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Models for the analysis of international interrelations of the EU ETS and of a CBAM

Extended model overview

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Abstract: Models for the analysis of international interrelations of the EU ETS - Part 3: Extended model overview

The aim of this report is to provide an overview of different models that are, in principle, capable of representing the key topics of this research project: namely, a) the potential "carbon leakage" impacts – in terms of emissions and key economic indicators - which may result from "uneven" carbon pricing, b) policies that address this risk, e.g. a carbon border adjustment mechanism (CBAM), and c) more general, key economic impacts of GHG mitigation scenarios with different total global mitigation ambitions. This includes the two models applied in the project reports "Climate Protection Scenarios until 2050 considering CO_2 price differences and carbon leakage" (Lutz et al. 2024a; Lutz et al. 2024b): GINFORS-E and GEM-E3.

First, we present in section 2 key model features that we consider to be central for models for addressing the central project questions stated above. These features refer to their capacity to analyse national and international macroeconomic and feedback effects, as well as their granularity in terms of sectors, countries/regions and technologies, and finally, the statistical dimension. Section 3 then presents an overview of the main types of large-scale models, leading over to a more detailed contrasting discussion of the two model types used in this project: namely, macroeconometric models and computable general equilibrium (CGE) models. The same section then provides table overviews of concrete models of the types energy economic, macroeconomic (i.e., macroeconometric and CGE) modelling, and integrated assessment models. Section 4 describes selected CGE models in more detail, which includes also summarizing overview tables for the CGE models on their main principles and types of assumptions in terms of production, consumption, capital and labour markets, trade, and investment features.

In section 5, we contrast the two models used in our project – GINFORS-E and GEM-E3 - with six other models selected from the overviews in previous sections which we view as possible alternatives for corresponding model simulations of carbon leakage and measures to address it, such as a CBAM. This is done by a detailed factsheet for each presented model.

In the final section 6, based on an overview of available international databases, recommendations for model improvements are developed with a view to a more detailed representation of carbon-intensive industries.

Kurzbeschreibung: Modelle zur Analyse internationaler Wechselwirkungen des EU ETS – Teil 3: Erweiterter Modellüberblick

Das Ziel dieses Berichts ist es, einen Überblick über bestehende Modelle unterschiedlicher Typen zu geben, die im Prinzip grundsätzlich in der Lage sind, die zentralen Fragestellungen dieses Forschungsprojekts abzubilden: a) die potenziellen "Carbon Leakage"-Auswirkungen in Bezug auf Emissionen und wirtschaftliche Schlüsselindikatoren, die sich aus einer "ungleichen" CO_2-Bepreisung ergeben können, b) politische Maßnahmen, die diesem Risiko entgegenwirken, z.B. ein Grenzausgleichsmechanismus (Carbon Border Adjustment Mechanism, CBAM), und c) allgemeinere, zentrale wirtschaftliche Auswirkungen von THG-Minderungsszenarien mit unterschiedlichen globalen Minderungszielen. Der Überblick enthält auch die beiden Modelle, die in den Projektberichten "Climate Protection Scenarios until 2050 considering CO_2 price differences and carbon leakage" (Lutz et al. 2024a; Lutz et al. 2024b) genutzt werden: GINFORS-E und GEM-E3.

Zunächst stellen wir in Abschnitt 2 die wichtigsten Modelleigenschaften vor, die wir als zentral für Modelle für die Beantwortung der oben genannten Projektfragen ansehen. Diese Merkmale beziehen sich auf ihre Fähigkeit, nationale und internationale makroökonomische und Rückkopplungseffekte zu analysieren, ihre Granularität in Bezug auf Sektoren, Länder/Regionen und Technologien, und schließlich die statistische Dimension. Abschnitt 3 gibt anschließend

einen Überblick über die wichtigsten Arten von groß-skaligen Modellen und leitet über zu einer detaillierteren vergleichenden Diskussion der beiden in diesem Projekt verwendeten Modelltypen, nämlich makroökonometrischer Modelle und berechenbaren allgemeinen Gleichgewichtsmodellen (CGE). Derselbe Abschnitt bietet dann tabellarische Übersichten über konkrete Modelle der Typen energiewirtschaftliche, makroökonomische (d. h. makroökonometrische und CGE-) Modellierung und integrierte Bewertungsmodelle (IAM). Abschnitt 4 beschreibt ausgewählte CGE-Modelle detaillierter, was auch zusammenfassende Übersichtstabellen für die CGE-Modelle über die wichtigsten Annahmen und Prinzipien in Bezug auf Produktion, Konsum, Kapital- und Arbeitsmärkte, Handel und Investitionsmerkmale beinhaltet.

In Abschnitt 5 stellen wir die beiden in unserem Projekt verwendeten Modelle - GINFORS-E und GEM-E3 - sechs ausgewählten anderen Modellen gegenüber, die wir aus den Übersichten in den vorangegangenen Abschnitten beziehen und die wir als mögliche Alternativen für entsprechende Modellsimulationen von Carbon Leakage und z.B. eines CBAM ansehen. Dies geschieht durch ein detailliertes Factsheet für jedes Modell.

Im abschließenden Abschnitt 6 werden auf der Grundlage eines Überblicks über verfügbare internationale Datenbanken Empfehlungen für Modellverbesserungen im Hinblick auf eine detailliertere Darstellung der kohlenstoffintensiven Industrien entwickelt.

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List of abbreviations

AIDADS	An implicitly directly additive demand system
AIM	Asia-Pacific Integrated Model
AIDADS	An implicitly directly additive demand system
CBAM	Carbon Border Adjustment Mechanism
CDE	Constant differences in elasticity
CES	Constant elasticity of substitution
CET	Constant-elasticity-of-transformation
CGE	Computable General Equilibrium
CL	Carbon leakage
CO2	Carbon dioxide
d-PLACE	Dynamic version of PLACE model
E3ME	Energy-Environment-Economy Macro Econometric Model
EIA	US Energy Information Agency
ELES	Extended Linear Expenditure System
EMPAX	Economic Model for Environmental Policy Analysis
ETS	Emissions Trading Systems
FDI	Foreign direct investment
GDP	Gross domestic product
GEM-E3	General Equilibrium Model – E3
GHG	Greenhouse gases
GINFORS-E	Global Interindustry Forecasting System - Energy
GLORIA	Global Resource Input-Output Assessment
GTAP	Global Trade Analysis Project
IAM	Integrated Assessment Model
IO	Input-output
JRC	Joint Research Center
LCA	Life-Cycle Assessment
LES	Linear Expenditure System
MRIO	Multiregional input-output
PACE	Policy Analysis based on Computable Equilibrium
PE	Partial equilibrium
PLACE	Polish Laboratory for the Analysis of Climate and Energy
RES	Renewable Energy Sources
RoW	Rest of world
SAM	Social Accounting Matrix
SSP	Shared socioeconomic pathway
WIOD	World input-output database

1 Introduction

The aim of this report is to provide an overview of existing models of different types that are, in principle, capable of representing the key topics of this research project: a) the potential "carbon leakage" impacts – in terms of emissions and key economic indicators - which may result from "uneven" carbon pricing, b) policies that address this risk, e.g. a carbon border adjustment mechanism (CBAM), and c) more general, key economic impacts of GHG mitigation scenarios with different total global mitigation ambitions. This includes the two models applied in our project report "Climate Protection Scenarios until 2050 considering CO_2 price differences and carbon leakage": GINFORS-E and GEM-E3 (Lutz et al. 2024a; Lutz et al. 2024b):. The summary of the project results (Lutz et al. 2024c) and all reports can be found at https://www.umweltbundesamt.de/en/publications.

This report is primarily aimed at practitioners in institutions (governmental and nongovernmental) that intend to commission or are interested in model-based analyses for questions on a) the economic impacts of different climate policy ambitions, including "uneven" carbon pricing internationally, and b) the economic impacts of measures that (can) address carbon leakage, such as the allocation mode of an emissions trading system (ETS) or a carbon border adjustment mechanism (CBAM). The report can also help interpret results from own (commissioned or self-performed) model-based analyses and (to some extent) analyses in external publications. In addition, it provides information for model builders to classify and compare their own work and identify research gaps. Over the past two decades, several macro-economic as well as integrated assessment models (IAMs) have been developed and applied to analyse the impacts of climate policies for the economy, the society and the environment. However, a structured analysis of the models focusing on complex carbon leakage issues is currently lacking. In order to determine the usability of existing models, i.e. in how far these address the specific questions, the following steps have been implemented in this report:

Step-1: Present the key features that models should have in order to engage in applied energy and climate policy analysis, with a focus on their suitability to address the key questions of our project, i.e. mitigation scenarios with carbon leakage, different design options of an emissions trading system in this context, and specific measures to minimize carbon leakage such as a CBAM (section 2).

Step-2: Develop a list and mapping of large-scale macro-economic and integrated assessment models that are used for assessments of ambitious global or regional mitigation policies. The main output of this step is a comprehensive list of major models used worldwide to assess climate policy impacts. These include macroeconometric models and computable general equilibrium (CGE) models; furthermore, to get a broader picture, model types have been included in the analysis that may be less suitable but are often used in modelling climate mitigation such as IAMs and partial equilibrium energy systems models. These models are classified according to their characteristics (section 3).

Step 3: As CGE models are very prominent among the large-scale models for comprehensive, economy wide analyses including international effects: describe prominent CGE models in more detail and subsequently summarized according to central principles and assumption types on production, consumption, capital and labour markets as well as assumptions on trade and investment (section 4).

Step-4: Compare the two models used in our project – GINFORS-E and GEM-E3 - with six other models selected from the overviews in previous sections which we view as possible alternatives for corresponding model simulations of carbon leakage and measures to address it such as a CBAM. This is done by a detailed factsheet for each presented model (section 5).

Step-5: Based on a general overview of available international databases, recommendations on model improvements with regard to more detailed representation of carbon intensive industries are developed (section 6).

2 Model requirements for assessment of carbon leakage and CBAM measures

The quantification of the socio-economic implications of energy and climate policies is a complex task that requires the simultaneous representation of all economic agents and the detailed capturing of their dynamic interactions within a transparent and robust framework. It is evident that the behavior of the agents but also the dynamics of the system are subject to a multitude of factors that also change over time – hence the uncertainty in any attempt to capture the evolution of the systems is high.

In order for modelling tools to be useful in applied policy analysis they need to have a number of features that are summarized below. Sufficient sectoral and regional granularity is required in order to be able to capture both the potential of substitution possibilities but also to identify the contribution of domestic content to abatement activities. For the adequate mapping of carbon leakage and policies to mitigate it like CBAM, sectoral and regional granularity are therefor most important: This may also mean that models to capture carbon leakage and policies to mitigate it specialize in this (section 6), possibly neglecting other issues mentioned below as well.

- **Regional granularity**: As carbon leakage also depends on transport costs, sufficient regional differentiation of economies with different CO_2 prices is a key requirement of informative quantitative analyses. Countries that play an important role for carbon leakage due to their proximity and economic structure must be modeled separately. The same applies to the transformation in the energy sector. The availability of renewable energy sources as well as cheap electricity and in the future also hydrogen are an important prerequisite for the expansion of green industries and play an important role in the question of whether leakage takes place or the EU industry is greening. For example in many models, clean energy technologies are included in a wider sector (equipment goods) that exists almost in all countries – however manufacturing capacity of Wind, PV at a scale and competitive costs exists only in a few countries. Models that do not identify separately these sectors tend to underestimate the costs of abatement – as they prefer domestic demand more than they should.

- **Sectoral and technology granularity**: At the same time, the sectoral differentiation must be large enough to adequately represent the potential leakage. Key sectors need to be presented bottom-up. Detailed representation of the options available to economic agents to engage in production and consumption is important as it is more accurate on capturing the substitution potential and its associated costs. Often, substitution possibilities of complex production processes are captured by only one elasticity – an approach which may have significant impacts on cost assessment.

  Since the statistics and internationally available data sets only differentiate between technologies and goods to a limited extent, e.g. only basic metals or at most the differentiation into iron and steel and non-ferrous metals, or only the chemical industry as a whole, this is probably where the greatest need for future research exists. This is because the EU's CBAM policy is partly aimed at much more delimited products such as fertilizers or even new technologies such as hydrogen production, which have not yet been recorded separately in the statistics at all.

- **Robust and transparent methodological framework**: For any policy analysis it is essential that the method used is in accordance with the most recent scientific evidence. To this end published results and methods to top-ranked scientific journals are desired. Model inventories such as MIDAS of the EU Commission also serve transparency. Users of the model must have the necessary access to its data and methods that allows them to understand the key mechanisms of the model and the drivers of its results. It is important that users can distinguish between the actual model insights and model artifacts when reviewing the results. Artifacts include exogenous assumptions and incomplete or unrealistic model relationships. For the modelling of climate policies and carbon leakage it is important to model in detail the energy/carbon intensity of production and consumption activities but also the available substitution options as well as the full feedback loops on the economy (endogenous bilateral trade, inter-dependencies of industries and households). Central assumptions such as myopic or rational expectations of economic agents must be clear. Representation of important dynamics, interdependencies of economic agents and feedback loops should be appropriate.

- **Up-to-date statistics:** Recent statistics are essential as they set the base on which models are calibrated. However, it is important that statistics do not include short-term short-lasting disturbances that may impact long term projections – if possible short-lasting disturbances and structural changes should be identified.

3 Mapping of large-scale global energy-economy, macro-economic and Integrated Assessment Models

In the literature, there are various classifications according to which models that combine the fields of economy, energy and climate can be divided. An early distinction between top-down and bottom-up approaches, short-term and long-term, and analyzing the sectoral coverage stems from Grubb et al. (1993).

A paper by Nikas et al. (2019) divides the models into 6 classes, drawing on a detailed literature review. The following descriptions from a to f are directly cited from this source:

a) **"Optimal growth (or welfare optimisation) IAMs** represent the economy as a single all-encompassing sector. IAMs are designed to determine the climate policy and investment that maximize welfare (future against present consumption) over time, by identifying the emission abatement levels for each time step. They tend to be simple, highly aggregated and transparent models that capture the trajectory of an economy and its interaction with climate in a fully integrated way.

b) **General equilibrium** (or usually referred to as computable general equilibrium—CGE) models have a more detailed representation of the economy with multiple sectors and often include higher resolution of energy technologies and regional detail. Rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. One of the key characteristics of CGE models can be considered the rational behavior of agents – which is not a realistic assumption in some cases.

c) **Partial equilibrium models** provide a detailed analysis of the interaction between environmental impacts and a particular sector of the economy. These are usually used to assess potential climate-induced damages to a specific sector of the economy and are often linked to computable general equilibrium models.

d) **Energy system models** can be considered as a subcategory of partial equilibrium models that provide a detailed account of the energy sector, i.e. energy technologies and their associated costs. These are often used to determine the least-cost ways of attaining greenhouse gas (GHG) emission reductions or the costs of alternative climate policies. They are often linked with CGE or macroeconometric models in order to add the desired level of insight to top-down approaches.

e) **Macroeconometric models**, like CGE models, can be quite detailed in terms of economic sectors and regional coverages and are also used to evaluate alternative climate policies. A major difference is that they do not assume that consumers and producers behave optimally or that markets clear and reach equilibrium in the short term. Instead, they use historical data and econometrically estimated parameters and relations to simulate the behaviour of the economy dynamically and more realistically.

f) **Other IAMs** refer to models that may have little in common except that they do not fit neatly into any of the previous well-known groups. A key departure is that they model the economy in a highly "reduced form" or simply use exogenous growth scenarios (no model at all). Although they significantly differ from one another, they all tend to be more policy-oriented than models of the other five classes."

Tänzler et al. (2018) also describe different model families, approaches and types. They differentiate between optimisation and econometric models, top-down, and bottom-up models, partial equilibrium and general equilibrium models. For the time horizon of agents they differentiate myopic, limited foresight and perfect foresight. Colmenares et al. (2020) differentiate growth models, econometric studies including macroeconometric models, simulation studies including CGE models, and integrated assessment models. An early comparison between CGE and macroeconometric models can be found in West (1995). The use of different model types for catching impacts of energy efficiency improvements is presented in IEA (2013). Of course, in addition to these general model types, there are also intermediate forms and model specifics that need to be examined in more detail with a view to the analysis options.

Nikas et al. (2019) see the distinction of the terms top-down and bottom-up models also as very important. While top-down models explain economic development from a macroeconomic perspective and tend to take information about energy technologies (where relevant for a particular analysis) from other model contexts, bottom-up models describe the energy system from a technological perspective. Economic variables are usually exogenous assumptions, while the energy system is cost optimized. Both types of models are often used together.

For modelling the economic effects of a) different climate protection ambitions in different countries, and b) policy measures to address carbon leakage, such as a CBAM, only macroeconomic models that also have a sufficiently high sector resolution come into question. Carbon leakage as the relocation of production and thus ultimately GHG emissions from a country with high carbon prices to countries with lower carbon prices is a problem primarily for a few carbon-intensive sectors such as the steel industry, the chemical industry or non-metallic minerals, which include cement production. Moreover, economic policy measures such as a CBAM may be phased-in, for practical reasons, quicker for certain subsectors of the industry sectors stated before than for others.

Based on the findings below, only CGE models and macroeconometric models with sufficient sector detail are currently suitable for the analysis of carbon leakage and measures to avoid it. Models therefore need to cover the macroeconomic effects and industry detail as well as energy use and emissions on country level. Bottom-up models lack economic feedback mechanisms, IAMs in turn lack sector and regional granularity.

Key aspects of these two approaches are summarized in Table 1. The main differences are the utilization rate of resources, assumptions about the behaviour of economic agents (firms and households / optimization/ empirical), the handling of imperfections, the role of savings and investment and the price system. CGE models are supply-driven, macroeconometric models emphasize more the demand side. The econometric estimates describe past behavioural patterns and allow for longer-term market imperfections. Agents are assumed to have myopic expectations. CGE models focus on optimization under rational expectations. Markets are cleared. However, advanced CGE models such as GEM-E3 allow for imperfections as long-run unemployment, among others. CGE models are strict regarding macroeconomic closure. Only what is saved elsewhere can be invested. In contrast, macroeconometric models assume idle financial resources that are available for additional investments without cost increases. While CGE models, based on Walras, depict a relative price system (numéraire = 1), macroeconometric models include price indices (base-year = 1) to convert nominal into price-adjusted variables. Both approaches can model behaviour of different agents. The models used for policy analyses from both methodologies are less different in actual use than this overview might suggest. In some points, such as the consideration of unemployment, they converge. Other important assumptions are examined in sensitivity calculations to determine their significance for the results.

Table 1: Main features of CGE and macroeconometric models

	Neo-classical (CGE)	Post-Keynesian (macroeconometric)
Dynamics	Supply driven: Economy mainly grows through technical progress, capital accumulation and population.	Demand driven: Increase in demand for goods and services mobilises unused capital and labour
Agents Behaviour	Optimisation, rational expectations	Empirical estimation of past behaviour
Market imperfections	Labour market (unemployment), capital market (imperfect competition and oligopoly), taxation/subsidies	Empirical estimation allows to capture imperfections both in investment as different interest rates and labour market(unemployment)
Macroeconomic Closure	Savings equal financing. Hence in cases where agents have to find additional funding, they need to cancel already decided investment/consumption plans and/or to reduce savings	Savings not necessarily match investments. Idle financial capital allows funding new investments projects with no impact on costs of capital.
Price System	Relative	Nominal and Real
Agents Heterogeneity	Can capture agents' heterogeneity	Can capture agents' heterogeneity

Own compilation.

In a literature search, we identified more than 40 models that represent the economy and climate and classified them according to the following variables: Model name, model type, carbon leakage and CBAM impacts for energy-intensive sectors covered, product or sector coverage, regional coverage, author and reference. This survey builds on Tänzler et al. (2018), which examines models with regard to linking of Emissions Trading Systems (ETS). The level of sectoral disaggregation must be high when analyzing competitiveness and carbon leakage.

The literature search has been difficult because many models are used frequently, sometimes by different researchers and institutions. The models are updated again and again, specifications are partly adjusted to specific research questions, and characteristics such as the database with sector coverage and regional coverage can change between different versions. In this regard, a certain time lag must always be considered for publishing results and updating model descriptions.

Only three macroeconometric models have been identified in the literature review, which are briefly described in Table 2. They build on (partly) different databases for the central input-output tables: GINFORS-E on the OECD IO database, E3ME on a combination of Eurostat data for EU and OECD data for other countries, and NEMESIS on the WIOD database, which has been produced in different EU research projects. It should be added that Eurostat and the OECD also coordinate their work closely. Only GINFORS-E and E3ME are global models, while NEMESIS only covers EU ETS countries. With such a model, which only represents Europe and not the rest of the world explicitly, carbon leakage and measures to prevent it cannot be modelled on a bilateral trade basis. Further information on GINFORS-E and E3ME is provided in factsheets in section 5. A comparison of the E3ME and GINFORS models is provided in Barker et al. (2011a). A comparison of both models with regard to an environmental tax reform, i.e. unilateral carbon pricing in Europe, can be found in Barker et al. (2011b). Further general information on macroeconometric models can be found in Lehr & Lutz (2020).

We also add the system dynamics model ASTRA in this list, although there are some differences in the model philosophy compared to macroeconometric models. A detailed comparison of a national macroeconometric model, similar to GINFORS and the national system dynamics model ASTRA-D can be found in Lehr et al. (2011).

Table 2: Macroeconometric models

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
GINFORS-E	36	65, global	OECD	GWS	Lutz et al. (2024); factsheet in Section 5
E3ME	EU 69; RoW 43	71, global	Eurostat, OECD	Cambridge Econometrics	Markkanen et al. (2021); factsheet in Section 5
NEMESIS	30	31	WIOD	ERASME	ERASME (2019)
ASTRA	65	28	Eurostat	Fraunhofer ISI, M-FIVE	TRT et al. (2022)

Own compilation.

The number of CGE models is much larger in comparison. Most of them build on different versions of the Global Trade Analysis Project (GTAP) database. Because GTAP contains many countries and many sectors on the one hand, but on the other hand solution algorithms are slow or solutions are difficult to be achieved with a large number of countries and/or sectors, in most analyses a limited number of countries and sectors are selected, or countries are aggregated into country groups and sectors into sector groups. A more detailed comparison of some of the models can be found in section 4. Of the models listed, GEM-E3, JRC-GEM-E3, PACE, D-PLACE, and GTAP-E appear to be the most promising for the analysis of carbon leakage in terms of regional and sector coverage and are also presented in comparable factsheets in section 5.

Table 3: Computable general equilibrium (CGE) models

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
AIM-CGE	44	17 incl. EU-25, global	???	National Institute for Environmental Studies Kyoto University	Fujimori et al. (2017)
CGEBox	65	141	GTAP	Britz, van der Mensbrugghe	http://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_e.htm, https://doi.org/10.21642/JGEA.030203AF GTAP Resource 5192
DART		21, global	GTAP	Kiel Institute for the World Economy (IfW)	Peterson & Weitzel (2016)
D-PLACE	20	19, global	GTAP	Institute of Environmental Protection - National Research Institute (IOS-PIB)	Factsheet in Section 5, Boratynski et al. (2022)

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
EMPAX-CGE	35[1]	5 US regions	IMPLAN based on various US government sources	EPA	https://www3.epa.gov/ttn/ecas/models/empax_model_documentation.pdf
EmuSe (DSGE)	3/57	2/1	WIOD	Bundesbank	Deutsche Bundesbank (2022); Hinterlang et al. (2022)
ENVISAGE			GTAP	World Bank, OECD	https://minzp.sk/files/iep/env10.pdf
ENV-Linkages	22	29	GTAP	OECD	https://doi.org/10.1787/19970900
EPPA	14	18, global	GTAP	MIT	MIT Joint Program on the Science and Policy of Global Change (2022)
FTAP	8	19	GTAP	Hanslow et al., Australian Productivity Commission	https://www.pc.gov.au/research/supporting/ftap-structure
G-cubed	12	9-12, global		McKibbin, Wilcoxen	McKibbin Software Group (2022)
GEM-E3	67	46, global	GTAP	E3Modelling	Central report, WP 2 (Lutz et al. 2024a); factsheet in Section 5
GTAP-E	65	20 (121), global	GTAP	Hertel, Chepeliev (22 sectors, 20 regions)	Factsheet in Section 5, Hertel (2013), Hertel (1997), Chepeliev (2021); GTAP Resource #6498 GTAP Resource #6512 GTAP Resource #6544
IGEM	4	2, global	BLS	Harvard, Jorgenson	Jorgenson et al. (2013), Goettle et al. (2007)
IMACLIM-R	12	12, global	GTAP	CIRED	CIRED (2022)
JRC-GEM-E3	31	40, global	GTAP	JRC	JRC (2021), factsheet in section 5
MAGNET	65	141	GTAP	WECR, JRC	https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-magnet
MIRAGE-VA	23	27, global	GTAP	CEPII	Bellora & Fontagé (2022)

[1] Another national static version separates 384 sectors.

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
NEWAGE	18	18, global	GTAP	IER, Stuttgart	Cunha Montenegro et al. (2019)
ORANi-G		Australia		Horridge	https://vuir.vu.edu.au/29300/
PACE	36	23, global, plus 27 in EU	WIOD	ZEW	Factsheet in Section 5
PACE	36	19, global	GTAP, EXIOPOL	ZEW	Factsheet in Section 5, Gavard & Voigt (2017)
QUEST (DSGE)	1	EU-28	Eurostat, WIOD	EU COM	Varga et al. (2021)
RHOMOLO	5	267 NUTS2 regions of EU	Eurostat	JRC	Mercenier et al. (2016)
WORLDSCAN	16	16, global	GTAP	CPB, NL	Lejour et al. (2006)

Own compilation.

A third group includes partial equilibrium models of the energy market(s). They cannot represent socio-economic effects. They only present an economy without economic sector differentiation detail with regard to energy demand sectors and energy supply technologies. However, it should be examined whether they also distinguish other energy-intensive technologies or sectors in addition to energy technologies and whether information could be derived from them for a CGE or a macroeconometric model (see Central report for more information on potential coupling of PE and CGE or macroeconometric models).

Table 4: Partial equilibrium models (PE) of the energy system

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
GENeSYS-MOD				TU Berlin, DIW	Burandt et al. (2018)
Global Energy and Climate model		26-113		IEA	IEA (2022)
POLES	30/22	66		LEPII-CNRS, Enerdata	Enerdata (2022)
PRIMES	25	28		E3Modelling	Factsheet in Section 5
TIAM-UCL		16		UCL	UCL (2022)

Own compilation.

Another group of models are the integrated assessment models (IAM), which, however, do not contain a high resolution by economic sectors and thus cannot provide useful information on carbon leakage. As described above, IAMs tend to be simple, highly aggregated and transparent models that capture the trajectory of an economy and its interaction with climate in a fully integrated way (Nikas et al. 2019). For a detailed overview of these models and applications see e.g. Weyant (2017). He differentiates between detailed process IAMs and benefit-cost IAMs. "Detailed process IAMs are more disaggregated and seek to provide projections of climate change impacts at detailed regional and sectoral levels, with some using economic valuation and others using projections of physical impacts such as reductions in crop growth, land inundated by sea level rise, and additional deaths from heat stress. In contrast, benefit-cost IAMs provide a more aggregated representation of climate change mitigation costs and aggregate impacts by sector and region into a single economic metric. The main motivation for developing these benefit-cost IAMs has been to use them to identify "optimal" climate policies, but they have also been used to calculate the costs and benefits associated with polices for which marginal costs and marginal benefits are not equal." Both types lack the detail to model carbon leakage on sector level. Pindyck (2017) even argues "that integrated assessment models (IAMs) have flaws that make them close to useless as tools for policy analysis." This is definitely an exaggeration, but the analysis of concrete short-term policy measures is not their strength.

Table 5: Integrated Assessment models (IAM)

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
BET-GLUE		13		Central Research Institute of Electric Power Industry (CRIEPI), Japan	Tsutsui et al. (2020)
COFFEE, TEA	16 (COFFEE is IAM, TEA CGE model)	18, global	SSP database, GTAP for TEA	COPPE/UFRJ (Cenergia), Brazil	Cenergia (2022)
GCAM	3	14	Wide range of sources (UN, World Bank, IEA; FAO,…)	Pacific Northwest National Laboratory	Calvin et al. (2013), Kim (2010)
IMAGE	5 (industry, transport, residential, service, others)	26, global	Wide range of sources (UN, World Bank, IEA; FAO,…)	PBL	PBL (2022)

Model name	Sector coverage	Regional coverage	Main database	Author, institution	References
MERGE	single representative producer-consumer for each region	5, global		Stanford	Manne et al. (1995)
MESSAGE	Single representative producer-consumer in each world region, six energy demand categories	11, global	SSP database	IIASA	International Institute for Applied Systems Analysis (2020), Krey et al. (2020)
PROMETHEUS		10		E3Modelling	https://e3modelling.com/modelling-tools/prometheus/
REMIND-R	1	11		PIK	PIK (2020)
RICE/DICE	1	1, can be adjusted to different country's GDPs		Nordhaus	Nordhaus (2020), new DICE2022 version to be released soon
WITCH	One produced commodity	17, global		RFF-CMCC-EIEE	RFF-CMCC (2019)

Own compilation.

4 Detailed comparison of CGE models

In this section, some CGE models are described in more detail and compared with regard to essential properties. Where information is available the models are discussed with regards their ability to capture carbon leakage.

4.1 AIM

The AIM/CGE (Asia-Pacific Integrated Model/Computable General Equilibrium) is a general equilibrium model with global coverage focusing on the assessment of climate change impacts on the economy. The model includes 17 countries/regions of the world and differentiates between 45 activities, focusing on agriculture (10 distinct activities), energy (21 distinct activities) and energy intensive industries. Emission-wise, the AIM/CGE model covers all GHGs (CO2, CH4, N2O), F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6), and several pollutants (NOx, VOCs, CO, SO2, and BC/OC[2]). The model runs annually up to 2100 and is calibrated to 2005 statistics (base year), and the model's dynamics are driven by total factor productivity which is endogenously calculated to replicate exogenous GDP projections. Demographics and labour market projections are based on exogenous projections (SSPs, UN). The model includes 3 main factors of production: labour, capital and land. Land is further subdivided into 16 land-use categories, while the model keeps track of capital vintages (old and new capital), and labour is further disaggregated in two skills (skilled and unskilled). The model features no unemployment.

Households' and firms' decisions, regarding consumption and production, are driven by optimality conditions that stem from utility and profit maximization, while their foresight of agents is assumed to be myopic. Household's utility is formulated as a Linear Expenditure System (LES), while the production function of firms (for most sectors) features a nested Constant Elasticity of Substitution (CES) scheme. Energy-related sectors are broadly classified in 3 categories: i) extraction sectors (coal, oil, natural gas), ii) transformation sectors (refineries, coal and biomass transformation, electricity, and coal gas) and iii) biofuel sectors. For extraction activities, costs are determined by resource constraints, while for transformation activities energy inputs are determined by fixed coefficients (Leontief production function). With respect to electricity supply, alternative technologies enter the power mix depending on their production costs. The power generation mix is determined by a logit function. According to Fujimori et al. (2017)biofuels can be "supplied from first- and second-generation technologies. The former is made from cereals, sugars, and vegetable oils, which can easily be extracted using conventional technology. The latter is made from lignocellulosic biomass or woody crops and agricultural residues or waste, which makes it harder to extract the required fuel under current technology." The AIM/CGE model "assumes that the biomass supply is nested by logit function and there are three nodes, namely, first generation biofuels, second-generation biofuel from energy purpose-grown crops (e.g., switch grass), and wastes (crop residue or wood residue) (Fujimori et al. 2017)."

With respect to agricultural activities, "producers are assumed to maximize profits subject to [...] technology (production functions) and prices of inputs" (NIES 2020). The land input is assumed multiplying a coefficient to output. The main technologies related to improving land efficiency are fertilizer inputs, advanced cultivar, optimizing planting date, and irrigation. When we consider the climate change impact, the constraints caused by climate change are water and temperature. These conditions can be partly controlled by the latter three technologies. A

[2] Black Carbon and Organic Carbon

function whereby land is an input to produce crops and livestock products, and landowners change its use in accordance with the prices of producer goods on cropland, pastureland, and forest (NIES 2020). Finally, for trade the model adopts the Armington assumption, reflecting imperfect substitutability of commodities and assumes that real investments remain fixed (savings equal investments closure). Detailed description of the model can be found in Fujimori et al. (2017).

Table 6: AIM model

Feature	Characteristics
Regional Coverage	Global, 17 countries / regions focused on Asia
Sectoral Coverage	45, focus on agriculture and energy, energy intensive sectors
Time / Dynamics	Static or Recursive dynamic. Base year:2005, time steps: Annual, horizon: 2100
Distinctive Features	Detailed Energy and GHG emissions representation, biomass endogenous supply
Carbon Leakage	The model can capture the industry channel and partial the energy channel as there is no explicit representation of oil and gas reserves and pricing. Standard version has an aggregated representation of sectors vulnerable to carbon leakage.

Own compilation.

4.2 CGEBox

To ensure accurate representation, the following text describing the CGEbox model is taken from Universität Bonn (2024):

"CGEBox provides a flexible, extendable and modular code basis for CGE modelling in GAMS drawing on the GTAP data base, combined with a powerful user interface based on GGIG (GAMS Graphical User Interface Generator). Its core draws on the GTAP Standard model version 7 in GAMS by Britz & van der Mensbrugghe (2018). Like most global, multi-regional CGE models, this default model layout assumes perfect markets for product and factors, suppliers and demanders without market power, cost-minimizing firms and utility maximizing consumers. A representative household owns the primary factors, which are allocated to firms such as to maximize revenues. International trade is depicted by the Armington assumption such that each region produces a specific quality of a product. Specific to the GTAP Standard model is the so-called global bank, which distributes global savings such as to maximize expected returns to changes in the capital stock. This mechanism allows for endogenous changes in the balance of trade in simulations. Some of these assumptions, such as no market power, can be relaxed in specific modules of CGEbox. This also for the so-called regional household approach where all income is collected by a virtual agent in each region and distributed to government and private consumption as well as savings such as to maximize a social welfare function.

The code of CGEBox and its user interface is open source and can be downloaded from the internet (for details, see Documentation section). As the model draws on the GTAP Data Base, an appropriate GTAP license is required or older, by now for-free versions of this data base can be used. The system aims at complex applications, including solving very large models, but its user interface and options to visualize and analyze results in tables, maps and graphs render it also useful for classroom use.

The model can be extended in a modular fashion where most modules are compatible with each other. The following basic choices are available:

- A recursive-dynamic version G-RDEM by Roberto Roson and Wolfgang Britz, instead of the standard comparative-static set-up.
- Non-diagonal make matrices where one sector can produce several outputs or one output can be produced by several sectors, with matching CET/CES nests.
- Support for flexible nestings[3] in the production function, for factor supply and for CES-subnests under final demand, based on set-definitions in GAMS. Does not require additional coding of equations and variables.
- Choice between CDE, CD, LES and MAIDADS as functional forms in final demand. The MAIDADS system is econometrically estimated to capture structural changes in demand under larger income changes, relevant for G-RDEM (see below).
- A single region model with fixed import prices and FOB prices driving bi-lateral export demand
- Partial equilibrium set-up where only one or some commodity markets clear and the remaining cross-prices and input demands are fixed and accounts are not closed.

Besides this basic flexibility, modules can be added as discussed below.

A pre-solve algorithm, careful scaling of the model's equations and substituting out linear relationships ensure that even the model in the full resolution of the GTAP 10 data base (e.g. 65 sectors and 141 regions) solves in a reasonable time under larger shocks. On demand, the model can be solved as a Mixed Complementarity problem (MCP[4]) to capture production and tariff quotas. The code supports the GTAP7, GTAP8, GTAP9 and GTAP10 data bases, including the land use data linked to Agri-Ecological Zoning (AEZ) dis-aggregation and the GTAP9 version covering water as a primary factor in crop production as well as the CO2, Non-CO2, air emissions and energy use in oil equivalent data bases, as well as the GTAP-Power Data Base and the Global Migration model (GMig) extension.

The data driver allows to dis-aggregate the global Social Accounting Matrix (SAM) to more sector and commodity detail based on user supplied split factors. The FABIO MRIO can be used to automatically generate split factors to increase the agri-food detail of the global SAM."

Table 7: CGEBox model

Feature	Characteristics
Regional Coverage	All GTAP countries (depending on the version this reaches up to 141)
Sectoral Coverage	All GTAP sectors (depending on the version this reaches up to 65)
Time / Dynamics	Static / Linearised
Distinctive Features	Modular can incorporate many modules including agriculture, energy, regional NUTS2, imperfect competition in international trade

[3] CGE models have different nesting schemes per economic activity according to the substitution possibilities of the production factors (e.g. in refineries the crude oil input lies in the first nesting level and is complementary with all other production factors).

[4] Complementarity problems are systems of equations that incorporate a mixture of equations and inequalities where associated variables are complementary to the system e.g. the Supply > Demand inequality holds as equality and the associated variable which is the price is non negative or holds as inequality and price is zero. The interested reader can access https://www.recs-solver.org/MCP.html for more information.

Feature	Characteristics
Carbon Leakage	Sufficient Sectoral and Regional detail. Better suited for industry channel leakage. Not elaborated energy system hence emissions intensities may vary from real statistics.

Source: Own compilation

4.3 EMPAX-CGE

The EMPAX-CGE (Economic Model for Environmental Policy Analysis – Computable General Equilibrium) is a multi-sectorial CGE model developed to assess the macroeconomic impact of environmental policies for the US. The model has two static and one dynamic version with different spatial and sectorial coverage. The static model has a national and a regional version while the dynamic model has only regional scope. The standard regional static version of the model includes 81 sectors, producing 82 commodities (6 energy commodities) and 10 regions, while the standard national version includes 385 commodities produced by 384 activities. Finally, the typical dynamic version includes 35 sectors (6 energy) and 5 regions. All versions share the same database. Energy consumption data and forecasts are drawn from U.S. Energy Information Agency's (EIA) Annual Energy Outlook. The version of EMPAX-CGE described hereafter is the dynamic one.

The dynamic model runs up to 2050, with 5-year steps, is calibrated to 2005 and replicates EIA forecasts. The model embodies the following drivers of economic growth: energy efficiency, changes in labour supply and productivity, increase of natural resources and capital accumulation. The model's dynamics are inter-temporal; households maximize their utility choosing the optimal levels of aggregate consumption, savings, and leisure (or labour supply) under perfect foresight. Hence, future policies are foreseen by agents, and behavioural adjustments take place earlier. In terms of energy demand, households consume energy for private transport and for other purposes (e.g., heating and cooking). Transportation is distinguished from other consumption categories (consumer goods bundle in the model) and is further disaggregated into purchased transport (public transport means) and private transport (private transport means). If households decide not to use public transportation modes, they must buy the necessary equipment (and services) and fuels (petroleum products) for the use of transport means. The model can include up to four income classes of households per region (multiple households feature).

Firms maximize their profits under technology constraints. The technology of production is described by a nested CES function, based on Capital-Labour-Energy-Material (KLEM) separability scheme. In this way, the model can capture fuel switch and energy efficiency changes as the increase in energy prices triggers substitution of energy with KL bundle. Three factors of production can be employed by firms, namely, capital, labour, and land/natural resources. Land is linked to agricultural production and is coupled with the use of materials in the nesting scheme (a limited substitutability between the two bundles is assumed). Natural resources are linked to fossil fuels sectors, and their supply is built around the forecasted production provided by the Annual Energy Outlook, adjusted (using a supply elasticity) to reflect changes associated to the depletion/discovery of reserves. Refineries produce 3 distinct commodities (distillate fuels, motor gasoline, other petroleum), while the electricity generation is disaggregated into fossil fuel-based generation and RES/nuclear generation. The elasticity of substitution between the two aggregate sources of electricity generation is infinite while the share of RES and nuclear is fixed to EIA's Annual energy outlook. Total investments are determined by the existing capital stock, net investment demand, and the speed of adjustment factor, following Uzawa (1969).

With respect to trade, the model follows the Armington specification: Agents consume a composite good that is made up of imported and domestically produced commodities which are perceived by the consumers as imperfect substitutes (as postulated by Armington). The model assumes an extra node in the CES, as goods originated from the U.S. are aggregate into a single bundle; goods originating from U.S. regions are perfect substitutes reflecting that consumers have no preference over the regional origin of goods produced within the country borders.

Table 8: EMPAX model

Feature	Characteristics
Regional Coverage	National, Default version 5 regions
Sectoral Coverage	385 sectors in national version,35 sectors in global version
Time / Dynamics	Inter-Temporal, 2050, 5 years time step
Distinctive Features	Labour Migration and Remittances
Carbon Leakage	No

Own compilation.

4.4 ENV-Linkages

The OECD ENV-Linkages is a multi-sectorial, multi-regional, recursive-dynamic Computable General Equilibrium (CGE) with global coverage, that describes how economic activities are inter-linked across several macroeconomic sectors and regions. The model relates economic activity to environmental pressure, more specifically to emissions of greenhouse gases (GHGs). Emissions data are drawn from the GTAP database. The model includes 22 sectors of activity and 7 power generation technologies, for 29 regions. The model runs up to 2050.

The model assumes a representative firm that minimizes production costs under constant returns to scale. The production function is described by a nested-CES scheme. The top nest distinguished between an aggregate bundle that includes all production inputs on the one hand and an aggregate bundle including non-CO2 emissions associated to the firm's output. Demand for intermediate inputs is coupled with an aggregate KSFLE bundle (Capital-Specific Factor-Energy); furthermore, the use of intermediate inputs is further disaggregated into domestically produced goods and imported goods which are further distinguished by country of origin. In that sense the model adopts the Armington assumption for bilateral trade. The KLE bundle is disaggregated into demand for labour and KSFE (Capital-Specific Factor-Energy). This specification allows to model the adoption of more efficient production technologies that are more capital and less energy intensive. The model also includes capital vintages, linking vintages with intersectoral mobility and substitutability frontiers between capital and energy inputs. "new" capital is assumed to be mobile between sectors and has higher substitutability with energy inputs while "old" capital has lower intersectoral use. "Capital accumulation is modelled as in traditional Solow/Swan neo-classical growth model" (Château et al. 2014). Most sectoral production processes are described by the above-described nesting scheme except for agricultural production. The nesting scheme is adjusted allowing the model to introduce the concept of intensive or extensive production. Hence, land is coupled with the use of fertilizers for crops and with feed for livestock production.

With respect to household's, the model assumes a representative agent who maximizes utility choosing the optimal consumption-savings mix. Savings are considered as a standard good and the maximization behaviour is described by an "Extended Linear Expenditure System" (ELES).

"The government in each region collects various kinds of taxes in order to finance a given sequence of government expenditures. Further, given a sequence of public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income" (Château et al. 2014). They dynamics of the model are driven by capital accumulation and putty/semi-putty technology specification (OECD 2014).

Table 9: ENV-Linkages model

Feature	Characteristics
Regional Coverage	29 regions
Sectoral Coverage	22 economic activities and 7 power generation technologies
Time / Dynamics	2050, Recursive Dynamic
Distinctive Features	Sector Specific Capital, Capital Vintages, Extended Linear Expenditure System
Carbon Leakage	Sufficient regional, sectoral coverage and energy system representation.

Own compilation.

4.5 ENVISAGE

The ENVISAGE model shares the same core code with the OECD ENV-Linkages model but has some additional features. To ensure accurate representation, the following text describing the ENVISAGE model is taken from van der Mensbrugghe (2017):

"[It] is a recursive dynamic and global computable general equilibrium model. Dynamics involve three elements: i) Labour supply (by skill level) grows at an exogenously determined rate, ii) The aggregate capital supply evolves according to the standard stock/flow motion equation, i.e. the capital stock at the beginning of each period is equal to the previous period's capital stock, less depreciation, plus the previous period's level of investment, iii) Technological change. The standard version of the model assumes labor augmenting technical change—calibrated to given assumptions about GDP growth and inter-sectoral productivity differences. In policy simulations, technology is typically assumed to be fixed at the calibrated levels" (van der Mensbrugghe 2017).

"Production is implemented as a series of nested constant-elasticity-of-substitution (CES) functions the aim of which is to capture the substitutability of all inputs. Three production archetypes are implemented. The first is for crops that reflects intensification of inputs versus land extensification. The second is for livestock that reflects range-fed versus ranch-fed production. The final, also referred to as the default, revolves largely around capital/labour substitutability. Some production activities highlight specific inputs (for example agricultural chemicals in crops and feed in livestock) and all activities include energy and its components as part of the cost minimization paradigm. Production is also identified by vintage—divided into Old and New—with typically lower substitution possibilities associated with Old capital. Each production activity is allowed to produce more than one commodity—for example the ethanol sector can produce ethanol and distiller's dried grains with solubles (DDGS). And commodities can be formed by the output of one or more activities (for example electricity). Envisage therefore uses a different classification of activities and commodities. One of the features of the model is that it integrates the new GTAP power data base that disaggregates GTAP's electricity sector into 11 different power sources plus electricity transmission and distribution. Though the database has both the supply and demand side for all 11 power sources, the aggregation facility permits the aggregation of electricity demand into a single commodity and the 'make' matrix specification combines the output from the different power activities into a single electricity commodity.

The model incorporates multiple utility functions for determining household demand. There is a set of three household demand functions linked to the ubiquitous linear expenditure system (LES): the standard LES, the extended LES (ELES) that incorporates household saving into the utility function, and 'an implicitly directly additive demand system' (AIDADS), that allows for non-linear Engel curves in the LES framework. The fourth option uses the constant differences in elasticity (CDE) utility function that is used in the core GTAP model (Hertel 1997). The ELES incorporates the decision to save in a top-level utility function. The other demand systems assume savings is an exogenous proportion of disposable income. The consumer utility function determines consumer demand bundles that are subsequently converted to produced goods using a consumer demand 'make' or transition matrix. Investment is savings driven and equal to domestic saving adjusted by net capital flows.

Trade is modeled using the so-called Armington specification that posits that demand for goods are differentiated by region of origin. The model allows for domestic/import sourcing at the aggregate level (after aggregating domestic absorption across all agents), or at the agent-level. A second Armington nest allocates aggregate import demand across all exporting regions. Irrespective of the specification of the top level sourcing between domestic goods and the aggregate import bundle, the second level Armington nest is done at the aggregate level, i.e. it is not agent specific. Exports are modeled in an analogous fashion using a nested constant-elasticity-of-transformation (CET) specification. The domestic supply of each commodity is supplied to the domestic market and an aggregate export bundle using a top-level CET function. The latter is allocated across regions of destination using a second-level CET function. Each bilateral trade node is associated with four prices: 1) the producer price; 2) the export border price, also referred to as the free-on-board (FOB) price; 3) the import border price, also referred to as the cost, insurance and freight (CIF) price; and 4) the end-user price that includes all applicable trade taxes. The wedge between the producer price and the FOB price is represented by the export tax (or subsidy if negative) and the wedge between the CIF and end-user prices represents the import tariff (and perhaps other import related distortions). The wedge between the CIF and FOB prices represents the international trade and transport margins. These margins represent the use of real resources that are supplied by each region. The global international trade and transport sector purchases these services from each region so as to minimize the aggregate cost" (van der Mensbrugghe 2017).

Table 10: ENVISAGE model

Feature	Characteristics
Regional Coverage	All GTAP countries (depending on the version this reaches up to 141)
Sectoral Coverage	All GTAP sectors (depending on the version this reaches up to 65)
Time / Dynamics	2050, Recursive dynamic or static
Distinctive Features	Multiple LES based utility functions, one activity can produce many products, capital vintages, knowledge stock driving productivity
Carbon Leakage	Same as ENV-Linkages

Own compilation.

4.6 G-CUBED

To ensure accurate representation, the following text describing the G-CUBED model is taken from McKibbin Software Group (2022) and McKibbin & Wilcoxen (2013):

"The G-Cubed model was developed by Warwick McKibbin and Peter Wilcoxen (McKibbin Software Group 2022). The model has been constructed to contribute to the current policy debate on environmental policy and international trade with a focus on global warming policies, but it has many features that will make it useful for answering a range of issues in environmental regulation, microeconomic and macroeconomic policy questions. It is a world model with substantial regional disaggregation and sectoral detail. In addition, countries and regions are linked both temporally and intertemporally through trade and financial markets. G-Cubed contains a strong foundation for analysis of both short run macroeconomic policy analysis as well as long run growth consideration of alternative macroeconomic policies. Intertemporal budget constraints on households, governments and nations (the latter through accumulations of foreign debt) are imposed. To accommodate these constraints, forward looking behavior is incorporated in consumption and investment decisions. G-Cubed also contains substantial sectoral detail. This permits analysis of environmental policies which tend to have their largest effects on small segments of the economy. By integrating sectoral detail with the macroeconomic features of the MSG2 model, G-Cubed can be used to consider the long run costs of alternative environmental regulations yet at the same time consider the macroeconomic implications of these policies over time. The response of monetary and fiscal authorities in different countries can have important effects in the short to medium run which, given the long lags in physical capital and other asset accumulation, can be a substantial period of time.

Overall, the model is designed to provide a bridge between computable general equilibrium models and macroeconomic models by integrating the more desirable features of both approaches" (McKibbin Software Group 2022).

"The cost of this versatility is that G-Cubed is a fairly large model. It has over 10000 equations holding in each year, is typically solved annually for 100 years in each simulation and has over 100 intertemporal costate variables" (McKibbin & Wilcoxen 2013). "Unlike many general equilibrium models, however, G-Cubed draws on macroeconomic theory by representing saving and investment as the result of" (McKibbin & Wilcoxen 2013) forward-looking intertemporal optimization. Firms choose investment to maximize the stock market value of their equity. "Production is broken down into n industries and each is represented by an econometrically estimated cost function. […] We assume that each of the 12 sectors can be represented by a price-taking firm, which chooses variable inputs and its level of investment in order to maximize its stock market value. Each firm's production technology is represented by a tier-structured constant elasticity of substitution (CES) function" (McKibbin & Wilcoxen 2013).

"Households maximize an intertemporal utility function subject to a lifetime budget constraint, which determines the level of saving. […] Households have three distinct activities in the model: they supply labor, they save, and they consume goods and services" (McKibbin & Wilcoxen 2013). "The model allows for short-run wage rigidity (varying in degree across countries) and therefore allows for significant periods of unemployment depending on the labor market institutions in each country. […] We assume that labor is perfectly mobile among sectors within each region but is immobile between regions. Thus, wages will be equal across sectors within each region, but will generally not be equal between regions. In the long run, labor supply is completely inelastic and is determined by the exogenous rate of population growth. Long-run wages adjust to move each region to full employment. In the short run, nominal wages are assumed to adjust slowly according to an overlapping contracts model where wages are set based on current and expected inflation and on labor demand relative to labor supply. This can lead to short-run unemployment if unexpected shocks cause the real wage to be too high to clear the labor market. At the same time, employment can temporarily exceed its long-run level if unexpected events cause the real wage to be below its long run equilibrium" (McKibbin & Wilcoxen 2013).

Table 11: G-CUBED model

Feature	Characteristics
Regional Coverage	11 regions
Sectoral Coverage	20
Time / Dynamics	Intertemporal
Distinctive Features	Empirical estimated investment function, financial sector, assessment of impacts on financing variables, short term disequilibrium
Carbon Leakage	Specific sectoral and regional coverage may not cover all configurations to examine carbon leakage.

Own compilation.

4.7 Summary of the main CGE models features

From the review of these CGE models, one can derive a core list of common modelling approaches and a number of extensions to the standard approaches. A key difference in the choice of modular building is that for some models a number of extensions are available but are not active in the core version of the model. Models are also differentiated according to agents expectations (myopic versus full foresight), the representation of dynamics (drivers for investment, semi-endogenous technical progress versus exogenous), the trade representation (imperfect substitutes of imports and domestically produced goods versus firms heterogeneity), the households decision process and detail (single versus multiple households), the clearing of labour market (flexible wages – full employment versus rigid wages – unemployment) and the capital market representation (explicit representation of financial assess, foreign direct investments etc.). Below we summarise the key shared modelling features as well as the distinctive features / extensions.

Production - Firms

Most of the models assume perfect competition and a nested CES production function. The key extensions in the representation of firms considered were: i) Imperfect Competition, ii) Product Differentiation, iii) Econometric estimation of cost functions, and iv) Circular economy modelling.

Table 12: Production key model features

Model Name	Key Features
AIM	Perfect Competition, Nested CES
CGEBox	Nested CES – Option for Imperfect Competition
EMPAX-CGE	Perfect Competition, Nested CES
ENV-Linkages	Perfect Competition, Nested CES

Model Name	Key Features
ENVISAGE	Perfect Competition, Nested CES, each production activity is allowed to produce more than one commodity
FTAP Model	Nested CES
G-Cubed	Perfect Competition, Nested CES, Econometrically estimated cost function.
GEM-E3	Perfect Competition, Nested CES
GTAP-E	Perfect Competition, Nested CES
EPPA	Perfect Competition, Nested CES
MAGNET	Nested CES, Endogenous Land Supply, Circularity module
Mirage	Perfect Competition, Nested CES

Own compilation.

Consumption – Households

The majority of the models reviewed represent a single household that is maximising a LES utility function (see e.g. Stone 1954). In a LES total expenditure is first allocated to subsistence and then to supernumerary requirements. The key extensions in the representation of households as undertaken in some models were: i) Elaborated functional forms beyond LES as ELES, ii) Multiple households (i.e. assumed household heterogeneity and associated differentiated production functions).

Table 13: Consumption key model features

Model Name	Key Features
AIM	LES
CGEBox	LES, AIDSADS
EMPAX-CGE	CES
ENV-Linkages	ELES
ENVISAGE	Multiple utility functions, LES, ELES, AIDSADS, CDE
FTAP Model	LES
G-Cubed	CES
GEM-E3	LES, Multiple Households, Non-Durable and Durable Goods, consumption purposes according to statistical COICOP classification, Consumption Matrix, which links consumption purposes and industries
GTAP-E	CDE
EPPA	CES
MAGNET	CDE, Multiple Households
Mirage	CES
ORANI-G	LES

Own compilation.

Trade

The majority of the models reviewed represent trade using the Armington assumption. The key extensions in the representation of trade were: i) Firms heterogeneity using the Melitz approach, ii) Detailed origin-destination flows and tariffs.

Table 14: Trade key model features

Model Name	Key Features
AIM	Armington
CGEBox	Armington, Firms heterogeneity
EMPAX-CGE	Armington
ENV-Linkages	Armington
ENVISAGE	Armington
FTAP Model	Armington
G-Cubed	Armington
GEM-E3	Armington
GTAP-E	Armington, Firms heterogeneity
EPPA	Armington
MAGNET	Armington, Firms heterogeneity
Mirage	Detailed representation of trade barriers (quotas, explicit representation of Free Trade Agreements and regionals single markets).
ORANI-G	Armington

Own compilation.

Capital Market – Financial Market

The majority of the models reviewed represent a fully malleable capital and assume perfect (costless/frictionless) capital mobility across firms. The key extensions of the capital market are: i) explicit representation of FDI, ii) differentiated risk premium per activity, iii) explicit modelling of financial assets and alternative macro-economic closures, iv) capital vintages.

Table 15: Financial market key model features

Model Name	Key Features
AIM	Full mobility at the National level
CGEBox	Full mobility at the National level
EMPAX-CGE	Full mobility - National; Global BANK
ENV-Linkages	Capital Vintages (Putty – Semi Putty, Putty – Clay)
ENVISAGE	Full mobility - National
FTAP Model	FDI, International Mobility, Differentiated risk premium by country
G-Cubed	Explicit modeling of money and other financial assets, Capital flows take the form of portfolio investment

Model Name	Key Features
GEM-E3	Explicit modelling of financial Sectors, Different options for capital mobility
GTAP-E	Full mobility - National
EPPA	Full mobility – National, Vintages
MAGNET	Full mobility - National
Mirage	Installed capital is assumed to be immobile (putty-clay) – gradual adjustment of capital stock
ORANI-G	Full mobility - National

Own compilation.

Labour Market

Most of the models considered assume full employment and full labour mobility across sectors. The key extensions in the labour market are: i) Representation of involuntary unemployment, ii) Gradual adjustment of wage and clearing of the labour market, iii) Multiple occupations, iv) Endogenous supply of labour, v) labour migration and remittances.

Table 16: Labour market key model features

Model Name	Key Features
AIM	Full Employment
CGEBox	Full Employment, labour migration between countries and remittances of workers
EMPAX-CGE	Full Employment
ENV-Linkages	Full Employment
ENVISAGE	Full Employment
FTAP Model	Full Employment
G-Cubed	The model allows for short-run wage rigidity (varying in degree across countries) and therefore allows for significant periods of unemployment depending on the labor market institutions in each country.
GEM-E3	Unemployment through labour supply curve – by skill, full labour mobility
GTAP-E	Full Employment
EPPA	Full Employment
MAGNET	Full Employment
Mirage	Full Employment,
ORANI-G	Full Employment

Own compilation.

Investment

For the recursive-dynamic or inter-temporal models the investment decision is a critical factor affecting the dynamic properties of the models. Many models follow a savings-led approach where agents decide on the optimum amount of savings and then investments follow. The allocation of aggregate investments across firms is made either through fixed coefficients or through endogenous mechanisms based on Tobins Q theory. The table below shows the key features regarding investment decision in each model.

Table 17: Investment key model features

Model Name	Key Features
AIM	Static
CGEBox	Different options: i) Net new investment is allocated across regions using the same proportions as in the baseline, ii) fixed capital account, iii) fixed ratio of net capital flows with respect to regional income
EMPAX-CGE	Forward-looking, full intertemporal optimization approach in which households have perfect foresight and maximize the present value of all future consumption.
ENV-Linkages	In each period, the model equates investment to saving (which is equal to the sum of saving by households, the net budget position of the government and foreign capital flows). Hence, given exogenous sequences for government and foreign savings, this implies that investment is ultimately driven by household savings.
ENVISAGE	Investment is savings driven. Household and government savings were discussed above. Foreign savings, in the default closure are fixed. Thus investment is largely influenced through household savings
FTAP Model	Aggregate investment can be determined by one of two user configurable mechanisms. First, global net saving can be allocated between regions in fixed shares. Second, elasticities of future expected rates of return with respect to future capital stocks can be postulated, and in each region determined so as to equalise the future expected rates of return.
G-Cubed	Households maximize an intertemporal utility function subject to a lifetime budget constraint, which determines the level of saving, and firms choose investment to maximize the stock market value of their equity
GEM-E3	Endogenous interest rate drives investment and savings. Allocation among industries is made using Tobins Q
GTAP-E	Static
EPPA	Household decides endogenously on savings that determine the level of investments. Allocation among activities is based on the coefficients derived by the GTAP dataset regarding the investments demand by sector.
MAGNET	Static
Mirage	Installed capital is assumed to be immobile. This confers investment an important role, as the only adjustment device for capital stock. This putty-clay hypothesis is important, because it implies, along with the investment specification that capital stock adjusts gradually
ORANI-G	Static

Own compilation.

5 Factsheets for selected models

In this section, we contrast the two models used in the "central" modelling report of this project (see report "Climate Protection Scenarios until 2050: Considering CO_2 price differences and carbon leakage") **with six selected other models** that we see as possible alternatives for corresponding model simulations of carbon leakage and measures to address it, such as a CBAM. This is done in the following six factsheets. Three of the models listed are other macroeconometric or CGE models. One other model listed – JRC-GEM-E3 – is an adapted version of GEM-E3, as adjusted and applied by the Joint Research Center (JRC) of the European Commission. The last presented model -PRIMES – is an energy system model focusing on the EU, which is not in itself suitable for addressing carbon leakage effects and policies counteracting it. We describe it here because it can, in principle, be coupled with some of the models described here with the goal of enhancing the sectoral, and energy use and technology detail.

It must be taken into account that the actively used models can change over time when new databases are published or the models are used for new research questions. The information stated here is therefore a snapshot. The model characteristics we apply in our factsheets are partly based on the publication by Tänzler et al. (2018), in which similar factsheets have been created for most of the models.

Table 18: GEM-E3 model overview

Model	GEM-E3 General Equilibrium Model for Energy Economy and Environment
Author	E3-Modelling
Type	CGE, market imperfections, recursive dynamic
Temporal dimension	Timeframe covering 2014-2100 on five-year time steps
Solution	Optimisation. It is an empirical, large-scale model, written entirely in structural form. The model computes the equilibrium prices of goods, services, labour and capital that simultaneously clear all markets under the Walras law. Therefore, the model follows a computable general equilibrium approach.
Base year	2014
Main purpose/objective	GEM-E3 is a global applied general equilibrium model with a particular focus on the European Union member states taken individually or as a whole and provides details on the macro-economy and its interaction with the environment and the energy system. The aim of GEM-E3 in supporting policy analysis, is the consistent evaluation of distributional effects, across countries, economic sectors and agents. The burden sharing aspects of policy, such as for example energy supply and environmental protection constraints are fully analysed.
Exogenous variables	Population, active population, labour productivity (semi-endogenous), total factor productivity (semi-endogenous), autonomous energy efficiency improvements
Sectors	67 product/industries;
EITE / CBAM sectors covered	Pulp, paper and printing, Chemicals; Basic metals (primarily: ferrous metals); Non-ferrous metals, Non-metallic minerals (possibly also: other energy intensive sectors).
Regions	Global: 46 regions, including all G20 and EU Member States explicitly, plus a set of regions
Emissions	CO2, CH4, N2O, HFCs, PFCs, SF6; from fossil fuel combustion and processes;

Model	GEM-E3 General Equilibrium Model for Energy Economy and Environment
Main databases	GTAP, EUROSTAT, IEA, ILO, UNFCCC
Link to full model documentation	https://e3modelling.com/modelling-tools/gem-e3/
Link to recent CL or CBAM application	https://afep.com/en/publications-en/trade-climate-friends-or-foes-making-the-case-for-cbam-and-green-trade-rules/

Source: E3Modelling

For the EU Impact Assessment in 2021 for establishing a carbon border adjustment mechanism (EC 2021) the GEM-E3 model has been improved to model aluminium, fertilisers, cement and iron and steel separately. This means that data on cost and use shares for these subsectors had to be taken from EXIOBASE and adjusted, so that a consistent global database, which details the subsectors as other sectors in GTAP was set up.

Table 19: JRC-GEM-E3 model (as applied in the Impact Assessment to the European Commission's CBAM proposal – EC (2021))

Model	JRC-GEM-E3 General Equilibrium Model for Energy Economy and Environment
Author	Capros et al. (2013); adjusted for sectoral detail by JRC (EC (2021)
Type	CGE, market imperfections, recursive dynamic
Time horizon of the model / Temporal dimension	Timeframe covering 2014-2100 on five-year time steps
Solution	Optimisation. It is an empirical, large-scale model, written entirely in structural form. The model computes the equilibrium prices of goods, services, labour and capital that simultaneously clear all markets under the Walras law. Therefore, the model follows a computable general equilibrium approach.
Base year	2014
Main purpose/objective	GEM-E3 is a recursive dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment. It is especially designed to evaluate energy, climate and environmental policies. GEM-E3 can evaluate consistently the distributional and macro-economic effects of policies for the various economic sectors and agents across the countries.
Exogenous variables	Population, active population, Labour productivity (semi-endogenous), Total factor productivity (semi-endogenous), Autonomous energy efficiency improvements
Sectors	31 product/industries; explicitly modelling aluminium (separating it from the other non-ferrous metals, fertilisers (separate from the other chemicals), cement (separate from the other non-metallic minerals) and iron and steel based on EXIOBASE cost and trade shares
EITE / CBAM sectors covered	See CBAM application below
Regions	Global: 40 all EU Member States and UK explicitly, plus 12 additional countries and regions
Emissions	CO2, CH4, N2O, HFCs, PFCs, SF6; from fossil fuel combustion and processes;
Main databases	GTAP, EUROSTAT, IEA, ILO, UNFCCC, EXIOBASE

Model	JRC-GEM-E3 General Equilibrium Model for Energy Economy and Environment
Link to full model documentation	https://ec.europa.eu/jrc/en/gem-e3/model
Link to recent CL or CBAM application	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021SC0643

Source: own compilation based on information in EC (2021)

Table 20: GINFORS-E model overview

Model	GINFORS-E
Author	GWS
Type	Macroeconometric, demand-driven flows in input-output tables, non-equilibrium model (markets do not necessarily clear),
Time horizon of the model / Temporal dimension	Timeframe covering 1990-2050 on an annual basis
Solution	Recursive dynamic (myopic), simulation (no optimization)
Base year	(1990-) 2015
Main purpose/objective	GINFORS-E is a global model with country and sector detail for 64 countries and one rest of world region mainly based on OECD and IEA data. It is designed for assessments of economic, energy, climate and environmental policies up to the year 2050. The model be used to analyse the macroeconomic effects of a variety of price changes and policies in individual countries in the global context. See central report
Exogenous variables	Population, autonomous energy efficiency improvements, tax rates, international energy prices
Sectors	36 (OECD IO)
EITE / CBAM sectors covered	Basic metals, chemical, non-metallic minerals, energy (electricity)
Regions	Global: 64 countries and 1 region rest of world, including all G20 and EU Member States explicitly (based on OECD Input-Output tables)
Emissions	CO2, CH4, N2O, from fossil fuel combustion and processes;
Main databases	- OECD's Input-Output and STAN database, UN, World Bank, IMF, ILO and national statistics - Bilateral trade: OECD - Energy fuel use and energy efficiency technology development: IEA energy balances and IEA Energy Technology Perspectives - Energy price data: IEA Energy statistics by country and fuel Emissions: IEA CO2 emissions from fuel combustion; EDGAR for other emissions
Link to full model documentation & EU Modelling Inventory (MIDAS)	https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-ginfors-e
Link to recent CL or CBAM application	Lutz et al. (2024a)

Source: GWS

Table 21: E3ME model overview

Model	Energy-Environment-Economy Macro Econometric Model (E3ME)
Author	Cambridge Econometrics
Type	Macroeconometric, Demand-driven flows in input-output tables, non-equilibrium model (markets do not necessarily clear),
Time horizon of the model / Temporal dimension	Timeframe covering 1970-2050 on an annual basis
Solution	Recursive dynamic (myopic), simulation (no optimization)
Base year	(1970-) 2014
Main purpose/objective	Macroeconomic modelling enabled several variations of an EU CBAM to be tested against a baseline case in which the EU achieves its emissions reduction targets without implementing a CBAM.
Exogenous variables	Population, Labour productivity, Total factor productivity, Autonomous energy efficiency improvements
Sectors	EU: 69 product/industries; defined in terms of NACE Rev.2 (with separate aviation) Other countries: 43 product/industry classifications, defined in terms of the NACE Rev1.1 (with separate aviation)
EITE / CBAM sectors covered	Basic metals, other chemicals (fertilizers, inorganic chemicals), non-metallic minerals, electricity
Regions	Global: 71 global regions, including all G20 and EU Member States explicitly, plus a set of regions
Emissions	CO2, CH4, N2O, HFCs, PFCs, SF6; from fossil fuel combustion and processes; only CO2 reported per sector, others reported by region
Main databases	- Accounting balances for commodities from input-output tables and for institutional incomes and expenditures from the national ac-counts: Eurostat, AMECO, Asian Development Bank, OECD's STAN database, UN, OECD, World Bank, IMF, ILO and national statistics - Bilateral trade: Comtrade (for manufacturing), OECD (services), national statistics - Energy fuel use and energy efficiency technology development: IEA energy balances and IEA Energy Technology Perspectives for FTT:Power - Energy price data: IEA Energy statistics by country and fuel
Link to full model documentation & EU Modelling Inventory (MIDAS)	https://www.e3me.com/wp-content/uploads/sites/3/2019/09/E3ME-Technical-Manual-v6.1-onlineSML.pdf https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-e3me
Link to recent CL or CBAM application	https://www.cisl.cam.ac.uk/resources/publications/eu-cbam-and-its-place-world-trade from autumn 2021

Source: based on Tänzler et al. (2018), pp. 170-171.

Table 22: GTAP-E model overview

Model	GTAP-E
Author	GTAP
Type	CGE, static
Time horizon of the model / Temporal dimension	Timeframe covering 2014-2050 on five year time steps
Solution	Optimisation
Base year	2007,2011,2014
Main purpose/objective	Quantitative analysis of global economic issues within an economy-wide framework.
Exogenous variables	Population, active population, Total factor productivity, Autonomous energy efficiency improvements
Sectors	65 product/industries
EITE / CBAM sectors covered	See CBAM application below
Regions	Global: 145
Emissions	CO2
Main databases	GTAP, IEA
Link to full model documentation	https://www.gtap.agecon.purdue.edu/resources/download/1203.pdf
Link to recent CL or CBAM application	https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=6512

Source: E3Modelling

Table 23: d-PLACE model overview

Model	d-PLACE
Author	Institute of Environmental Protection - National Research Institute (IOS-PIB)
Type	Global, recursive-dynamic computable general equilibrium (CGE) model.
Time horizon of the model / Temporal dimension	Timeframe covering 2014-2050
Solution	Recursive dynamic (myopic), optimization
Base year	2014
Main purpose/objective	Examine the possible scale of the carbon leakage using different assumptions and policy scenarios within the EU
Exogenous variables	Elasticity assumptions based on GEM-E3 model
Sectors/commodities	20 (6 energy and 14 non-energy)
EITE / CBAM sectors covered	Chemical industry, non-metallic minerals, iron and steel, non-ferrous metals, paper-pulp-print, electricity
Regions	Global: 19 regions, 1O EU and 9 non-EU (26 in the CL modelling)
Emissions	CO2, CH4, N2O, HFCs, PFCs, SF6; from fossil fuel combustion and processes;
Main databases	GTAP 10, data for 2014 used for calibration GTAP-E for energy and CO_2 emissions GDP projections from IMF and OECD outlooks
Link to full model documentation	https://www.researchgate.net/publication/359578633_THE_CGE_MODEL_D-PLACE_TECHNICAL_DOCUMENTATION_FOR_THE_MODEL_VERSION_20
Link to recent CL or CBAM application	https://climatecake.ios.edu.pl/wp-content/uploads/2019/07/CAKE_CL_Risk-of-CL_ENG.pdf

Source: GWS

Table 24: PACE model overview

Model	Policy Analysis based on Computable Equilibrium (PACE)
Author	ZEW, Mannheim
Type	Global computable general equilibrium (CGE) model with technology-discrete bottom-up electricity sector representation.
Time horizon of the model / Temporal dimension	Timeframe covering 2011-2030 (2050) in five-year steps
Solution	Optimization, forward-looking rational expectations or myopic
Base year	2011
Main purpose/objective	Analysis of EU climate and energy policy developments and Commission's proposals from 2016 to prepare climate pledges for 2030
Exogenous variables	Elasticity assumptions based on Okagawa & Ban (2008); exogenous technological progress from GTAP
Sectors/commodities	36
EITE / CBAM sectors covered	Fertilizers and other nitrogen compounds; Organic chemicals; Inorganic chemicals; Cement; Brick, tiles and construction products; Glass, Ceramics; Manufacturing of iron and steel; Manufacturing of aluminum;
Regions	Global: 19 regions, 8 EU and 11 non-EU
Emissions	CO_2; from fossil fuel combustion and processes;
Main databases	GTAP 9, data for 2011 used for calibration WIOD emissions US Department of Energy (Energy Information Administration 2013) for non-EU EXIOPOL, EuroStat, and UN for disaggregation of energy-intensive sectors IEA for emissions
Link to full model documentation	https://data.europa.eu/doi/10.2826/830079 Gavard & Voigt (2017)
Link to recent CL or CBAM application	https://data.europa.eu/doi/10.2826/830079 Gavard & Voigt (2017)

Source: based on Tänzler et al. (2018), pp. 180-181.

Table 25: PRIMES model overview

Model	Price-Induced Market Equilibrium System (PRIMES)
Author	E3-Modelling
Type	Energy market equilibrium, optimisation
Time horizon of the model / Temporal dimension	Timeframe covering 2015-2050 on five year time steps
Solution	
Base year	2015
Main purpose/objective	PRIMES provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions for each individual European country and for Europe-wide trade of energy commodities.
Exogenous variables	Macroeconomic figures (could be used from GEM-E3)
Sectors	25 sectors(6 energy, 18 industries, 1 agriculture), 45 energy commodities
EITE / CBAM sectors covered	Electricity
Regions	EU-28, plus 8 EFTA or accession countries
Emissions	CO_2, from fossil fuel combustion and processes;
Main databases	EuroStat, technology databases
Link to full model documentation	https://e3modelling.com/modelling-tools/primes/
Link to recent CL or CBAM application	See EC (2021), soft coupling with JRC-GEM-E3

Source: based on Tänzler et al. (2018, pp. 205–208).

6 International databases and future research options

The central prerequisite for a detailed modelling of carbon leakage and measures to avoid it, such as a CBAM, is the availability of global data sets that distinguish different respective economic sectors. In the following, central data sets are briefly described with regard to current sector differentiation in carbon intensive industries, base year and planned updates and extensions. The data sets are global Multiregional Input-Output (MRIO) databases, that are difficult to be constructed due to the huge amount of data, consistency issues and data constraints. An evaluation from 2014 lists AIIOT, Eora, EXIOBASE, GTAP, OECD ICIO, YNU-GIO, and WIOD (Inomata & Owen 2014). At the end of 2022, more recent versions of EXIOBASE, GTAP, OECD and WIOD are available. Eora has been transformed and renamed into GLORIA. The YNU-GIO database, constructed by Yokohama National University, does not seem to have been updated since 2015. The same applies to the Asian International Input-output tables AIIOT. A newcomer is the FIGARO database, which is published by Eurostat. GTAP, OECD, GLORIA and FIGARO are currently updated regularly. The situation is somewhat unclear for EXIOBASE, and there have been no updates for WIOD since 2016. Databases from public institutions as OECD and Eurostat are available for free. Access to other databases is ruled by licenses and in some cases as GTAP only possible against a license fee.

For improved modelling of carbon leakage effects and possible measures such as CBAM to avoid undesired leakage effects, the availability of consistent data sets is a key prerequisite. To this end, the comparison above shows that sector differentiation is also limited due to the limitation of national input-output tables to the 2-digit level of statistics. Production statistics and foreign trade statistics offer a much deeper product and sector differentiation. However, little is known from official statistics about intermediate input chains in this deep sectoral breakdown. Nevertheless, individual databases differentiate certain sectors more deeply. In most cases, further differentiations are available for individual years on the basis of in-depth analyses. For EXIOBASE, for example, the years 2000 and 2007 were broken down in great detail in two EU projects and the information was then updated on the basis of the 2-digit data. In order to assess the quality of the data, it is helpful to check for which year the detailed analysis was carried out and what the thematic focus was, for example when a database such as GLORIA is commissioned by the International Resource Panel.

With regard to carbon intensive sectors, the OECD, WIOD and FIGARO distinguish paper, chemicals, rubber and plastics, basic metals and electricity as part of the electricity, gas, steam, air conditioning sector. GTAP additionally separates basic metals into iron and steel and non-ferrous metals and reports electricity and steam separately from gas and air conditioning.

Two databases, GLORIA and EXIOBASE, provide detailed sector data for various chemical product groups, metals and non-metallic minerals. A problem with databases such as GLORIA and EXIOBASE is that they are multi-regional input-output tables that are extended to include environmental aspects such as emissions and other satellite variables such as employment. For models described in section 4, further data on macroeconomic variables such as disposable income, prices and wages are required. In addition, a theoretical framework is needed to go beyond static modelling, in which the structures of the past remain unchanged. Nevertheless, these data could be used for more in-depth model analyses or linked with the data sets of other models, as has been done with the PACE model by ZEW (Gavard & Voigt (2017)) and the JRC-GEM-E3 model, that have both been extended for carbon-intensive sectors by EXIOBASE data.

This is possible in future research in principle, but it will require additional effort. Methodological questions arise when the substitution possibilities between such additional subsectors are different from the higher aggregation levels. In this case, specific assumptions may have to be made with regard to model specification. For example, for different types of fertilizers, quite different relationships could apply compared to different metals. Further sector-specific information will have to be obtained to get realistic results for the subsectors. Furthermore, each additional sector differentiation increases the data volume and possibly also the solution time of a model, while transparency decreases. As an alternative, partial analyses at the subsector level may be an alternative. With global data, e.g. on production, trade and prices of fertilisers, elasticities could also be estimated and impacts of price changes calculated without including general equilibrium or induced macroeconomic effects.

Another approach could be to link detailed product data from Life-Cycle Assessment (LCA) analyses with input-output data to build so-called hybrid global input-output models with high sector or product detail. This is currently the focus of the Danish research project "getting the data right"[5]. The project aims to provide "an up-to-date climate footprint generator, based on a consistent physical and monetary model of global production and consumption activities and their climate impacts, at an extraordinary level of detail (>1000 activities and product groups) and geographical specificity." After completion by 2025, the data set will contain high-resolution data that are necessary for the analysis of carbon leakage at product group level.

The Global Input Output AccouNTs or GIANT (2023) initiative is a new inter-agency network consisting of the Asian Development Bank, the European Commission, the OECD, the International Monetary Fund and the United Nations Economic Commission for Latin America and the Caribbean. According to a common presentation at the 29th International Input-Output Conference its goal is to converge on a common global benchmark for the input data used by the five partner organizations to produce global Inter-Country Supply, Use and Input-Output tables (IIOA 2023). However, it is likely to take years before the initiative will produce an improved global database.

Table 26: Global MRIO databases

Name and lead organization if different; access	Coverage	Base year(s)/ last update	Carbon-intensive sectors coverage	References
Global Trade Analysis Project (GTAP 11), Purdue University, license	141 countries, 65 sectors	2019	Paper, chemicals, rubber and plastics, non-metallic minerals, iron and steel, non-ferrous metals, electricity, steam	Aguiar et al. (2019)
OECD ICIO, free	76 countries, 45 sectors	1995-2020 (2022)	Paper, chemicals, rubber and plastics, non-metallic minerals, basic metals, electricity, gas, steam and air conditioning; Production for basic metals separated in iron and steel and non-ferrous metals in STAN	OECD (2022)
WIOD, provided by consortium of research institutions based on projects funded by the EU, led by University of Groningen	43 countries, 56 sectors	2007; 2000-2014 (2016)	As OECD	no more updates since 2016. Timmer et al. (2015)

[5] https://www.en.plan.aau.dk/getting-the-data-right/

Name and lead organization if different; access	Coverage	Base year(s)/ last update	Carbon-intensive sectors coverage	References
EXIOBASE, provided by consortium of research institutions based on projects funded by the EU, led by Norwegian University of Science and Technology (NTNU)	44 countries; 163 industries/ 200 products	1995-2011/ 2007 (2021)	5 chemicals (incl. 2 fertilizers) 6 non-metallic minerals 13 metals (prim and sec) electricity	Parts with more recent data; nowcast/forecast until 2022 Stadler et al. (2021)
GLORIA, provided by the global MRIO Lab, a consortium of different international research institutions, led by the University of Sydney; free for scientific use, license for commercial use	164 regions, 120 sectors	1990-2020 (2021)	2 (types of) fertilizers 5 chemicals 5 non-metallic minerals 8 metals Electric power	https://ielab.info/resources/gloria Lenzen et al. (2017), Lenzen et al. (2022)
FIGARO, developed by Eurostat and JRC; free	64 industries, 46 countries	2010-2020 (2021)	Paper, chemicals, rubber and plastics, non-metallic minerals, basic metals, electricity, gas, steam and air conditioning	Contributing to OECD IOT Eurostat (2022)

Own compilation.

Models based on these databases can best answer questions of competitiveness, carbon leakage and measures such as CBAM. However, models based on other data bases such as GEM-E3 – as in the case of EC (2021) - and GINFORS-E could also be extended to include the corresponding information on carbon-intensive sectors.

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A Appendix

A.1 Glossary

A	
AIDS-ADS	Almost Ideal Demand System
Agent	Economic entities that make decisions within a CGE model, typically households, firms, government, and the rest of the world
Allocation	The distribution of resources or goods among various uses or agents in an economy
Armington Assumption	The assumption that goods are differentiated by region of origin, leading to imperfect substitutability between domestic and imported goods
Adjustment Costs	Costs that agents incur when changing the level or composition of production or consumption
B	
Baseline Scenario	A counterfactual analysis in which the economy evolves without any policy changes, serving as a reference case for comparison with alternative scenarios
C	
Calibration	The process of adjusting model parameters so that the model's output matches actual data for a base year
Capital Accumulation	The growth of capital stock over time through investment
CD	Cobb Douglas
CDE	Constant Difference of Elasticities
Closure Rule	The set of conditions specified to determine the values of variables that are endogenous in one context and exogenous in another within the CGE model
Constant Elasticity of Substitution (CES) Function	A functional form that assumes a constant percentage change in factor proportions in response to a percentage change in relative factor prices
Consumption Bundle	The mix of goods and services consumed by households
COICOP	The acronym "COICOP" stands for the Classification of Individual Consumption According to Purpose
D	
Dynamic CGE Model	A CGE model that simulates changes over time, incorporating elements such as investment, technological change, and capital accumulation

E	
Elasticity of Substitution	The percentage change in the ratio of two inputs used in production relative to a percentage change in the ratio of their prices
ELES	Extended Linear Expenditure System
Endowment	The initial allocation of factors of production, such as labor, capital, and natural resources, to agents
Equilibrium	A state where supply equals demand for all markets in the model
Exogenous	Variables whose values are determined outside the model
F	
Factor Markets	Markets for inputs used in production, typically including labor, capital, and natural resources.
Fiscal Policy Module	A component of the CGE model that simulates the impact of government taxation and spending decisions.
G	
General Equilibrium	An economic state where all markets (goods, services, factors) are in equilibrium simultaneously
H	
Homothetic Preferences	Preferences where the ratio of goods consumed does not depend on income level, only on relative prices
I	
Input-Output Table	A matrix representation of the inter-industry flows within an economy, showing how outputs from one industry become inputs to another
Intermediate Goods	Products used as inputs in the production of other goods and services
L	
Leontief Production Function	A production function assuming fixed input proportions, with no substitution between inputs
LES	Linear Expenditure System
Linked non-Durable Goods	Goods whose consumption is linked to the use of a durable good (e.g. fuel and car)
M	
Marginal Cost	The cost of producing an additional unit of a good or service
Market-Clearing Price	The price at which the quantity supplied is equal to the quantity demanded

N	
Nested Production Function	A hierarchical combination of CES functions used to represent production processes with multiple layers of substitution possibilities
P	
Policy Simulation	The use of a CGE model to assess the economic impacts of policy changes
Production Function	A mathematical representation of the relationship between input factors and the output of goods or services
Productivity Shock	A change in the efficiency with which inputs are transformed into outputs
R	
Representative Agent	A hypothetical entity in a CGE model that embodies the average characteristics of a group, such as a 'representative household'
Rest of the World	In CGE models, this term represents all economic agents and activities outside the domestic economy
S	
Social Accounting Matrix (SAM)	A comprehensive, economy-wide data framework that captures all transactions and transfers between different agents of an economy
Sticky Prices	Prices that do not adjust immediately to changes in supply and demand conditions
Substitution Elasticity	See Elasticity of Substitution
T	
Tariff Revenue	Income that the government receives from taxes imposed on imported goods
Technology Matrix	A matrix that details the technology used in the production process, indicating the input-output coefficients for each sector
Total Factor Productivity (TFP)	The portion of output not explained by the amount of inputs used in production. It is often interpreted as the effect of technological progress
W	
Welfare Analysis	The study of how the well-being of economic agents changes under different economic conditions or policy scenarios