turns it into a small increase in average domestic supply in the EU. Because CBAM hinders international trade, it reduces productivity gains from Ricardian selection (on average across sectors, derived from the Eaton Kortum theory) in the EU and the World. It decreases the Ricardian productivity gains compared with EUETS in ROG but increases them in LSX. These effects are, however, small. The overall price level (true cost-of-living index) slightly increases due to the import taxation of CBAM (by approximately 0.5 % points in LSX and ROG). Similarly, total income slightly increases in both considered German regions compared with the benchmark scenario (by approximately 1 % in LSX and 0.5 % in ROG). With CBAM, Lower Saxony (LSX) and the Rest of Germany (ROG) reduce CO₂ emissions in the EU ETS more than with EUETS only (almost 57 % and almost 44 % compared to the benchmark).

We are particularly interested in the differences in the welfare effects of CBAM (EUETS plus import tariffs) compared with those of EUETS alone (see above) as displayed in the right column of Table 4 in percentage points. All resulting welfare losses across the model regions are smaller than 0.7 %, while welfare gains are smaller than 0.5 %. CBAM intensifies the effects of the EUETS and creates typical trade policy effects: With power on international markets, EU ETS members can gain from import taxation by improving the terms-of-trade in their favor. From a global perspective, however, import taxation causes a distortion of international

trade and hence a welfare loss. Additionally, carbon-based import taxation changes the allocation of emissions across countries/regions and sectors and the CO₂ price. This can create winners and losers. Finally, because the benchmark data contain existing taxes (tariffs) and subsidies, the model describes a second-best world, in which additional policies can have complex and unexpected effects.

According to Table 4, the EU is hardly affected (tiny negative effect) by CBAM compared with EUETS whereas the entire World (*WRLD*) slightly loses (by 0.02 % points) compared with EUETS. The Rest of the World (*ROW*) significantly loses (by 0.14 % points) due to CBAM.

CBAM significantly reduces the EUETS-induced loss of the Rest of Germany (*ROG*, 0.19 %) by 0.14 % points (to 0.05 %). Similarly, CBAM substantially increases the EUETS-induced gain of Lower Saxony (*LSX*, 0.17 %) by 0.25 % points (to 0.42 %). France (*FRA*), the United Kingdom (*GBR*) and Italy (*ITA*) benefit from CBAM (by 0.08, 0.04 and 0.01 % points, respectively). While the Rest of the EU (*EUR*) gets worse off (by 0.12 % points), the Rest of the EU ETS (*ROE*) becomes equally better off (also by 0.12 % points). The entire EU (*EU27*) is not significantly affected by CBAM compared with EUETS.

The Former Soviet Union (*FSU*) countries lose significantly due to CBAM (by 0.20 % points), because fossil fuel imports as well as imports of carbon-intensive goods into the EU are hindered. Japan (*JPN*) and Korea (*KOR*) gain slightly (by 0.02 and 0.04 % points) due to CBAM, while Canada (*CAN*) and Mexico (*MEX*) lose slightly (by 0.05 and 0.04 % points).

Large open economies, in particular, the USA (a 0.01 % point loss in CBAM compared with EUETS), China (*CHN*, approximately 0.00 % points) and India (*IND*, a 0.02 % point loss) are affected (negatively) to a minor extent. This result indicates that the USA's vulnerability to EU tariffs is low, especially when the tariff rates are moderate, because it is a large economy with many trading partners.

The qualitative pattern of the policy spillovers of CBAM on other countries/regions in the world derived from the new quantitative trade model is very similar to the pattern found by Hübler et al. (2024) derived from an Armington (1969) type trade model using trade elasticities aligned to the estimated elasticities used in our analysis here. Quantitatively, the magnitudes of the effects of CBAM compared to those of EUETS are also similar to those found by Hübler et al. (2024). This outcome is in accordance with trade theory because both model types assume perfect competition and constant returns to scale (compare Arkolakis et al. 2012). One notable exception is the small welfare loss of the Rest of the EU due to CBAM displayed in Table 4 that contrasts with the small gain found by Hübler et al. (2024). Considering the entire EU-27 (*EU27*), according to Table 4, however, this negative effect is neutralized by the positive effects in the explicitly modeled EU countries such that an EU-wide effect of CBAM is hardly visible. This outcome highlights

the relevance of modelling single countries within a larger political or geographic macro-region (here the EU) because the effects within a macro-region can be heterogeneous. The small magnitudes of the simulated effects of CBAM are also in line with Korpar et al. (2023) but smaller than in previous studies, e.g., by Mattoo et al. (2013).

In summary, the CBAM results confirm that regional disaggregation matters: the positive regional effects of CBAM on Lower Saxony are substantially stronger than those on the Rest of Germany.

3.5 Sectoral Analysis

This section provides an analysis of the sectoral emission, sales and trade effects of EUETS and CBAM to illustrate the model mechanisms at the sectoral level and to derive insights in international competitiveness effects. We focus on the same German regions as before.

Appendix Figures A2 and A3 illustrate the relative reductions in CO₂ emissions from fossil fuel inputs coal (COAL), natural gas (NGAS), crude oil (CRUD) and refined petroleum (PETR) in the carbon-intensive EU ETS sectors electricity (ELEC), iron and steel (IRST), chemicals (CHEM), paper and pulp (PAPR), mineral products (NMMS) and non-ferrous metals (NFMS) (without PETR which is less relevant for the considered German regions). In both regions, the EU ETS sectors achieve the most substantial mitigation of CO₂ emissions via reductions in the COAL input which has the highest carbon content among fossil fuels. Overall, emission reductions are slightly larger under CBAM than under EUETS. Both policy scenarios result in an increase in emissions from PETR in all sectors except ELEC because of its low carbon content compared with COAL and NGAS. While LSX experiences a small decrease in emissions from CRUD in the ELEC sector, emissions from CRUD increase in ROG. In addition, relative emission reductions in the ELEC sector are significantly greater in LSX than in ROG due to its substantial renewable energy (especially wind power) capacity.

Let us now consider sectoral sales as a production and competitiveness indicator. In Lower Saxony (LSX) and the rest of Germany (ROG), the coal (COAL), electricity (ELEC) and natural gas (NGAS) sectors are by far most strongly affected by EUETS in terms of reductions in their sales (e.g., a reduction in coal sales by more than 55 % compared to the benchmark in ROG). Crude oil (CRUD) and refined petroleum (PETR) sales are hardly affected or slightly decline (PETR in LSX) because they can replace more carbon-intensive fossil fuels, particularly coal. Energy-intensive and trade-exposed sectors (iron and steel, IRST, non-ferrous metals, NFMS, mining, MINE, chemicals, CHEM, paper and pulp, PAPR) in LSX and ROG suffer from sales reductions of two to three percent (compared with the benchmark) due to

EUETS. Agriculture (AGRI) in LSX and ROG, crude oil (CRUD) in ROG (as a substitute for coal and gas), construction (CONS) in LSX and manufacturing (MANU) in ROG are slightly better off regarding their sales under EUETS. Other sectors, such as transport (TRNS), services (SERV), mineral products (NMMS) or food (FOOD), are barely affected.

CBAM supports some domestic sectors in terms of their sales (e.g., iron and steel, IRST, in LSX and ROG) but also creates some sectoral disadvantages (e.g., non-ferrous metals in LSX and ROG) and barely affects other sectors (e.g., paper and pulp, PAPR, in LSX and ROG). The magnitudes of these effects are small.

In the Eaton and Kortum trade model, international trade is reflected by international trade shares between two trading partners (see Appendix Equation 5). For each good (produced in each sector), it reflects the fraction of varieties that are delivered by one trading partner at the lowest cost among all trading partners.

Let us consider China (CHN) as a major trading partner of Germany with relatively carbon-intensive production as a case study and focus on energy-intensive, trade-exposed EU ETS sectors (IRST, CHEM, PAPR, NMMS, NFMS). According to the simulation results, EUETS leads to an increase in the import shares from China to Lower Saxony (LSX) or to the Rest of Germany (ROG) in these sectors (e.g., by 6.5 % compared with the benchmark in the iron and steel, IRST, sector of LSX) because the considered carbon pricing makes domestic supply from these carbon-intensive sectors more expensive relative to Chinese production/imports. On the contrary, CBAM renders imports from China (due to their significant carbon contents) more expensive (relative to other countries/regions) and hence reduces the import shares from China (e.g., by 7.5 % compared with the benchmark or 1.0 % points below EUETS in the IRST sector of LSX).¹⁰ However, leaving aside (carbon-based) export rebates, EUETS and CBAM also reduce the export shares from LSX or ROG to CHN (e.g., 7.9 % under EUETS and 12.7 % under CBAM compared to the benchmark) due to higher fossil fuel input costs and higher intermediate good import costs that reduce the competitiveness of German producers on the international market.

3.6 Decomposition Analysis

Figure 2 depicts a decomposition of the policy-induced CO₂ emission changes in the production sectors of Lower Saxony (LSX) and the Rest of Germany (ROG) based on Pothén and Hübler (2018), similar to Larch and Wanner (2017) and Sogalla et al. (2024) building on the seminal work by Grossman and Krueger (1993) and Copeland and Taylor (1994) (cf. Cherniwchan et al. 2017; Copeland et al. 2022, for further

10 Except non-ferrous metals (NFMS) in the Rest of Germany (ROG).

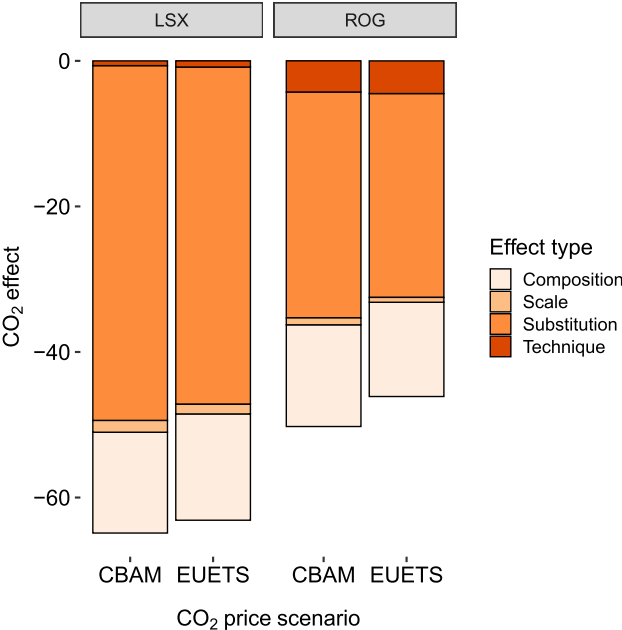


Figure 2: Decomposition of simulated policy-induced changes in CO₂ emissions in Lower Saxony (LSX) and the Rest of Germany (ROG). The CO₂ effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario in percent.

contributions). It incorporates the usual scale effect (changes in output) and decomposition effect (changes in sector sizes). To capture the well-known technique effect, it measures sectoral productivity gains via Ricardian selection emerging from the Eaton and Kortum trade model. To take the replacement of fossil fuels by each other or other inputs into account, it includes an input substitution effect. It uses the multiplicative Log-Mean Divisia Index Method I (LMDI I) developed by Ang and Liu (2001).

According to the results, under EUETS, emission reductions are mainly achieved by replacing fossil fuel inputs by other inputs creating lower or zero CO₂ emissions (substitution effect), to a much smaller extent by shifting production towards less CO₂-intensive sectors (composition effect) and to a minor extent via Ricardian productivity gains (technique effect) and output reductions (negative scale effect). This result shows that the additional mechanism of Ricardian selection and resulting productivity gains provided by the Eaton and Kortum model has numerically little relevance for this analysis. Notwithstanding, according to the estimates, the technique effect is considerably stronger in the Rest of Germany (ROG) than in Lower Saxony (LSX) which underlines the relevance of regional differences, also for advanced trade modelling.

CBAM intensifies the predominant substitution effect in the EU ETS that reduces CO₂ emissions (see Figure 2). The magnitude of the composition effect is

much smaller than in Larch and Wanner (2017).¹¹ While CBAM slightly extends the composition effect in the Rest of Germany, it reduces it in Lower Saxony. Because CBAM hinders international trade, Ricardian productivity gains decline in LSX and ROG compared with EUETS.

To conclude, CO₂ reductions are mainly achieved via (fossil fuel) input substitution. The technique effect measured as Ricardian selection derived from the Eaton and Kortum theory differs between the two German regions under consideration. The contribution of Ricardian selection to CO₂ reductions is, however, small according to our analysis. As before, the climate policy effects differ across European countries/regions.

3.7 Sensitivity Analysis

To check the robustness of our policy analysis and to obtain additional insights regarding the effect of model and scenario assumptions, we carry out a couple of sensitivity checks. First, we change the CO₂ emission target of the EU ETS which is the main determinant of the impacts of both policies, EUETS and CBAM. Second, we vary the sectoral trade elasticities of the Eaton and Kortum model because this is the key parameter governing the reaction of international trade to policy changes. A full sensitivity analysis of the underlying model including a Monte Carlo analysis with thousands of random draws of parameter values can be found in Pothén and Hübner (2018).

First, we vary our original 44 % CO₂ reduction in the EU ETS sectors to 30 %, 60 % and 70 %. The results are reported in Appendix Table A3. Under the 30 % target, the welfare gain of Lower Saxony (LSX) compared with the benchmark scenario becomes much smaller (0.064 %) than under 44 % (0.17 %); assuming 60 % the gain further increases (0.25 %) but under 70 % it decreases (0.21 %). Intuitively, gains from emission trading due to low marginal abatement costs have their limits and cannot compensate losses induced by ambitious emission targets. In the Rest of Germany, this relationship looks more straightforward, i.e., more stringent targets lead to higher welfare losses (between 0.16 % under the 30 % target and 0.28 % under the 70 % target). The welfare loss of the EU reaches 0.84 % when assuming the 70 % reduction. These qualitative and quantitative differences in the policy effects underline the relevance of regional analyses.

The scrutinized more stringent emission targets of the EU ETS render CBAM considerably more efficient regarding the reduction of carbon leakage so that

¹¹ Whereas Larch and Wanner (2017) measure the composition effect as a change in the average energy cost share, we measure it as changes in the (output-related) shares of all sectors (with different CO₂ intensities) in total regional output.

global emissions decline by 2.5–2.9 %, similar to the results found by Sogalla (2023). Regarding welfare effects on the EU, however, a typical “optimal tariff” relationship emerges, in which the terms-of-trade and hence welfare are improved in an inverted U-shaped manner. Under the 44 % CO₂ target, CBAM has on average a negligible welfare effect on the entire EU. The less stringent 30 % CO₂ target results in a lower CO₂ price and hence lower tariff rates which creates on average a minor welfare gain of the EU from CBAM compared to the EU ETS alone in accordance with Korpar et al. (2023). A more stringent CO₂ target, however, results in a substantially higher CO₂ price and hence higher tariff rates creating on average a higher welfare loss of the EU compared to EUETS alone (0.83 % and hence an additional 0.23 % points loss under the 60 % target and 1.43 % and hence an additional 0.59 % points loss under the 70 % target). While the global welfare loss (*WRLD*) due to EUETS amounts to 0.21 % under the 70 % target, CBAM more than doubles that loss reaching 0.46 %.

In the decomposition of CO₂ reductions induced by EUETS or CBAM, sectoral shifts (decomposition effect) first become stronger in the Rest of Germany (ROG) with more stringent CO₂ targets as found by Sogalla (2023) but then become weaker. In Lower Saxony (LSX), they become overall weaker. This means, more stringent CO₂ reductions are mainly achieved by replacing fossil fuels by other inputs (substitution effect) and to a small extent by reducing output (negative scale effect).

Second, we vary all sector-specific trade elasticities, i.e., the inverse spread of productivity as defined by the Eaton and Kortum theory, in all sectors and regions simultaneously by ± 20 %. Their initial values have been derived from a structural estimation as detailed in Pothén and Hübler (2018) (especially Table 3) and are displayed in our Appendix Table A2. The results are reported in Appendix Table A4. Interestingly, it is not evident whether lower/higher values of the trade elasticities result in larger/smaller magnitudes of the (positive or negative) welfare effects of EUETS or CBAM in the model regions. In any case, the welfare deviations are small so that the model specification is relatively robust with respect to uncertainty in the trade elasticities.

4 Regional Data Provision and Modelling Strategies

For regional analyses, several priorities of future research and data provision emerge from the reviewed literature, the available data and the limitations of our model and our policy simulations.

First, we have identified a scarcity of available regional input-output tables (RIOTs) of several German federal states, especially of the eastern federal states.

Official regional data from statistical offices seem to be exceptional and sometimes outdated. Considering the large differences in the economic importance of certain sectors across regions (e.g., wind energy in Lower Saxony and Schleswig-Holstein versus coal mining in Lusatia and North-Rhine Westphalia), this discrepancy could be addressed by researchers in order to accurately quantify the regional impacts of climate policy measures. Consequently, the creation and public provision of an up-to-date standardized/harmonized German regional database with federal state-level resolution covering all federal states (following the multi-regional input-output, MRIO, tables created by Többen 2017a, 2017b; Krebs 2020) and providing further region-specific information, as discussed in the following, could be supported by public funding to facilitate cooperation between scholars and statistical offices. Then it should be updated regularly and, as far as possible, aligned with existing standard databases, such as GTAP, regarding available sectors, years and variables to facilitate policy modelling.

Second, further disaggregation of RIOTs within federal states to individual regions is required to narrow down specific policy effects. The evaluation of such effects at a more granular level can be crucial for regions that are strongly affected by climate change impacts or climate/energy policy measures. In this regard, the German district level (“Kreisebene”) data (VGRdL 2022a) containing the gross domestic product, (sectoral) value added, (sectoral) employment and further information provide a relevant data basis. This includes regions whose production depends on energy- or greenhouse gas-intensive production sectors or production chains with the resulting negative effects of carbon pricing but also regions that benefit from the subsidization of climate-friendly technologies or from financial compensation, such as Lower Saxony or Lusatia (see Seibert et al. 2018; Stürmlinger and Fuchs 2021; Sgarciu et al. 2023).

Third, suitable additional data and further practical model implementations are recommendable to take imperfect factor mobility into account (besides perfect mobility and perfect immobility) because trade and factor mobility between regions within a country differ from *international* trade and factor mobility. In the context considered in this analysis, mobility of people (workers) is higher between regions within countries than between EU countries, which is in turn higher than between EU and non-EU countries. A classical approach to modelling rural-urban migration (labour mobility) has been introduced by Harris and Todaro (1970). Further approaches to modelling migration (labour mobility) have been pioneered by Tabuchi and Thisse (2002) and Redding (2016). They can be implemented by using data on migration patterns (from Eurostat and Institut für Arbeitsmarkt- und Berufsforschung, IAB, for Germany) and labor elasticities (estimated or taken from the literature), see the implementations by Redding (2016) and

Ahlfeldt et al. (2015). Monte et al. (2018) model commuting by using draws of workplace-residence pairs (for Germany by using IAB workplace-residence data). Similarly, foreign direct investment (FDI) and international financial transfers (portfolio investments) can be implemented by modelling different degrees of capital mobility between regions or sectors.

Furthermore, in the context of international trade and international investments, multinational enterprises and “global players” play a central role with regard to regional policy effects. Within each country, they reside in specific federal states or regions and there is likely regional concentration of producers and suppliers making use of supplier-customer relations within the supply chain, business relations, exchange of workers and ideas, i.e., knowledge spillovers, and so forth (e.g., in the Silicon Valley). Consequently, domestic, foreign or international policies affecting multinational enterprises have strong effects on their regions of residence and smaller effects on other regions. Quantitative models with multinational enterprises have been developed (e.g., the pioneering work of Ramondo 2014) and could be integrated in regional modelling.

The extension of the availability of ready-made data on (regional and international) migration, (regional and international) capital mobility and regional trade (of regions or federal states within countries with each other and with other countries) in standard data sets, such as GTAP, or from national statistical offices (in suitable formats that match standard data sets, such as GTAP, regarding the sectoral resolution etc.) could enhance the broader use of these valid modelling approaches.

Fourth, the sectoral structures of federal states or regions can significantly differ (e.g., the relevance of agriculture or the automotive industry). However, these structures may not be perfectly covered by constructed data sets, and data on (sectoral) intermediate goods inputs are often missing. Inadequate approximations of input patterns, in particular fossil fuels, however, affect sectoral CO₂ emissions and hence climate policy effects. Furthermore, the available sectoral resolution can be insufficient. For the purpose of climate/energy policy analysis, Pothén and Hübler (2018, 2021), for example, combine the regional disaggregation with the disaggregation of the power sector distinguishing different energy sources/technologies (and the latest GTAP data make a step forward in this regard). Depending on the policy question, such a sectoral disaggregation can also be relevant for other sectors. In the climate/energy policy context, the representation of specific energy-/CO₂-intensive industries (cf. Hübler and Löschel 2013), such as cement, possibly including process emissions, can be relevant (in combination with regional disaggregation). Other examples for sectors that are important (for Germany) but not separately visible in common data, are the automotive industry and specific types of machinery or information and communication technologies. Consequently, a better sectoral resolution of regional data is recommendable, and the sectoral structures of regional data should match those of standard country-wise datasets, such as GTAP.

Fifth, for regional climate and energy policy analysis, the transfer of electricity (and other types of energy carriers, such as gas or hydrogen) is of particular interest. Due to elaborated within-country grids, energy exchange between regions within countries is presumably larger than between countries. Improvements and extensions of energy transfer and storage that are necessary for the expansion of renewable energy, such as the North-South transmission line in Germany, need to be considered. In this regard, links to power grid models or their results and insights can be helpful, for example, considering decentralization of power supply, high-voltage grids, electricity-heat coupling, renewable energy fluctuations and storage (e.g., Böing et al. 2018). For this purpose, the design of a comprehensive modeling framework, for instance, within an interdisciplinary project, can be helpful (see, for example, the interdisciplinary NEDS – Nachhaltige Energieversorgung Niedersachsen – project on Northwest Germany; Blaufuß et al. 2019). For practical policy modelling, simplified approaches to the integration of engineering aspects into economic models would be helpful, especially in the field of energy supply, storage, transfer and demand with an increasing share of energy from renewable sources.

Sixth, the available regional data (from Germany) may not contain the required detailed patterns of income sources and consumption expenditures on different goods/services. In the absence of these data, the standard assumption (also adopted in our analysis in Section 3) is that the income and consumption patterns of the representative consumer of each federal state mimic those of the average nationwide consumer. This assumption, however, neglects discrepancies in income and inequality within a country (here, Germany) that are related to differences in income sources. Income sources are in turn related to region-specific (in-situ) natural resource endowments, including fossil fuels. Climate/energy policy, however, significantly devaluates fossil fuels and thus has significant negative income effects on fossil fuel owners (cf. Hübler et al. 2024) which can be expected to show up as region-specific losses. Additionally, capital ownership may differ across regions. Hence, further data and research are required.

Seventh, the distinction of household/consumer income groups is another relevant dimension of disaggregation. While disaggregated income groups have been implemented at the German-wide level (Hübler et al. 2024) and led to significant differences in policy effects across income groups, the investigation of inequality effects at the regional within-country level is missing. Because average income differs regionally between rural and urban areas and, particularly, across federal states in Germany, regional differences in the inequality effects of policies can be expected. Therefore, the combination of regional data with household income group data can provide new insights. The required data are basically available within the German Household Budget Survey (EVS, FDZ 2024).

Eighth, like most model and input-out data analyses, our policy assessment does not consider climate change impacts that are often region-specific. Therefore, as far as possible, the new generation of regional data should also contain climate change impacts linked to (global budgets of) greenhouse gas emissions or concentrations.

5 Conclusions

We have reviewed the literature on policy effects in German regions and carried out a new policy analysis of the European Carbon Border Adjustment Mechanism (CBAM) that is currently being implemented regarding its regional effects within Germany as a new aspect.

According to our policy simulation results, CBAM is an effective instrument to reduce carbon leakage. Under the EU ETS CO₂ emission reduction target envisaged for the year 2030, CBAM has on average a negligible welfare effect on the EU. Whereas a less stringent CO₂ target creates a minor average welfare gain of the EU from CBAM compared with the EU ETS alone, more stringent targets applicable towards the year 2050 lead to an additional average welfare loss of the EU due to substantially higher CO₂ prices. More stringent targets, however, also improve the effectiveness of CBAM in reducing carbon leakage and, therefore, global emissions.

While CBAM enhances the emission reductions of energy-intensive, trade-exposed sectors, CBAM affects the competitiveness of these sectors in terms of their sales to different degrees. Consequently, there is no guarantee that such policies are beneficial for all producers or industries.

Large open economies, in particular, the USA, China and India are affected negatively by CBAM but to a minor extent. With regard to tariff increases of the EU in response to tariff increases of the USA, this result indicates that the USA's vulnerability to EU tariffs is relatively low, because it is a large economy with many trading partners. This insight questions the effectiveness of CBAM in incentivizing climate action of large CO₂ emitters, especially the USA when carbon-based tariffs are dominated by a new wave of strategic tariffs. Nonetheless, our results and considerations point to significant regional and sectoral differences of policy effects. For example, high US tariffs on EU automobiles could significantly hurt German regions where automotive industries are located although these local effects average out at moderate effects at the German or European economy-wide level.

Like other computable general equilibrium assessments, our policy analysis is subject to uncertainty of parameter values, in particular those governing the reaction of inputs, outputs, trade and consumption (i.e., elasticities of substitution and trade elasticities) to policies. More flexibility in the modelling system (reflected

by higher elasticity values) basically allows stronger adjustments to policies, including easier replacements of fossil fuels to reduce CO₂ emissions, and hence smaller welfare effects. Our sensitivity test and the detailed sensitivity analysis in Pothén and Hübler (2018), however, indicate that the model results are relatively robust to changes in such parameter values. Nonetheless, all specific numerical results, especially those from the regional analysis, should be treated with caution.

Regarding the use of the Eaton and Kortum (2002) theory for modelling climate and trade policy, our analysis indicates that the contribution of Ricardian selection to CO₂ reductions is small and confirms that the policy modelling results are similar to those derived from a comparable Armington (1969) type trade model, in particular, Hübler et al. (2024) (also see Böhringer et al. 2012; Larch and Wanner 2017). Armington models are easier to handle regarding calibration (to standard data) and computation. They also ease the calculation of basic trade indicators, such as import and export volumes, average import and export prices and the terms-of-trade based on import and export bundles. Nonetheless, for the analysis of specific aspects, such as trade costs or free trade agreements, Eaton and Kortum type models are useful theory-based tools for applied numerical research (cf. Pothén and Hübler 2018). Compared to these perfect competition models, Melitz (2003) type imperfect competition models, however, provide an additional important margin of adjustment that is numerically relevant (Arkolakis et al. 2012; Costinot and Rodríguez-Clare 2014; Jafari and Britz 2018; Caliendo et al. 2023; Kucheryavyy et al. 2023).

In summary, our analysis combined with a literature review highlights relevant regional differences in policy effects. It underlines that world region-wide (e.g., the EU) or country-wide (e.g., Germany) policy results can be misleading for giving reliable national region-wide (e.g., Lower Saxony) policy advice. Consequently, more regional data and practical modelling approaches are required.

In contrast to these insights, our review of available regional data within Germany reveals a dearth of publicly available official and constructed data. Therefore, the overarching goal is the provision of an up-to-date, standardized, country-wide multi-regional input-output (MRIO) table (as developed by Többen 2017a, 2017b; Krebs 2020). It shall cover all regions (e.g., federal states) within the country and contain the required information for various policy modelling purposes, for example, CO₂ emissions. Such a comprehensive data set could be officially and publicly provided by the country-wide or federal state-specific statistical offices (such as Statistisches Bundesamt) in an easily accessible way (online access). It should be updated regularly and, as far as possible, aligned with broader standard databases (such as GTAP) regarding sectors, years and variables/indicators.

With such a database, researchers could verify how far the results found in the literature and in our own analysis are robust to the choice of the regional disaggregation procedure and the availability of accurate and comprehensive data. Results

can also differ when more regions (federal states) within countries are modeled separately/explicitly, which requires further research.

Importantly, interactions across regions via interregional trade (compared to international trade) and interregional factor movements (labor mobility, i.e., migration, capital mobility, i.e., geographic flexibility of investments) are conceptually different within countries compared with the mechanisms across countries, for which established theories and (numerical) models exist. Therefore, better practical modelling solutions are required that describe interregional trade and flexible factor mobility across regions within countries.

In the context of climate/energy policy and energy transition, interregional power grids and transmission lines (together with energy storage) create important interregional linkages and require an interdisciplinary economics-engineering approach (Böing et al. 2018; Göke et al. 2018; Blaufuß et al. 2019).

On the production side, the combination of regional with further sectoral disaggregation can be advisable, especially in the power sector and in energy-intensive sectors. In this way, process emissions can also be considered. On the consumption side, the distribution of income as well as land/resource ownership is regionally different. Therefore, the combination of regional disaggregation with consumer disaggregation can provide new insights in regional inequality effects.

Considering that shocks or policies can have a restricted local/regional scope and country-wide policies can have extraordinary local/regional effects due to local/regional circumstances (e.g., coastal off-shore wind power expansion in Northern Germany or the coal phase-out in Lusatia), a more detailed geographic resolution of the provided data than the federal state level is useful, at least for selected relevant areas.

In this context, multinational enterprises and “global players” play a crucial role in the determination of local/regional policy impacts, such as production and employment effects of trade policy or electromobility expansion. They are not only affected by local policies but also by policies abroad or changes in international regulation or on international markets. Because such enterprises are located or concentrated in certain areas, economic effects can be locally significant but average out at the country-wide level. This requires more granular data.

Overall, we have identified a number of modelling and data challenges and corresponding improvements. We believe that this regional analysis of Germany embedded in the EU provides insights that are relevant for other countries as well. In a world with increasing strategic trade barriers at arbitrary rates, environmental taxation, such as CBAM, provides an alternative strategy, setting well-grounded, transparent, reliable, beneficial, peaceful and hopefully broadly acceptable tariffs.

Acknowledgement: We gratefully acknowledge funding from the German Federal Ministry of Education and Research (BMBF) for the project “Mitigation Policies in

a Globalized and Developing World: The Role of Structural Change and Distributional Effects” (ROCHADE, grant 01LA1828C). This work originates from the project “NEDS – Nachhaltige Energieversorgung Niedersachsen” supported by the Lower Saxony Ministry of Science and Culture and the Volkswagen Foundation through the “Niedersächsisches Vorab” grant programme (grant ZN3043). We thank Johannes Hampp for updating the model calibration and Malin Wiese and Frank Pothén for very helpful comments. We are very grateful to Editor Mario Larch and two anonymous reviewers for very knowledgeable, constructive and helpful comments.

References

- Adeel, Z., A. M. Alarcón, L. Bakkensen, E. Franco, G. M. Garfin, R. A. McPherson, et al. 2020. “Developing a Comprehensive Methodology for Evaluating Economic Impacts of Floods in Canada, Mexico and the United States.” *International Journal of Disaster Risk Reduction* 50: 101861.
- Ahlfeldt, G. M., S. J. Redding, D. M. Sturm, and N. Wolf. 2015. “The Economics of Density: Evidence from the Berlin Wall.” *Econometrica* 83 (6): 2127–89.
- Ang, B. W., and F. L. Liu. 2001. “A New Energy Decomposition Method: Perfect in Decomposition and Consistent in Aggregation.” *Energy* 26 (6): 537–48.
- Arkolakis, C., A. Costinot, and A. Rodríguez-Clare. 2012. “New Trade Models, Same Old Gains?” *American Economic Review* 102 (1): 94–130.
- Armington, P. S. 1969. “A Theory of Demand for Products Distinguished by Place of Production.” *Staff Papers – International Monetary Fund* 16 (1): 159–78.
- Blaufuß, C., C. Busse, M. Dumeier, J. Geldermann, M. Hübner, M. Kleinau, et al. 2019. *Development of a Process for Integrated Development and Evaluation of Energy Scenarios for Lower Saxony, Final Report of the Research Project NEDS – Nachhaltige Energieversorgung Niedersachsen*. Göttingen, Germany: Schriftenreihe des Energieforschungszentrums Niedersachsen (efzn) Band 61.
- Böhringer, C., E. J. Balistreri, and T. F. Rutherford. 2012. “The Role of Border Carbon Adjustment in Unilateral Climate Policy: Overview of an Energy Modeling Forum Study (EMF 29).” *Energy Economics* 34: S97–110.
- Böing, F., A. Murmann, C. Pellingner, A. Bruckmeier, T. Kern, and T. Mongin. 2018. “Assessment of Grid Optimisation Measures for the German Transmission Grid Using Open Source Grid Data.” *Journal of Physics: Conference Series* 977: 012002.
- Bröcker, J., J. Burmeister, and E. Sudheimer. 2016. *Wertschöpfungs- und Beschäftigungseffekte als Folge des Ausbaus der Offshore-Windenergie in Norddeutschland*. Kiel, Germany: Beiträge aus dem Institut für Regionalforschung der Universität Kiel 46. Institut für Regionalforschung der Universität Kiel.
- Bundesagentur für Arbeit. 2016a. “Sozialversicherungspflichtig und geringfügig Beschäftigte nach Wirtschaftszweigen der WZ 2008 in Deutschland. Statistik der Bundesagentur für Arbeit, Nürnberg, Germany.” <http://statistik.arbeitsagentur.de>.
- Bundesagentur für Arbeit. 2016b. “Sozialversicherungspflichtig und geringfügig Beschäftigte nach Wirtschaftszweigen der WZ 2008 in Niedersachsen. Statistik der Bundesagentur für Arbeit, Nürnberg, Germany.” <http://statistik.arbeitsagentur.de>.
- Bundesagentur für Arbeit. 2022. “Beschäftigung nach Wirtschaftszweigen (WZ 2008) (hochgerechnet) – Deutschland, Länder und Regionaldirektionen (Monatszahlen). Nürnberg, Germany:

- Bundesagentur für Arbeit." https://statistik.arbeitsagentur.de/SiteGlobals/Forms/Suche/Einzelheftsuche_Formular.html?nn=20898&topic_f=beschaeftigung-sozbe-monatsheft-wz.
- Caliendo, L., R. C. Feenstra, J. Romalis, and A. M. Taylor. 2023. "Tariff Reductions, Heterogeneous Firms, and Welfare: Theory and Evidence for 1990–2010." *IMF Economic Review* 71: 817–51.
- Caliendo, L., and F. Parro. 2015. "Estimates of the Trade and Welfare Effects of NAFTA." *The Review of Economic Studies* 82 (1): 1–44.
- Caliendo, L., F. Parro, E. Rossi-Hansberg, and P.-D. Sarte. 2018. "The Impact of Regional and Sectoral Productivity Changes on the U.S. Economy." *The Review of Economic Studies* 85 (4): 2042–96.
- Cazcarro, I., R. Duarte, and J. Sanchez Cholí. 2013. "Multiregional Input–Output Model for the Evaluation of Spanish Water Flows." *Environmental Science & Technology* 47 (21): 12275–83.
- Cherniwchan, J., B. R. Copeland, and M. S. Taylor. 2017. "Trade and the Environment: New Methods, Measurements, and Results." *Annual Review of Economics* 9 (1): 59–85.
- Copeland, B. R., J. S. Shapiro, and M. S. Taylor 2022. "Globalization and the Environment." In *Handbook of International Economics*, Vol. 5, edited by G. Gopinath, E. Helpman, and K. Rogoff, 61–146: Elsevier.
- Copeland, B., and M. S. Taylor. 1994. "North-South Trade and the Environment." *Quarterly Journal of Economics* 109 (3): 755–87.
- Costinot, A. and A. Rodríguez-Clare 2014. "Trade Theory with Numbers: Quantifying the Consequences of Globalization." In *Handbook of International Economics*, Vol. 4, edited by G. Gopinath, E. Helpman, and K. Rogoff, 197–261: Elsevier.
- Destatis. 2022. *Database of the Federal Statistical Office of Germany*. Wiesbaden, Germany: Statistisches Bundesamt. <https://www-genesis.destatis.de/genesis/online>.
- Dettmer, B., and T. Sauer. 2014. "Regionalökonomische Auswirkungen eines geplanten Pumpspeicherkraftwerks: Eine Input-Output-Analyse für den Freistaat Thüringen." *Zeitschrift für Energiewirtschaft* 4 (38): 255–68.
- Eaton, J., and S. Kortum. 2002. "Technology, Geography, and Trade." *Econometrica* 70 (5): 1741–79.
- Flegg, A. T., and T. Tohmo. 2013. "Regional Input–Output Tables and the FLQ Formula: a Case Study of Finland." *Regional Studies* 47 (5): 703–21.
- Flegg, A. T., and C. D. Webber. 2000. "Regional Size, Regional Specialization and the FLQ Formula." *Regional Studies* 34 (6): 563–9.
- Flegg, A. T., C. D. Webber, and M. V. Elliott. 1995. "On the Appropriate Use of Location Quotients in Generating Regional input–output Tables." *Regional Studies* 29 (6): 547–61.
- Forschungsdatenzentren (FDZ) der Statistischen Ämter des Bundes und der Länder. 2024. "Einkommens- und Verbrauchsstichprobe (EVS) 2013, Grundfile 5 (HB), Scientific-Use-File (SUF)." <https://doi.org/10.21242/63221.2013.00.00.3.1.1>.
- Göke, L., M. Kittel, C. Kemfert, C. Lorenz, P.-Y. Oei, and C. von Hirschhausen. 2018. "Successful Climate Protection via Rapid Coalphaseout in Germany and North Rhine-Westphalia." *DIW Weekly Report – at a glance* 33: 302–11.
- González-Eguino, M., I. Galarraga, and A. Ansuategi. 2012. "The Future of Old Industrial Regions in a Carbon-Constrained World." *Climate Policy* 12 (2): 164–86.
- Grossman, G., and A. Krueger. 1993. "Environmental Impacts of a North American Free Trade Agreement." In *The U.S.-Mexico Free Trade Agreement*, edited by P. M. Garber, 13–56. Cambridge, MA: MIT Press.
- Haigner, S., F. Schneider, and F. Wakolbinger. 2015. *Volkswirtschaftliche Bedeutung der Existenzgründungsförderung der L-Bank. Eine Studie im Auftrag der Landeskreditbank Baden-Württemberg*. Tech. rep. Innsbruck, Germany: Gesellschaft für angewandte Wirtschaftsforschung.

- Harris, J., and M. Todaro. 1970. "Migration, Unemployment, and Development: A Two-Sector Analysis." *American Economic Review* 60 (1): 126–42.
- Heindl, P., and S. Voigt. 2012. *Employment Effects of Regional Climate Policy: The Case of Renewable Energy Promotion by feed-in Tariffs*. ZEW Discussion Paper 12-066. Mannheim, Germany: ZEW — Leibniz Centre for European Economic Research.
- Hübler, M., and A. Herdecke. 2020. "The US Trade Dispute: Blunt Offence or Rational Strategy?" *Applied Economics Letters* 27: 690–6.
- Hübler, M., and A. Löschel. 2013. "The EU Decarbonisation Roadmap 2050: what Way to Walk?" *Energy Policy* 55: 190–207.
- Hübler, M., M. Wiese, M. Braun, and J. Damster. 2024. "The Distributional Effects of CO₂ Pricing at Home and at the Border on German Income Groups." *Resource and Energy Economics* 77: 101435.
- Jafari, Y., and W. Britz. 2018. "Modelling Heterogeneous Firms and Non-tariff Measures in Free Trade Agreements Using Computable General Equilibrium." *Economic Modelling* 73: 279–94.
- Jin, Y.-X. 1991. "Estimating Regional Input–Output Tables from Available Data." *Economic Systems Research* 3 (4): 391–8.
- Kittel, M., L. Göke, C. Kemfert, P.-Y. Oei, and C. von Hirschhausen. 2020. "Scenarios for Coal-Exit in Germany — A Model-Based Analysis and Implications in the European Context." *Energies* 13: 2041.
- Koch, A., C. Lerch, C. Rammer, G. Klee, and N. Meyer. 2019. *Die Bedeutung der industrienahen Dienstleistungen in Baden-Württemberg unter besonderer Berücksichtigung der Digitalisierung*. Tech. rep. Tübingen u.a.: University of Tübingen, Institut für Angewandte Wirtschaftsforschung (IAW) e.V. u.a.
- Korpar, N., M. Larch, and R. Stöllinger. 2023. "The European Carbon Border Adjustment Mechanism: a Small Step in the Right Direction." *International Economics and Economic Policy* 19: 95–123.
- Koschel, H., U. Moslener, B. Sturm, U. Fahl, B. Rühle, and H. Wolf. 2006. *Integriertes Klimaschutzprogramm Hessen: Klim 2012 Endbericht*.
- Krebs, O. 2020. *RIOTs in Germany — Constructing an Interregional Input-Output Table for Germany*. Working Papers in Business and Economics 132. Tübingen, Germany: University of Tübingen.
- Kreickemeier, U., and P. M. Richter. 2014. "Trade and the Environment: the Role of Firm Heterogeneity." *Review of International Economics* 22 (2): 209–25.
- Kronenberg, T. 2009. "Construction of Regional Input-Output Tables Using Nonsurvey Methods: The Role of cross-hauling." *International Regional Science Review* 32 (1): 40–64.
- Kronenberg, T. 2010. "Erstellung einer Input-Output-Tabelle für Mecklenburg-Vorpommern." *ASTA Wirtschafts- und Sozialstatistisches Archiv* 3 (4): 223–48.
- Kronenberg, T. 2011. "Demographically Induced Changes in the Structure of Final Demand and Infrastructure Use." In *Demography and Infrastructure: National and Regional Aspects of Demographic Change*, edited by T. Kronenberg and W. Kuckshinrichs, 67–91. Dordrecht, Netherlands: Springer.
- Kronenberg, T., M. Schäfer, and J. Többen. 2018. *Arbeitsplätze schaffen durch Klimaschutz: Eine Szenarienanalyse für Nordrhein-Westfalen*. Working Paper Forschungsförderung 079. Düsseldorf, Germany: Hans Böckler Foundation.
- Kronenberg, T., and J. Többen. 2011. *Regional input-output Modelling in Germany: The Case of North Rhine-Westphalia*. MPRA Paper 35494. Jülich, Germany: Forschungszentrum Jülich.
- Kronenberg, T., and M. I. Wolter. 2017. "Harmonization of Regional and National Inputoutput Models: the Case of Germany." In *Paper Presented at the 25th IIOA Conference, June 19 — 23, 2017*. Atlantic City, U.S.

- Kucheryavyy, K., G. Lyn, and A. Rodríguez-Clare. 2023. "Grounded by Gravity: A Well-Behaved Trade Model with Industry-Level Economies of Scale." *American Economic Journal: Macroeconomics* 15 (2): 372–412.
- LAE. 2016a. Bruttostromerzeugung aus erneuerbaren Energieträgern in GWh. Länderarbeitskreis Energiebilanzen, Statistisches Landesamt Bremen, Germany. <https://www.lak-energiebilanzen.de/energiebilanzen/>.
- LAE. 2016b. Bruttostromerzeugung nach Energieträgern in GWh. Länderarbeitskreis Energiebilanzen, Statistisches Landesamt Bremen, Germany. <https://www.lak-energiebilanzen.de/energiebilanzen/>.
- Larch, M. and J. Wanner 2017. "Carbon Tariffs: An Analysis of the Trade, Welfare, and Emission Effects." *Journal of International Economics* 109: 195–213.
- Lehr, T., R. Albrecht, M. Schirmacher, and B. Winkler. 2013. *Wirtschaftsfaktor Sächsische Landwirtschaft*. Schriftenreihe des LfULG 29/2013. Dresden, Germany: Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie.
- Leimbach, M., M. Hübler, H. Mahlkow, L. Montrone, E. Bukin, G. Felbermayr, et al. 2024. "Macroeconomic Structural Change Likely Increases Inequality in India More than Climate policy." *Environmental Research Letters* 19: 044070.
- Lenzen, M., R. Wood, and T. Wiedmann. 2010. "Uncertainty Analysis for multi-region input–output models—a Case Study of the UK's Carbon Footprint." *Economic Systems Research* 22 (1): 43–63.
- Mattoo, A., A. Subramanian, D. van der Mensbrugghe, and J. He. 2013. "Trade Effects of Alternative Carbon border-tax Schemes." *Review of World Economics* 149: 102–10.
- Maucorps, A., R. Römisch, T. Schwab, and N. Vujanović. 2023. "The Impact of the Green and Digital Transition on Regional Cohesion in Europe." *Intereconomics* 58 (2): 102–10.
- Melitz, M. J. 2003. "The Impact of Trade on Intra-industry Reallocations and Aggregate Industry Productivity." *Econometrica* 71 (6): 1695–725.
- Monte, F., S. J. Redding, and E. Rossi-Hansberg. 2018. "Commuting, Migration, and Local Employment Elasticities." *American Economic Review* 108 (12): 3855–90.
- Penzkofer, H. 2002. "Wirtschaftliche Wirkungen der Frankfurter Messen." *Ifo Schnelldienst* 55 (01): 24–31.
- Pothen, F., and M. Hübler. 2018. "The Interaction of Climate and Trade Policy." *European Economic Review* 107: 1–26.
- Pothen, F., and M. Hübler. 2021. "A Forward Calibration Method for Analyzing Energy Policy in New Quantitative Trade Models." *Energy Economics* 100: 105352.
- Prognos. 2007. *Regionalökonomische Auswirkungen des Steinkohlenbergbaus in Nordrhein-Westfalen. Study Commissioned by Gesamtverband Steinkohle*. Basel, Switzerland: Prognos AG.
- Prognos. 2009. *Ökonomische Wirkungseffekte der „Konjunkturoffensive Hamburg“*. Study commissioned by the Free and Hanseatic City of Hamburg. Basel, Switzerland: Prognos AG.
- Ramondo, N. 2014. "A Quantitative Approach to Multinational Production." *Journal of International Economics* 93 (1): 108–22.
- Redding, S. J. 2016. "Goods Trade, Factor Mobility and Welfare." *Journal of International Economics* 101: 148–67.
- Schröder, A. 2010. *Regionalökonomische Effekte aus der Nutzung von Windenergie in der Region Hannover*. deENet Arbeitsmaterialien 3. Kassel, Germany: deENet.
- Schröder, T. 2012. *Beschäftigungseffekte der Offshore-Windenergie in Niedersachsen: Eine regionale Input-Output-Analyse*. STE Preprint 04/2012. Jülich, Germany: Forschungszentrum Jülich.

- Schröder, A., and K. Zimmermann. 2014. *Erstellung regionaler Input-Output-Tabellen: Ein Vergleich existierender Ansätze und ihre Anwendung für die deutsche Ostseeküstenregion*. Berlin, Germany: RADOST Berichtsreihe 33.
- Seibert, H., A. Weyh, O. Jost, U. Sujata, D. Wiethölter, and J. Carstensen. 2018. *Die Lausitz: Eine Region im Wandel*. IAB-Regional 03/2018. Nürnberg, Germany: Institut für Arbeitsmarkt-und Berufsforschung (IAB).
- Sgarciu, S., D. Scholz, and F. Müsgens. 2023. "How CO₂ Prices Accelerate decarbonisation—the Case of coal-fired Generation in Germany." *Energy Policy* 173: 113375.
- Sogalla, R. 2023. "Unilateral Carbon Pricing and Heterogeneous Firms." *DIW Berlin Discussion Papers* 2060 1—75, <https://hdl.handle.net/10419/280782>.
- Sogalla, R., J. Wanner, and Y. Watabe. 2024. "New Trade Models, Same Old Emissions." *DIW Berlin Discussion Papers* 2077 1—63, <https://doi.org/10.2139/ssrn.4792312>.
- Stöver, B. 2018. *The Local Impact and Multiplier Effect of Universities in Lower Saxony on the Labour Market*. Hannover Economic Papers 646. Hannover, Germany: School of Economics and Management, University of Hannover.
- Stürmlinger, M.-C., and S. Fuchs. 2021. "Der Kohleausstieg: Gesetzliche Ausgestaltung und Perspektiven." *Natur und Recht* 43 (5): 320—7.
- Tabuchi, T., and J.-F. Thisse. 2002. "Taste Heterogeneity, Labor Mobility and Economic Geography." *Journal of Development Economics* 69 (1): 155—77.
- Többen, J. 2017a. "Effects of Energy and Climate Policy in Germany." PhD thesis. Groningen, The Netherlands: University of Groningen.
- Többen, J. 2017b. "Regional Net Impacts and Social Distribution Effects of Promoting Renewable Energies in Germany." *Ecological Economics* 135: 195—208.
- Többen, J., and T. Kronenberg. 2015. "Construction of multi-regional input—output Tables Using the CHARM Method." *Economic Systems Research* 27 (4): 487—507.
- Tohmo, T. 2004. "New Developments in the Use of Location Quotients to Estimate Regional input—output Coefficients and Multipliers." *Regional Studies* 38 (1): 43—54.
- Towa, E., V. Zeller, S. Merciai, J. Schmidt, and W. M. Achten. 2022. "Toward the Development of Subnational Hybrid input—output Tables in a Multiregional Framework." *Journal of Industrial Ecology* 26 (1): 88—106.
- VGRdL. 2022a. Ergebnisse—Kreisebene. Volkswirtschaftliche Gesamtrechnungen der Länder. <https://www.statistikportal.de/de/vgrdl/ergebnisse-reisebene>.
- VGRdL. 2022b. Ergebnisse—Länderebene. Volkswirtschaftliche Gesamtrechnungen der Länder. <https://www.statistikportal.de/de/vgrdl/ergebnisse-laenderebene>.
- Wang, Y., A. Geschke, and M. Lenzen. 2017. "Constructing a Time Series of Nested Multiregion input—output Tables." *International Regional Science Review* 40 (5): 476—99.
- Weitzel, M., M. Hübler, and S. Peterson. 2012. "Fair, Optimal or Detrimental? Environmental vs. Strategic Use of Border Carbon Adjustment." *Energy Economics* 34: 595—123.
- WVEE. 2012. "Bruttostromerzeugung nach Energieträgern in GWh. Wirtschaftsverband Erdöl-und Erdgasgewinnung, Hannover, Germany." <https://www.bveg.de/>.
- Zhang, W.-W., B. Zhao, Y. Gu, B. Sharp, S.-C. Xu, and K.-N. Liou. 2020. "Environmental Impact of National and Subnational Carbon Policies in China Based on a multi-regional Dynamic CGE Model." *Journal of Environmental Management* 270 (15): 110901.

Supplementary Material: This article contains supplementary material (<https://doi.org/10.1515/ger-2024-0102>).