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Final report

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

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Abstract:

The key aim of this research project has been to improve the understanding of the suitability of two types of large-scale models differentiated by industries – macro-econometric models and computable general equilibrium (CGE) models – for analysing international emission effects and economic effects of scenarios in which the EU moves forward in climate policy and applies different design options in the already implemented emissions trading system in this context. In particular, we aim at extending and deepening the knowledge on how the two different models treat the design of the European Emissions Trading System (EU ETS) especially on allocation and of a carbon border adjustment mechanism (CBAM) as implemented under the fit-for-55 reform package, both with a view especially to industry sectors and overall economic activity as well as to changes in the EU industry products' trade flows and to the risk of carbon leakage.

The results from both models suggest that an effective CBAM can play a significant role in countering the risk of carbon leakage in the case of unilateral EU climate action. Moreover, a CBAM also has a noticeable positive effect on sectoral production in industry and especially in the sectors covered by the EU ETS, as well as on GDP. In essence, both models show that the carbon leakage risk is no convincing argument against EU climate action, if EU ETS and CBAM are properly designed.

In general, the macroeconomic effects of additional international climate mitigation efforts are small, while the carbon emissions are reduced strongly. It is important to note that the economic benefits of global climate protection in the form of lower losses and damages are not included in the scenarios. They are expected to be several times higher than the reported macroeconomic effects of ambitious climate mitigation. The message of the study is strong and positive: far-reaching climate protection worldwide is possible and leads only to marginal macroeconomic effects.

By conducting this project, we intend to contribute to the available research by a) providing key results on the economic and emission results for different scenario settings, b) providing indications on which results differ in particular between the two models, and c) improving insights on the influence of the choice of model on the results. Based on our model results, we suggest that there is a high likelihood that the type of model is clearly relevant at least for some specific indicators such as carbon leakage rates and economic quantity and price effects, both economy-wide and (while to a lesser extent) by industry.

In this way, we aim at assisting practitioners – governmental and nongovernmental – as well as researchers in interpreting the results from model-based scenario analyses on the above-mentioned questions. Such scenarios can be used for impact assessments, for example by the European Commission. In addition, ideally the report can assist practitioners or researchers when commissioning – or even conducting – own scenario research in the context mentioned here.

In addition to these model-based analyses, the project includes a module with an overview of existing models feasible for estimating carbon leakage and/or measures to address it. It focuses on the two model types applied in this project – CGE models and macro-econometric models.

Finally, the project includes an analysis on another type of large-scale model, namely integrated assessment models used for highly aggregated assessment scenario analyses with a time horizon until 2100.

Kurzbeschreibung:

Das Hauptziel dieses Forschungsprojekts bestand darin, das Verständnis der Eignung von zwei Arten von Wirtschaftsmodellen zu verbessern, die eine Branchendifferenzierung innerhalb der Industrie beinhalten: makroökonometrische Modelle, und berechenbare allgemeine Gleichgewichtsmodelle (CGE). Untersucht wurde die Anwendung dieser beiden Modelle für die Analyse internationaler Emissionseffekte und wirtschaftlicher Auswirkungen von Szenarien, in denen die EU in der Klimapolitik voranschreitet und in diesem Zusammenhang verschiedene Gestaltungsoptionen im bereits implementierten Emissionshandelssystem anwendet. Insbesondere soll das Wissen darüber erweitert werden, wie die beiden unterschiedlichen Modelle die Gestaltung des Europäischen Emissionshandelssystems (EU ETS) insbesondere in Bezug auf die Zuteilung und einen CO_2-Grenzausgleichsmechanismus (CBAM), wie er im Rahmen des Reformpakets „Fit for 55“ umgesetzt wurde, behandeln. Dies sowohl mit Blick auf die Industriesektoren und die gesamtwirtschaftliche Aktivität, als auch auf Veränderungen in den Handelsströmen der EU-Industrieprodukte und auf das Risiko der Verlagerung von CO_2-Emissionen („Carbon Leakage“).

Die Ergebnisse beider Modelle deuten darauf hin, dass ein wirksamer CBAM eine bedeutende Rolle bei der Bekämpfung des Carbon-Leakage-Risikos im Falle eines klimapolitischen Vorangehens der EU spielen kann. Darüber hinaus hat ein CBAM auch einen spürbar positiven Effekt auf die sektorale Produktion in der Industrie und insbesondere in den Sektoren, die unter das EU ETS fallen, sowie auf das Bruttoinlandsprodukt (BIP). Im Wesentlichen zeigen beide Modelle, dass das Risiko der Verlagerung von CO_2-Emissionen kein überzeugendes Argument gegen Klimaschutzmaßnahmen der EU ist, wenn das EU ETS und der CBAM passend konzipiert sind.

Im Allgemeinen sind die makroökonomischen Auswirkungen zusätzlicher internationaler Klimaschutzbemühungen gering, während die CO_2-Emissionen stark reduziert werden. Es ist wichtig zu beachten, dass die wirtschaftlichen Vorteile des globalen Klimaschutzes in Form geringerer Verluste und Schäden in unseren Analysen nicht berücksichtigt sind. Sie dürften um ein Vielfaches höher sein als die berichteten makroökonomischen Auswirkungen eines ehrgeizigen Klimaschutzes. Die Botschaft der Studie ist stark und positiv: Ein weitreichender weltweiter Klimaschutz ist möglich und führt nur zu geringfügigen makroökonomischen Auswirkungen.

Mit diesem Projekt wollen wir einen Beitrag zur bestehenden Forschung leisten, indem wir a) zentrale Ergebnisse zu ökonomischen Kennzahlen und Emissionspfaden für verschiedene Szenarien bereitstellen, b) Hinweise darauf geben, welche Ergebnisse sich insbesondere zwischen den beiden Modellen unterscheiden, und c) die Erkenntnisse über den Einfluss der Modellwahl auf die Ergebnisse verbessern. Auf der Grundlage unserer Modellergebnisse gehen wir davon aus, dass die Art des Modells mit hoher Wahrscheinlichkeit zumindest für einige spezifische Indikatoren wie die Carbon Leakage-Raten und die wirtschaftlichen Mengen- und Preiseffekte sowohl für die gesamte Wirtschaft als auch (wenn auch in geringerem Maße) für die einzelnen Branchen eindeutig relevant ist.

Ziel ist, auf diese Weise Praktiker*innen – staatliche und nichtstaatliche – sowie Forscher*innen bei der Interpretation der Ergebnisse modellbasierter Szenarioanalysen zu den oben genannten Fragen der internationalen Wechselwirkungen des EU ETS und eines CBAM zu unterstützen. Solche Szenarien werden unter anderem für Folgenabschätzungen beispielsweise von der Europäischen Kommission im Rahmen ihrer Legislativvorschläge verwendet. Darüber hinaus kann der Bericht im Idealfall Praktiker*innen oder Forscher*innen bei der Beauftragung – oder sogar Durchführung – eigener Szenarioforschung im hier genannten Kontext helfen.

Zusätzlich zu diesen modellbasierten Analysen umfasst das Projekt ein Modul mit einer Übersicht über bestehende Modelle, die für die Abschätzung von Carbon Leakage und/oder Maßnahmen zu dessen Adressierung geeignet sind. Der Schwerpunkt liegt auf den beiden in diesem Projekt angewandten Modelltypen – CGE-Modelle und makroökonometrische Modelle.

Schließlich umfasst das Projekt eine Analyse zu einem anderen Typ von großen Modellen, nämlich integrierten Bewertungsmodellen, die für hochaggregierte Bewertungsszenarioanalysen mit einem Zeithorizont bis 2100 verwendet werden.

Table of Content

List of figures

List of tables

List of abbreviations/Abkürzungen

BIP	Bruttoinlandsprodukt
CBAM	Carbon Border Adjustment Mechanism
CGE	Computable General Equilibrium
CO_2	Carbon dioxide
ETS	Emissions Trading System
ff55	Fit for 55
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
HLCCP	High-Level Commission on Carbon Prices
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contributions
RoW	Rest of world
SPA	Shared Climate Policy Assumption
SSP	Shared socioeconomic pathway
THG	Treibhausgase

1 Summary

The aim of this research project has been to improve the understanding of the suitability of two types of large-scale models differentiated by industries – macro-econometric models and computable general equilibrium (CGE) models – for analysing international emission effects and economic effects of scenarios in which the EU moves forward in climate policy and applies different design options in the already implemented emissions trading system in this context. In particular, we aim at extending and deepening the knowledge on how the two different models treat the design of the European Emissions Trading System (EU ETS) especially on allocation, and of a carbon border adjustment mechanism (CBAM) as implemented under the fit-for-55 reform package – both with a view especially to sector and overall economic activity as well as to changes in the EU's industry trade flows and to potential carbon leakage.

The main results of the three work packages within the project are summarized below. Work package 2 includes the analysis of given scenarios with two different macroeconomic models (GEM-E3 and GINFORS-E) – including the actually implemented setting under the EU's fit-for-55-reform package. This summary starts with motivation, approach and key findings of this work package (Section 1.1). The detailed results of the quantification of the policy-relevant scenarios are presented in the Central Report and are briefly presented here (Section 1.2). As part of the second work package, a Technical report was prepared, which primarily serves to harmonize the two models used and to analyse simple global mitigation scenarios (Section 1.3). The third work package provides an overview of models that can be used to analyse carbon leakage and specific policy measures (Section 1.4). In the first work package, long-term analyses with Impact Assessment Models (IAMs) were described and evaluated to prepare and select the own analysis (Section 1.5). This work package is therefore summarized at the end.

1.1 Motivation, approach and key findings of work package 2

Motivation

As mentioned above, the key aim of this research project has been to contribute to improving the understanding of the suitability of two types of large-scale models differentiated by industries – macro-econometric models and computable general equilibrium (CGE) models – for analysing international emission effects and economic effects of scenarios in the context of EU climate policy. In particular, we wanted to extend and deepen the knowledge on how the two different models treat the design of the European Emissions Trading System (EU ETS) especially on allocation and of a carbon border adjustment mechanism (CBAM) as a measure to address potential carbon leakage.

By attributing findings to model differences, we also aim at providing insights for the interpretation of the results obtained from modelling the international effects of the EU moving forward in climate mitigation and the impacts of "how this is done" in terms of policy choice. The idea is to get a better grasp on the "robustness" of the results in terms of how strongly the results depend on the choice of model; and indicative insights on which political questions, related to "uneven pace" of climate ambition, can be feasibly addressed by these two types of model.

Besides these primarily methodical goals, our results also contribute to understanding the projected economic and carbon leakage effects of the revision of the "fit-for-55" measures, especially the increased abatement ambition until 2030 and 2050 in the EU and the gradual introduction of a CBAM.

We therefore contribute to the available research by a) providing **key results** for different scenario settings **regarding ambition and design in the EU ETS and of a CBAM introduction** and b) providing indications on **which results differ in particular between the two models.** As can be seen below, we suggest that there is a high likelihood for the choice of model to be relevant at least for indicators such as carbon leakage rates and economic quantity and price effects, both economy-wide and by affected industry. The idea is to get a better grasp on the "robustness" of the results depending on the choice of model and indicative insights on which political questions, related to "uneven pace" of climate ambition, can be feasibly addressed by these two types of model.

In this way, we aim at assisting practitioners as well as researchers in interpreting the results from model-based scenario analyses on ETS design and on the effects of a CBAM. Such scenarios are applied, for example, in policy impact assessments by the European Commission. In addition, ideally the report can assist practitioners or researchers when commissioning – or even conducting – own scenario research in the context mentioned.

Approach

Two models, one each of the types mentioned above (**macro-econometric, GINFORS-E**) and **CGE (GEM-E3**) have been applied to policy scenarios that represent plausible political options. The model GEM-E3 (General Equilibrium Model – E3) is a general computable equilibrium (CGE) model that follows neoclassical theory, the other model GINFORS-E (Global Interindustry Forecasting System - Energy) is a macro-econometric model that follows a post-Keynesian approach. Both models are briefly described in sections 3, 4 and 7 of the "Central Report" (see section 1.2 of this summary).

In a first step, the models have been harmonised as far as possible in terms of external assumptions on, e.g., global population, GDP development and on energy prices, so that the differences in results in the later, policy related, scenarios are indeed related to model differences, and not simply to different key assumptions. In the course of harmonisation, the endogenous developments in sectoral production values, i.e. the economic structure, energy consumption and CO_2 emissions, have also been compared. This is **followed by exploratory scenario runs that address the impact of the EU moving forward versus the case that global uniform CO_2 prices achieve either a 2 degrees, or a 1.5 degrees** climate policy goal. **All these scenarios are sub-summarised in a "Technical Report" (see below in section 1.3).**

Next, **the central policy related scenarios** addressing the **details of the EU ETS** (i.e., primarily allocation) as well as the potential **introduction of a CBAM**, **have been analysed with both models, and the results contrasted to each other, This is presented in the "Central Report" of this project (see section 1.2 below).** This report treats the allocation and the CBAM as key elements for the main scenarios:

a) ETS ambition according to Fit-for-55 (FF55); free allocation for industry and auctioning for energy sectors; no CBAM.

b) ETS ambition according to FF55, auctioning for all ETS sectors, no CBAM.

c) ETS ambition according to FF55; auctioning gradually replacing free allocation for certain industry sectors as in the FF55, parallel gradual introduction of CBAM.

We approximate the actual CBAM scope, as prescribed in the EU "CBAM Regulation" 2023/956/EU, by assuming that the CBAM gradually replaces free allocation for the following industry sectors as covered in our models: Iron and Steel/Ferrous metals, Non-ferrous metals (both grouped together as "Basic metals" in GINFORS-E); Non-metallic minerals; and Chemical industry (where both industry sectors in our case include the entire respective sector e.g. also lime, glass and ceramics as well as organic and non-organic chemicals, as a further differentiation would require further sectoral differentiation than what is currently feasible in underlying databases of these models.

The analysis then added additional scenarios or sensitivities for d) the assumed international trade elasticities ("Armington elasticities"), e) the inclusion of indirect emissions into the CBAM (replacing compensation mechanisms in the EU for indirect emissions), and finally, f) of increased climate policy ambition in major trading partners of the EU. For GEM-E3, in addition g) a modified use of the budget revenues has been addressed. These results are also presented in the Central Report.

In addition to these modelling analyses, a further work package ("Extended model overview," chapter 1.4 in this summary) widened the perspective and **provides an overview of other existing CGE models and macro-econometric models.** These are presented in overview tables, short fact sheets, and summary plots on their key principles and assumptions.

Finally (see section 1.5 below), the analysis in this project has been supplemented work package 1 by **research into another type of large-scale model – namely integrated assessment models used for comparably highly aggregated assessment scenario analyses**. The characteristics in the form of regional and sectoral differentiation, as well as model philosophy and approach are identified, the time horizon is until 2100.

Overview of key project results

The key insights from our modelling analyses can be summarised as follows: The results from both models suggest that **an effective CBAM can play a significant role in encountering the risk of carbon leakage in the case of unilateral EU climate action.** This applies in particular compared to auctioning – a scenario that is plausible for the near future in view of the declining cap, which leaves ever less scope for sustained free allocations. Moreover, and related to this, a CBAM also has a noticeable positive effect compared to auctioning **on sectoral production in industry** and especially in the ETS-covered sectors, and also on **GDP,** which is less pronounced due to a limited share of the ETS industry in overall GDP.

Comparing the introduction of a CBAM as decided in the FF55 package to a prolonged free allocation, the differences for all indicators are much smaller. While leakage is still lower under CBAM, the sectoral production in 2030 is slightly higher under prolonged free allocation. It has to be made clear however, that even under a free allocation scenario this free allocation has to be phased out gradually after 2030 due to the declining cap. The size of the effects of a CBAM, and also of the choice of the allocation method, are larger for the sectoral carbon leakage rates than for sectoral production of the same industry sectors and still smaller differences between the scenarios can be seen for overall GDP.

These scenarios also show effects in major trading partners. Here, it can be seen that **especially exporting countries for (fossil) fuels** such as Russia, are expected to see a large loss of GDP in both models, **especially in the longer time-horizon until 2050.** Interestingly, however, sensitivity calculations under **both models suggest that increased climate policy ambition of major EU trading partner countries does not lead to clearly increased GDP in the EU, but rather constant or falling GDP.** A plausible explanation is that in both models a reduced GDP in the trading partner countries as a result of increased climate policy ambition, exerts feedback effects on trade with the EU, which in turn negatively affect EU GDP, and that this trade effect dominates the effect of increased Non-EU ambition on the relative production costs in the EU and in trading partners.

While the results are often consistent in direction and similar in size for both models, **there are nonetheless some substantial differences**. These are in general **more pronounced for overall economic effects, such as GDP or CO_2 prices on national levels, than for changes in sectoral production levels**: As Figure 2 below shows, the overall GDP effects of the EU's unilateral **increase in climate ambition to 55%** emission reduction by 2030 rather than 40% reduction, in GEM-E3 **leads to substantial drops in GDP in the EU** and (to a lesser extent) in Russia (as main exporter of energy products). In contrast, in GINFORS-E the GDP effect is **clearly positive for the EU** and for all countries presented except for Russia, for which the negative GDP effects are even larger than in GEM-E3. Here, the different model philosophies, with, e.g. assumed significant "crowding-out" effects in GEM-E3 and in contrast positive feedback effects in GINFORS-E, have a major influence. These differences in the macroeconomic results can also be seen in other model comparisons. The more supply-oriented CGE models tend to emphasize the restrictions of additional climate policy, which leads to slightly negative effects on GDP, while more demand-oriented macroeconometric models tend to react slightly positively to additional climate mitigation investments.

But also the carbon leakage effects for the key ETS industry sectors estimated by GEM-E3 are larger than those under GINFORS-E. We conclude that the differences in model philosophies between the two types, especially on the factor markets for capital and labour, and different Armington elasticities for international trade, are the major driving forces behind these differences in results. They drive especially the overall, economy-wide effects which are represented here as GDP changes. On sectoral effects, the models differ in a relevant extent only for some sectors, especially the energy sector: Here, in GINFORS-E, until 2030 reductions in gas consumption are not compensated by higher electricity production so that total energy production decreases. In GEM-E3, energy production increases due to electrification in the economy and deployment of biofuels until 2030 and the deployment of hydrogen and clean gas until 2050. In general, the macroeconomic costs for the EU in the form of GDP losses are limited, however, in the GEM-E3 model. GINFORS-E even reports small GDP increases for the EU in the case of unilateral action.

Negative macroeconomic and sectoral effects can be further reduced by appropriate design of the EU ETS including a CBAM. It is important to note that the economic benefits of global climate protection in the form of lower losses and damages are not included in the scenarios. They are expected to be several times higher than the reported macroeconomic effects of ambitious climate mitigation. The message of the study is positive: far-reaching climate protection worldwide is possible and leads only to marginal macroeconomic effects. Of the various analysed design options for the EU ETS, CBAM (with auctioning) is the most suitable with regard to carbon leakage (i.e., shifts of domestic production to foreign countries as a result of differently high carbon prices which lead to increased emissions in those foreign countries). The economic effects (GDP and sectoral industry production), however, are slightly more positive with free allocation. The results for full auctioning without a CBAM are clearly the worst.

1.2 WP 2: Central report

The central report considers the socio-economic effects of EU climate change mitigation scenarios up to 2050 using the same two macroeconomic models with different model philosophies GEM-E3 and GINFORS-E. The two models are briefly described in section 7 of the central report. The core policy scenarios are mainly characterized by unilateral EU climate action so that the GHG reduction targets of -55% until 2030 and -95% until 2050 are achieved. The results of the policy scenarios are compared with a reference scenario representing EU climate policy before the Fit-for-55 policy package, which was adopted in 2023. More precisely, in the reference scenario the EU "only" reduces its GHG emissions by 40% by 2030 and by 80% by 2050 compared with 1990 levels. Mitigation ambition outside the EU, in contrast, is assumed to be only modest, with all major trading partner countries adhering to their respective Nationally Determined Contributions (NDC) targets by 2030, which are countries' plans for the post-2020 climate actions in line with the Paris Agreement, and after 2030 raising any potentially necessary carbon price for 2030 by the rate of real GDP.

By itself, raising the EU climate policy ambition by tightening the EU Emissions Trading System (EU ETS) cap likely leads to increased carbon prices which, in turn, could be a catalyst for carbon leakage via the relocation of production and associated emissions to third countries, especially in carbon-intensive industries. This could even be exacerbated by comparatively higher emission intensities there although this is only plausible in certain countries and industries. Next to that, reduced demand for fossil fuels in the EU could exert a notable negative effect on the prices of these commodities incentivising their consumption in other countries (fuel price-effect), which is not accounted for in the scenarios, as the same (fix) energy prices are assumed in both models. Among these effects, our models focus on the above-mentioned industry/trade carbon leakage channel (relocation of production - including via shifting investment). The effect of climate mitigation in the EU could thus be undermined. Moreover, production and thus value-added as well as jobs are relocated outside the EU. Measures to counteract leakage, such as the Carbon Border Adjustment Mechanism (CBAM) or free allocation, which was formerly the main instrument for this goal, are thus evaluated in different constellations across policy scenarios.

Quantitative results for a total of three core policy scenarios and various sensitivities have been obtained with the two models. A brief description of the scenarios is provided in Table 1. All scenarios consider the EU "moving forward" in achieving ambitious climate change targets for 2030 and 2050, while other countries are assumed to (only) achieve their 2030 NDCs submitted in 2020, with no significant further emission reduction efforts thereafter. The only exception being scenarios 13 to 15 which include also higher climate mitigation ambition outside Europe. The degree of this "moving forward" of the EU differs between the reference scenario (scenario 6, NDCs-Ref) and the other scenarios which, as indicated at the beginning, reflect increased ambition assuming a target of 55% reduction in the EU by 2030 and of 95% by 2050, in line with the Green Deal. The scenarios mainly differ in the allocation rule for the emissions: Free allocation in scenario 7 (EU_FA), full auctioning in scenario 8 (EU_AU), and finally scenario 9 (EU_ff55) that is oriented at the Fit-For-55-package including the gradual phase-in of a CBAM for the industry sectors iron/steel, non-ferrous metals, non-metallic minerals and chemical industry.[1] While there is some chance for increased climate policy ambition (and implementation) by major EU trading partner countries, the present analyses show the maximum possible negative economic impacts, that is, when the EU is the only jurisdiction raising its ambitions.

In addition, for both models the sensitivity of results was determined with respect to a) changes in the design of CBAM, b) the values of the Armington elasticities, and c) changes in climate protection policy ambition in the rest of the OECD and China. The Armington elasticities describe

[1] As the industry disaggregation level in our models does not further differentiate, we assume the coverage of these whole sectors, even though in the CBAM regulation only subsectors (aluminium, cement, and ammonia/fertilisers are covered).

the substitution possibilities between domestic and imported goods and between different supplier countries for imported goods.

In the central report, results of the GEM-E3 model are presented in section 3 and of the GINFORS-E model in section 4. A comparison of important results for both models is provided in section 5. It can already be seen in the historical data for 2015 that there are partly significant differences in the data serving as input to the models. In the case of GDP in purchasing power parities this is mainly due to different base years with different exchange rates (2014 in GEM-E3 and 2010 in GINFORS-E). An attempt has been made to align the GDP growth rates in both models after 2020. However, there are also historical differences in energy consumption and energy-related emissions between the two models, which are discussed in more detail in the respective technical report (Lutz et al. 2024).

Table 1: Scenarios

No.	Abbreviation	Short description
Reference scenario		
6	NDCs_Ref	The EU reduces its GHG emissions by 40% by 2030 and by 80% by 2050 compared with 1990 levels
Main scenarios		
7	EU_FA	EU targets in 2030 and 2050 reached; free allocation to ETS industry in EU (80% until 2030), gradually decreasing to 0 in 2050. Auctioning for all other sectors in EU. Non-EU and other assumptions for EU as in scenario 6
8	EU_AU	As 7, but full auctioning for all sectors in EU, and no compensation in any year for indirect emissions
9	EU_ff55	As 7, but EU fitfor55 as agreed including gradual shift from free allocation to auctioning and phase-in of CBAM on direct emissions from 2026 to 2034 according to the time path prescribed in the new CBAM regulation and the new ETS regulation. Compensation for indirect emissions phased out until 2040 (basic metals, paper).
Scenarios serving sensitivity analysis		
9a	EU_ff55_CBAM_dic	As 9, CBAM on direct and indirect emissions. Compensation for indirect emissions phased out until 2034.
9b	EU_ff55_CBAM_d	As 9, CBAM on direct emissions, no compensation in any year for indirect emissions
9r	REC	As 9, revenue recycling via energy efficiency investment in CBAM sectors
6D	NDCs_Ref_AD	Scenario 6 with doubled (GINFORS-E) elasticities
10	EU_FA_AH EU_FA_AD	Scenario 7 with doubled (GINFORS-E)/halved (GEM-E3) Armington elasticities
11	EU_AU_AH EU_AU_AD	Scenario 8 with doubled/halved Armington elasticities
12	EU_ff55_AH EU_ff55_AD	Scenario 9 with doubled/halved Armington elasticities

No.	Abbreviation	Short description
6a, 10a, 11a, 12a	NDCs_Ref_AG EU_FA_AG EU_AU_AG EU_ff55_AG	Scenarios 6 to 9 with Armington elasticities from GEM-E3 (only GINFORS-E)
13	EU_FA_RW	Scenario 7 with raising ambition in (some) RoW countries, China on path for carbon neutrality in 2060, advanced OECD countries introduce carbon prices of 50% of EU price
14	EU_AU_RW	Scenario 8 with raising ambition in (some) RoW countries as in scenario 13
15	EU_ff55_RW	Scenario 9 with raising ambition in (some) RoW countries as in scenario 13

Source: Own compilation.

The two models share many common features but also have fundamental differences. Both models are using similar datasets comprising of input-output tables, bilateral trade matrices, and energy balances. GEM-E3 is calibrated on a single base year. The GEM-E3 production and consumption functions are dynamically calibrated over time starting from their base year values following normative assumptions. GINFORS-E is calibrated on a time series of historical data. The factor demand and final demand functions in GINFORS-E are empirically estimated on long time series data. The price elasticities in GINFORS-E are generally lower than those assumed in GEM-E3. Consistent with this, lower Armington elasticities for international trade are also applied in GINFORS-E. This is based on the model philosophy that adjustment processes take longer than in the CGE model, which reflects faster adjustment processes.

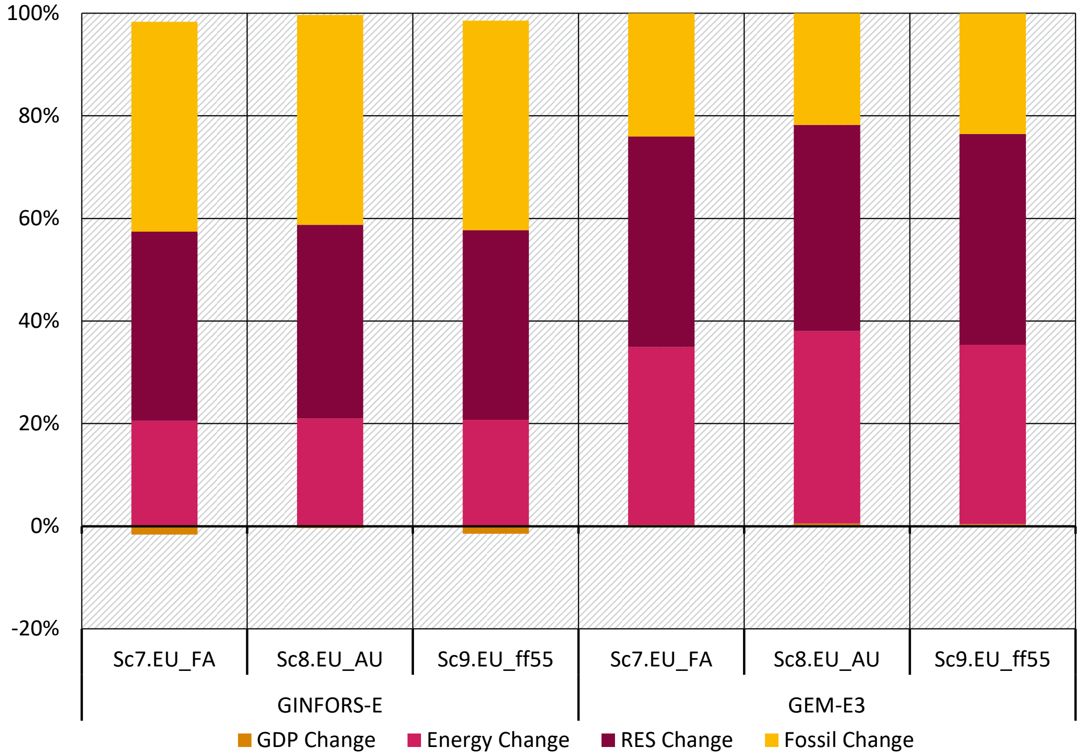
The key model differences explain some of the differences in results. Optimisation and full utilisation rate in GEM-E3 mean that the economy in the reference is at its optimum. Climate policy through higher CO_2 prices usually leads to slightly negative macroeconomic effects unless specific assumptions are made about additional financing. Investment is more constrained in GEM-E3 than in GINFORS-E. In contrast, the empirically estimated behavioural equations, together with the assumption that capacity is not fully utilized, allow for additional climate change investments in GINFORS-E, which can have a positive effect in the more demand-driven approach. Elasticities of substitution tend to be lower in GINFORS-E, which, together with assumptions about mark-up pricing, investment and financing, make the GINFORS-E model more responsive to climate policy in economic terms. Impacts in terms of GDP or production changes in non-carbon intensive sectors and not directly affected countries tend to be higher than in GEM-E3.

CO_2 emissions are modelled endogenously in both models. Carbon prices are a key factor influencing the development of energy-related emissions. They are adjusted in the models based on the previous year's price until the maximum annual CO_2 emissions are reached. In the reference scenario (NDCs_Ref), the carbon prices in both models are similar. In 2030, quite low prices of around or less than 50 USD are sufficient to achieve the target of a 40% GHG reduction compared to 1990. In the following years, prices rise sharply in both models and reach a level of about 300 USD to achieve a GHG reduction of 80% compared to 1990. In the target scenarios 7 to 9, the differences in CO_2 prices are significantly larger as higher price levels are necessary for reaching the more ambitious GHG reduction targets. While GINFORS-E requires a price of 226 USD2010/t in 2030, GEM-E3 requires a much lower price of around 76 USD2014. By 2050, the prices then converge again strongly and are at 524 USD2014 in GEM-E3 and 577 USD2010 in

GINFORS-E. These carbon prices indicate the following: In the short term the GEM-E3 is more flexible regarding the representation of abatement options (hence the lower carbon price). In the long-term remaining GHG emissions are harder to abate and both models have a similar and steeper "implied" marginal abatement cost curve. The scenario comparison only measures the delta between a 95% to an 80% GHG reduction in 2050. The following results do not describe the overall effects of climate protection in Germany and the EU, but only the effects of this difference.

Energy Transition: The two models show different adoption of the technological choices in decomposition analyses to reduce GHG emissions. GINFORS-E decarbonises the energy system mainly by substituting between fossil fuels and by renewable energy deployment. In GEM-E3, renewable energy deployment and energy efficiency improvements are ranked first. Changes in economic activities are marginal in both models, see Figure 1.

Figure 1: EU emission reduction Kaya decomposition for 2030 – compared to Sc6.NDCs_Ref in 2030 (left – GINFORS-E, right – GEM-E3)



Source: GEM-E3 and GINFORS-E.

Carbon Leakage: In the short term the EU escalating carbon prices increase production costs for EU located firms deteriorating competitiveness in the domestic market, due to competition with imports, and in the international markets. However, changes in costs are relatively low and both models report relatively modest carbon leakage rates below 34% for 2030 (see Table 2, with the exceptions of full auctioning for Chemicals and pharmaceutical products and Basic Metals in GEM-E3), with GEM-E3 having significantly larger rates in the case of free allocation and full auctioning (despite the lower 2030 carbon prices that the CGE model produces). A leakage rate of 10% means that if greenhouse gas emissions in the EU are reduced, 10% of this will be offset by higher emissions in the rest of the world. This result is partly driven by higher elasticities of substitution in GEM-E3 which increases substitution processes away from the carbon-intensive sectors and also increases carbon leakage. Higher assumed trade (Armington) elasticities in GEM-E3, allowing for easier substitution between domestic and imported products, also have an influence, but the above-mentioned general picture still holds even when applying identical trade elasticity assumptions between both models.

Table 2: Carbon leakage rates by sector for 2030 - each in comparison to Sc6.NDCs_Ref

	GINFORS-E			GEM-E3		
	Sc7.EU_FA	Sc8.EU_AU	Sc9.ff55	Sc7.EU_FA	Sc8.EU_AU	Sc9.ff55
Paper products and printing	1.10%	2.09%	1.35%	0.9%	9.2%	-2.2%
Chemicals and pharmaceutical products	5.87%	10.40%	5.63%	37.2%	88.7%	6.6%
Other non-metallic minerals	10.07%	19.52%	9.26%	1.8%	33.9%	-23.7%
Basic metals	18.34%	26.97%	17.99%	10.5%	95.8%	-124.8%

Source: GEM-E3 and GINFORS-E.

In scenario 9 (EU fit for 55 package including the gradual introduction of a CBAM), in GEM-E3 the introduction of CBAM is quite effective hence the carbon leakage rate - compared to the above-mentioned reference scenario - is actually nominally negative, i.e., leakage is lower. A reason for negative carbon leakage rates is that carbon prices for imports from non-EU countries to the EU increase by more than the carbon prices for products made in the EU (compared to scenario 6) due to scenario design, i.e. because of the existence of a carbon price in EU in the reference scenario: The increase for imports amounts to the full (high) carbon price observed in the CBAM scenario from zero in the reference scenario (Sc.6), while for domestic production it is merely the increase between the carbon prices of the reference scenario and the CBAM-scenario (Sc. 9) that result primarily from increased mitigation ambition. In GINFORS-E, the leakage rate in the CBAM scenario is also lower than under the scenarios without a CBAM for most ETS sectors, with the exception of paper.

Leakage rates of over (-)100% may come as a surprise, but they are possible in a global model because, unlike in a partial model with a fixed global production volume, e.g. for the steel industry, equilibrium or induced effects can lead to further effects in the total model, which in principle can lead to higher positive or negative effects globally on production and related emissions than in the EU itself.

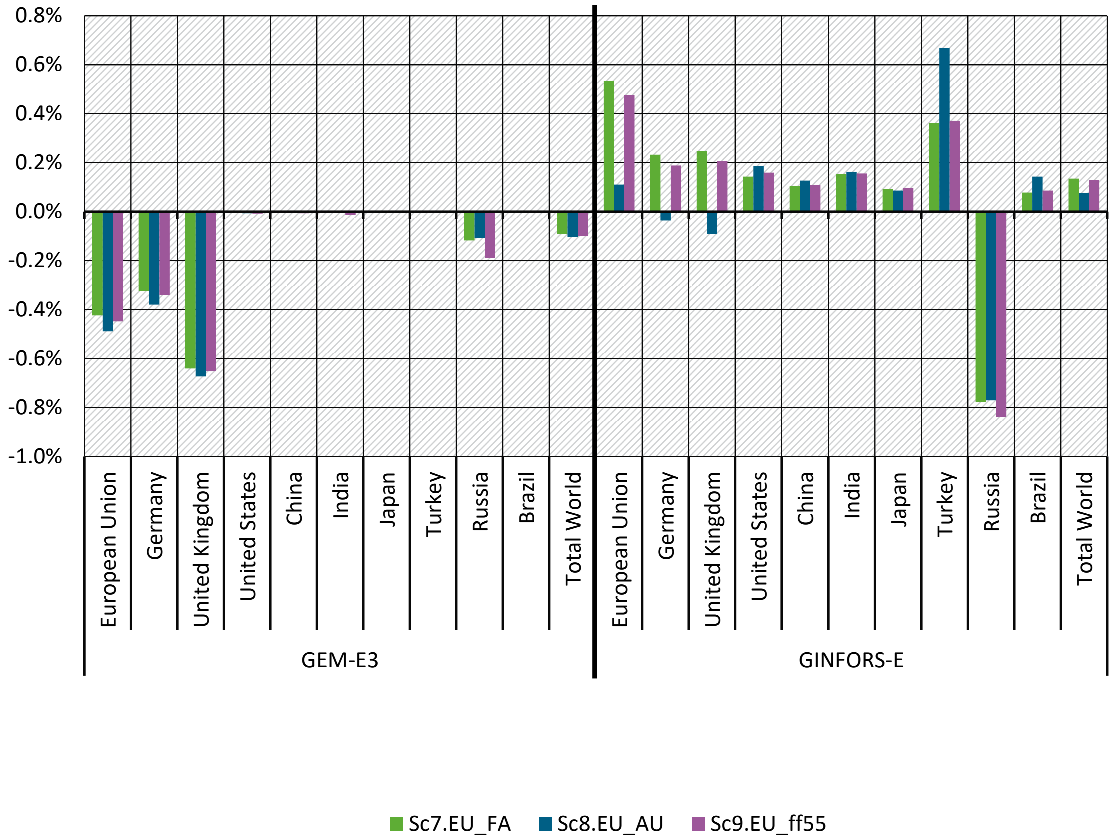
At a sectoral level, the leakage takes place in the carbon intensive and trade exposed sectors. According to both models, basic metals is the most vulnerable sector regarding carbon leakage. GEM-E3 also considers chemicals together with non-metallic minerals as sectors quite exposed. Both models present the highest carbon leakage rates in Scenario 8. Full auctioning increases the risk of carbon leakage considerably according to both models. At the same time, the differences for scenarios 7 and 8 *between* the two models are high. In GEM-E3, the leakage effects in the designated ETS sectors are between two- to ten-times higher than in GINFORS-E. In scenario 9 with the CBAM, GEM-E3 reports negative leakage rates for three of the four sectors listed in Table S-2, i.e. an additional emission reduction in non-EU countries takes place. A reason is that carbon prices for imports from non-EU countries to the EU increase by more than the carbon prices for products made in the EU: The increase for imports amounts to the full (high) carbon price observed in the CBAM scenario, while for domestic production it is merely the increase between the carbon prices of the reference scenario (Sc.6) and the CBAM-scenario (Sc. 9). In GINFORS-E, leakage rates are lower in scenario 9 than in the auction scenario 8 and even in the case of free allocation in scenario 7, with the exception of paper products and printing.

Aggregate Economic Effects: In the scenarios covering free allocation, full auctioning, and CBAM (scenarios 7 to 9), the country GDP effects are predominantly slightly negative in GEM-E3, and positive in GINFORS-E. Only in the case of Russia it is the other way around: the negative effects are much more pronounced in GINFORS-E than in GEM-E3. It is also interesting to note that the more positive GDP results in GINFORS-E apply both for EU countries with ambitious climate goals in scenarios 7-9 while also holding for (non-EU) countries without such goals. The difference in GDP in both models is driven by the crowding out effect and lower constraints in GINFORS-E as briefly described above. In GEM-E3 additional investments in clean energy have to be financed by cancelling investments of equal value elsewhere in the economy whereas in GINFORS-E the additional investments are financed from idle financial deposits. Additional investment has positive short-term demand effects but will increase capital costs in the long-term. So GINFORS-E allows for some temporal bringing forward of investments, which induces positive macroeconomic effects. In addition, the GEM-E3 model assumes full operation of equipment (factories), hence additional demand for goods may create inflationary effects (which lessen in the long term once investments increase the production capacity of the economy). On the other hand, GINFORS-E assumes utilization rates of below 1, i.e. availability of idle production capital, and it is possible for factories to meet the additional demand without the (full) inflationary effects.

As noted above, for the EU, the two models show different signs for the effects in 2030. In GEM-E3, the negative effects on GDP for the EU-28, Germany and the United Kingdom are between 0.3 and 0.6% compared to the reference. In the CGE model, higher CO_2 prices without any type of carbon revenues recycling leads to a deceleration of the growth rate in GDP. The effects are in a small range between 0.4 and 0.5 percentage points for the EU, strongest with full auctioning and smallest with free allocation of emission allowances. Other countries are hardly affected in GEM-E3. One exception is Russia, which can export less fossil fuels to the EU.

In GINFORS-E, on the other hand, the GDP effects in 2030 are positive for scenarios 7 to 9 compared to the reference for the EU, with the design of the EU ETS playing a significantly larger role. Here, the direction of the macroeconomic effects is open due to the structural changes induced by the carbon price increase, as the economy has unused resources in the reference. The increased CO_2 reduction in the core scenarios (7, 8 and 9) is associated with certain changes in production and consumption structures towards sectors with low carbon emissions and lower fossil fuel imports. Energy efficiency increases and clean energy technology costs are lower. While industrial production is slightly lower than in the reference, as prices increase, production in the construction and service sectors increases a bit. As these sectors account for most of the European production and value added, this change is sufficient for the slightly positive GDP effect in the EU.

Figure 2: GDP deviations from Sc6.NDCs_Ref for GEM-E3 and GINFORS-E in 2030

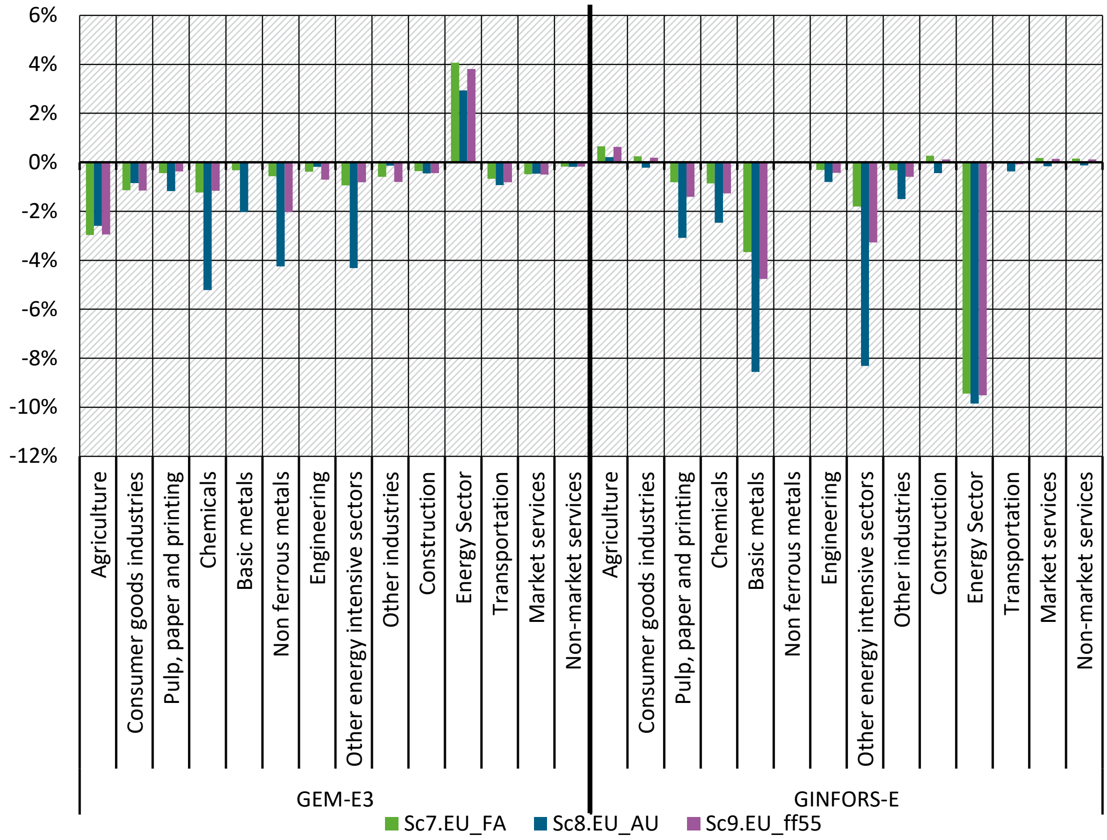


Source: GEM-E3 and GINFORS-E.

For the average annual growth rates, however, this means only very small differences between the results of the two models. When considering the differences in the sign of the GDP effects, it should always be considered that the long-term growth dynamics in both models are hardly changed by the climate protection measures.

Sectoral economic effects: The sectoral production effects in the carbon-intensive sectors are, by and large, negative in both models apart from the energy sector in GEM-E3. The degree of the production drop in the “Basic metals sector” and the “Other energy intensive sectors” (mainly non-metallic minerals such as cement) is somewhat larger in GINFORS-E. For “Chemicals” the drop for the auctioning scenario is larger in GEM-E3, while the effects for the other two scenarios are similar. In the other sectors, the overall effects also diverge, specifically for the Energy Sector.

Figure 3: EU sectoral production – deviations from Sc6.NDCs_Ref for GEM-E3 and GINFORS-E in 2030



Source: GEM-E3 and GINFORS-E.

In GEM-E3 and in GINFORS-E, the CBAM leads to less negative production effects than auctioning in all three energy-intensive sectors where it is applied – chemicals, basic metals, and other energy intensive sectors. Remarkably, in GEM-E3, CBAM even leads to positive production effects in 2050 for these three sectors compared to the reference scenario with less ambitious climate policy, whereas free allocation, and even more the auctioning case, have negative production impacts in these sectors. This might explain a part of the more positive effect in the CBAM scenario versus free-allocation scenario. In contrast, in GINFORS-E, the CBAM scenario leads to slightly larger drops in production than free allocation.

The effects on the energy sector go in opposite directions. In GINFORS-E, until 2030 reductions in gas consumption are not compensated by higher electricity production so that total energy production decreases. In GEM-E3, however, energy production increases due to electrification in the economy and deployment of biofuels until 2030 and the deployment of hydrogen and clean gas until 2050. In GEM-E3 and in GINFORS-E the CBAM protects the energy intensive industries in the domestic market, which leads to the reduction in imports. However, CBAM increases the production costs of downstream sectors (that are now purchasing more expensive imported materials). These downstream sectors include e.g. engineering, construction and agriculture, but also sectors covered by ETS, as they use their own products as inputs due to the broader sector coverage as well. This increase is having a negative impact on competitiveness and production. In non-energy-intensive sectors like services, the effects in GINFORS-E are slightly more positive.

Sensitivity analysis: The main leakage channel in both models is relocation of production and resulting changes in trade patterns, where the assumed values of Armington elasticities play a significant role. The analysis shows that higher elasticities lead to stronger effects in the carbon-intensive sectors. Moreover, GINFORS-E reacts more strongly to changes in the Armington elasticities than GEM-E3. A probable key factor here is the lower substitution elasticity, e.g., for the labour demand, in accordance with elasticities estimated by means of econometric analyses. With respect to CBAM design, the analysis shows that an extension of the scope towards indirect emissions of imports has a minor impact on results in both models, while the question of revenue recycling can notably improve the sectoral and aggregate impacts of unilateral EU climate action. Therefor it is important to recall that we assume a parallel phase-out of the current compensation payments for indirect costs by EU Member states. In this sense, recycling via e.g. the EU's Innovation Fund and Modernisation Fund, should be seen as essential elements of a successful climate mitigation policy.

Increasing non-EU ambition in climate mitigation in scenarios 13, 14 and 15 shows small negative impacts in the EU in GEM-E3 and in GINFORS-E. In 2050, unilateral action is slightly less economically beneficial in terms of GDP for the EU (due to lower demand of non-EU countries) than the participation of advanced OECD countries and China in climate mitigation in both models. But at least in GINFORS-E, climate mitigation with participation of other countries is still more beneficial than no additional climate action, at least in the cases of free allocation and full auctioning and close to zero in the CBAM case. These results partly contradict the expectation that global climate mitigation will be more economically advantageous for the EU than unilateral climate protection. This applies in any case to the carbon intensive industries in the EU. However, in other countries, increased climate protection sometimes results in slightly negative macroeconomic effects, which then more than offset the benefits for energy-intensive industries, which play only a minor role in the overall economy, for the EU as well.

Key insights: There is a risk of carbon leakage in the case of unilateral EU climate action. Carbon-intensive sectors lose international competitiveness and reduce production compared to a scenario without additional climate mitigation in both models. The macroeconomic costs in the form of GDP losses are limited in the GEM-E3 model. GINFORS-E even reports small GDP increases for the EU in the case of unilateral action. Negative macroeconomic and sectoral effects can be further reduced by appropriate design of the EU ETS including a CBAM. Both models show that the carbon leakage risk is no convincing argument against EU climate action, if EU ETS and CBAM are properly designed.

In general, the macroeconomic effects of additional international climate mitigation efforts are small, while the carbon emissions are reduced strongly. It is important to note that the economic benefits of global climate protection in the form of lower losses and damages are not included in the scenarios. They are expected to be several times higher than the reported macroeconomic effects of ambitious climate mitigation. The message of the study is positive: far-reaching climate protection worldwide is possible and leads only to marginal macroeconomic effects. CBAM (with auctioning) is the most suitable of the analysed design options of the EU ETS with regard to carbon leakage. The economic effects (GDP and sectoral industry production), in contrast, for the year 2030 are slightly more positive with free allocation. The results for full auctioning without a CBAM are clearly the worst.

Outlook: Future modelling could be improved in different directions in particular to better inform policy: Climate policy in the EU treats plants differently within individual industry sectors, which should also be better reflected in modelling. More sector detail is needed, especially for these CO_2-intensive sectors, because technologies and energy sources used, and thus CO_2 emissions, differ significantly. Furthermore, for policies such as the CBAM, current sector differentiation in the models is not adequate, as it (at its start at any rate) covers only parts of the sectors aggregated in the models (e.g. only fertilisers and ammonia, but not the chemical industry as a whole). In this regard, specific datasets such as EXIOBASE, GLORIA or GTAP could be explored to what extent more differentiated data is available and respective modelling is possible. This might follow the approach taken in the European Commission's Impact Assessment from July 2021 on the introduction of a CBAM which integrated data from EXIOBASE and included serval checks for consistency (EU 2021).

Distinguishing between parts of an industry that have already been transformed to climate neutrality and those that are still carbon-intensive would also be valuable for modelling. Model coupling with sector-specific models or energy system models could likewise be an approach for future improvements. Energy system or industry sector models have higher subsector differentiation and may also include technology differentiation, e.g. the separation between primary and secondary steel.

With regard to the industry sectors, it could also be considered and analysed in more detail how different behaviours and time horizons concerning low-carbon investment, which are also influenced by the political framework, can be depicted.

In addition, there is a need to further refine the modelling of climate policy design with a view to the sectors particularly affected and to better understand the impact channels. At the same time, a focus should also be on the newly emerging industries, which have played only a minor role in previous statistics and model data sets. They are at least as decisive for the socio-economic success of climate policy as the carbon-intensive industries. In political practice, policy measures often go beyond pure price instruments. These realities must also be included in climate policy modelling. In any case, it is important to understand what drives economic agents and how their behaviour can be targeted cost-effectively towards climate neutrality. To this end, data availability and computing capacities for modelling socio-economic impacts of climate mitigation policies are improving. At the same time, models will remain limited to relevant sub-areas of reality. To this end, they should be deepened in the future on the one hand and focused on central policy issues and product differentiations on the other.

1.3 WP2: Technical report

The technical report describes the methodical work to make both models largely consistent and subsequently apply four "exploratory" scenarios that do not refer to any particular policies but focus on different global ambition levels.

First, a common harmonization scenario assuming no substantial global climate protection is developed, which is used to calibrate the two models so that the model results in this scenario as well as central (predominantly) exogenous parameters correspond as closely as possible. For this purpose, the different databases and the model results for key results on population, economic growth, energy consumption and energy related GHG emissions are described.

The four exploratory scenarios cover a benchmark scenario and three global GHG reduction scenarios, two of which include uniform global carbon prices with which the 2° and 1.5° targets, respectively, can be achieved. In a further, modified 2° scenario, the EU achieves its climate targets from the “fit for 55” package in 2030 and 2050, while the rest of the world implements slightly less climate protection than in the “uniform price” 2° scenario, so that overall the global 2° target is reached. The results of the models are compared for important variables for selected countries and regions. The carbon prices are mostly higher in GINFORS-E than in GEM-E3, but in the “EU moves ahead” scenario, converge in the EU by 2050. The macroeconomic effects in both models are similar on global level. However, they differ significantly in terms of regional structure. While the EU and Germany in GINFORS-E benefit slightly from global climate mitigation in all scenarios, the effects in GEM-E3 are slightly negative in the scenario, in which the EU moves ahead, and in the scenario that achieves the 1.5° target. Compared to the foreseeable costs of climate change, the effects are small.

1.4 WP 3: Extended model overview

The aim of work package 3 is to provide an overview of different model types 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 report “Climate Protection Scenarios until 2050 considering CO_2 price differences and carbon leakage”: 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, macro-econometric models and computable general equilibrium (CGE) models. The same section then provides overviews of concrete models of the types of energy economic, macroeconomic (i.e., macro-econometric and CGE) modelling, and integrated assessment models. Section 4 describes selected macro-economic and 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.

1.5 WP 1: Effects of global CO_2 prices in long-term mitigation scenarios until 2100[2]

Integrated assessment models (IAM) derive global scenarios consistent with different global temperature targets. Out of the wealth of assumptions going into the models and the respective results, carbon price trajectories necessary to achieve the climate objectives have spurred the public and scientific debate. In 2017 the High-Level Commission on Carbon Prices (HLCCP) concluded that, "… in a supportive policy environment, the explicit carbon-price level consistent with the Paris temperature target is at least US$40–80/t$CO_2$ by 2020 and US$50–100/t$CO_2$ by 2030." (HLCCP 2017, p. 50). However, the price span is regarded as high. It also should be noted that the HLCCP conclusion looks at 2 °C scenarios. Carbon price levels for more ambitions climate mitigation scenarios will have to be higher and the price span likely to be higher.

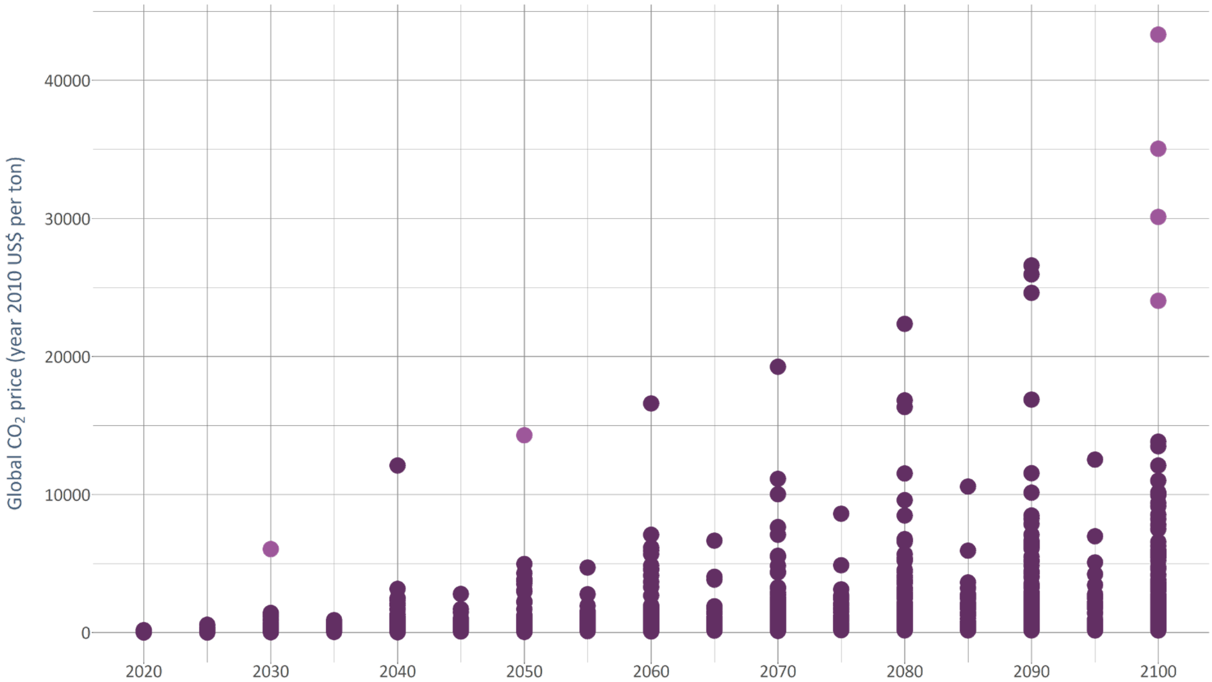
A first assessment of this correlation was presented by Guivarch & Rogelj (2017) who analysed simulation results from 18 ambitious integrated assessment studies from the Shared Socio-economic Pathways (SSP) database that limit global warming to below 2 °C with a probability greater than 66%. However, the data situation improved significantly thereafter with the publication of the Intergovernmental Panel on Climate Change (IPCC) special report on 1.5 °C global warming (IPCC 2018). 222 CO_2 price trajectories from integrated assessment studies of 2 °C and below-compatible emission pathways have been made publicly available together with other relevant data sets in the IAMC 1.5 °C Scenario Explorer (Huppmann et al. 2018; Huppmann et al. 2019). By analysing the global CO_2 price pathways reported in the February 2019 release 1.1 of this database, this work package 1 of the project therefore generated an extensive quantitative state of the art contribution to this debate.

The IAMC 1.5 °C Scenario Explorer has been published alongside the IPCC 1.5 °C Special Report. It provides a unique quantitative basis for further analyses of (among others) price trajectories observable in ambitious climate mitigation scenarios. By analysing this database, we complemented and extended the findings of the initial study of Guivarch & Rogelj (2017) by providing a broader and more robust empirical assessment. We reviewed and analysed characteristic trend dynamics of global carbon price projections from ambitious climate mitigation scenario simulations. The discussion of the prospects and challenges of in-depth bivariate econometric analyses of key impact factors is illustrated by individual correlation studies between simulated global carbon prices and selected model variables.

All annual price observations considered by us for these analyses are shown in Figure 4. Scenarios with reported year 2030 CO_2 prices below 5 US$/t have been excluded from our analyses. This reduced our analysed sample slightly to a total of 204 simulation result sets. For reporting years 2030, 2050 and 2100, light shaded dots indicate a total of six observations that were identified to represent apparent annual outlier values. These observations were therefore also removed from the sample in all subsequent year 2030, 2050 and 2100 analyses.

[2] This report has been published as a journal article in Environmental Research Communications (see Meyer et al. 2021). Major parts of the text in this summary are taken from this Journal Article.

Figure 4: Global carbon price simulations from 204 ambitious climate mitigation studies

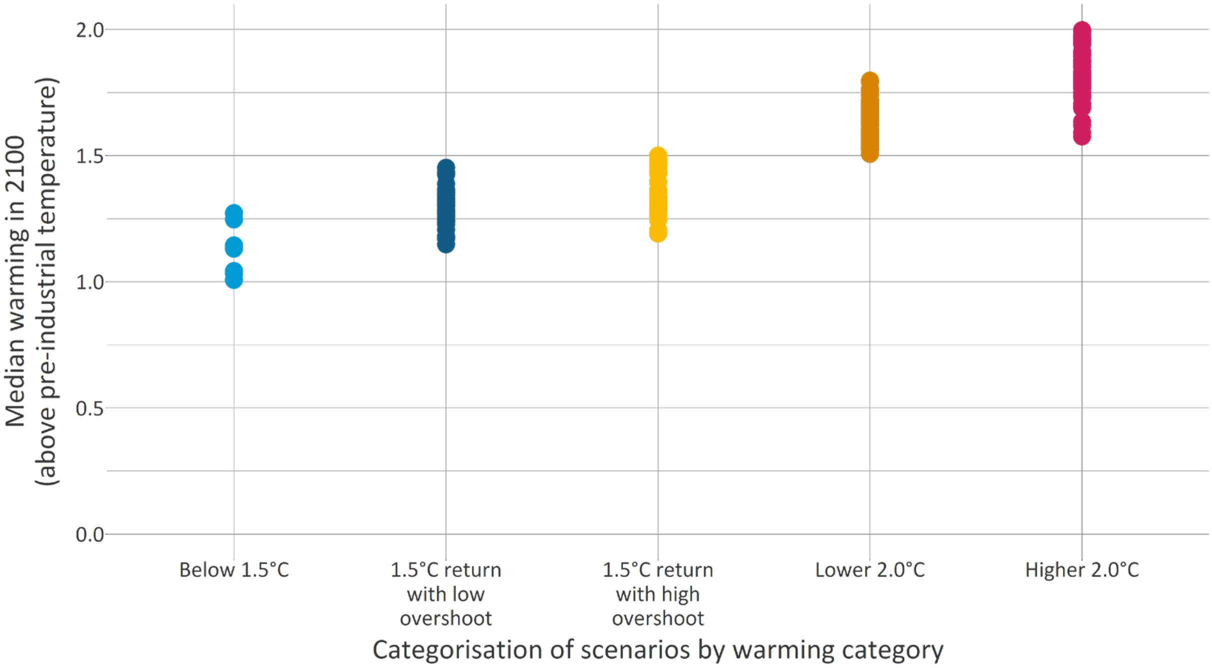


The figure merges annual global CO_2 price simulations as available in the IAMC 1.5 °C Scenario Explorer database from scenario simulations with median year 2100 warming levels remaining below 2 °C compared to pre-industrial levels. Scenarios with reported year 2030 CO_2 prices below 5 US$/t have been excluded.

Source: Huppmann et al. (2019). Own illustration, GWS.

For all observed 204 simulation result sets, their implied global warming effects are illustrated in Figure 5. This illustration assigns simulated year 2100 median warming levels from the scenarios to the respective IPCC warming categories. Most observations are assigned to the warming category "Lower 2 °C" (69 reported scenario results, marked in orange). 51 reported simulation results belong to the red marked, less ambitious but still 2 °C-compatible category "Higher 2 °C". The total set of 1.5 °C-compatible scenarios is represented by 84 simulation studies: 43 result sets are available from the class of "1.5 °C, low overshoot" scenarios marked in dark blue. 34 CO_2 price simulations are assigned to "1.5 °C, high overshoot" scenarios marked in yellow. From the most ambitious scenario class ("below 1.5 °C", marked in light blue), only seven CO_2 price time series have been analysed.

Figure 5: Categorization of analysed scenarios by year 2100 warming levels



The figure shows simulated year 2100 warming levels (°C compared to pre-industrial levels) resulting from the 204 scenario simulations from which the CO_2 prices shown in Figure 1 were extracted.
Source: Huppmann et al. (2019). Own illustration, GWS.

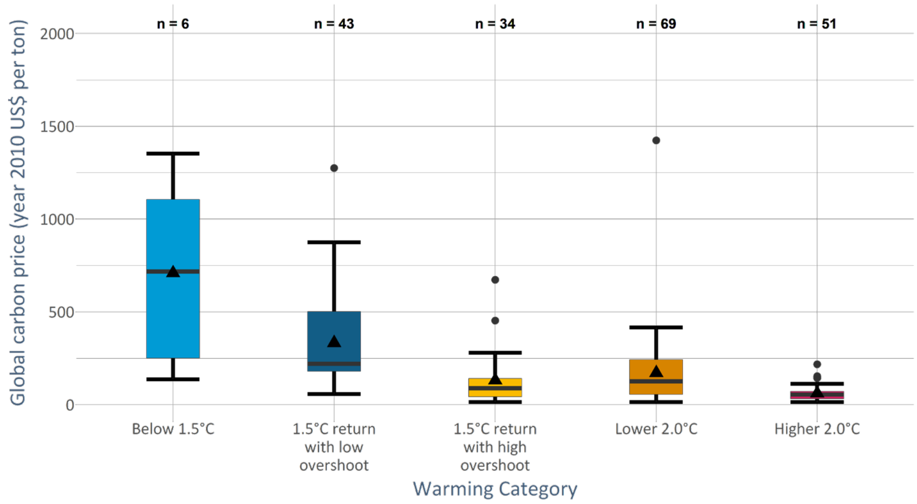
The distribution of global CO_2 prices observed in our sample for the years 2030 (upper graph), 2050 (middle graph) and 2100 (lower graph) are shown in Figure 6. The boxplots give median values of the observed annual carbon prices per warming category individually marked by a horizontal line; corresponding mean values are indicated by a triangle. Coloured boxes indicate the range of carbon prices between the first and the third quartile per warming category. Associated sample sizes are designated as *n*. As noted before, in this and all subsequent figures, individual annual outliers have been removed from the respective samples. For more details and additional comprehensive descriptive statistical information, see Meyer et al. (2021).

The simulated CO_2 prices increase significantly over time. Denominated in year 2010 prices, the median values for all carbon price observations analysed in Figure 6 equal about 106 US-$ in the year 2030 (which is in line with HLCCP, 2017), 319 US-$ in the year 2050 and 1477 US-$ in the year 2100. Referring to conditional median values, the comparison across respective warming classes shows that more ambitious climate protection levels tend to be simulated with higher carbon prices. This finding is valid for the short as well as for the medium to long term. However, this finding is not unambiguous. Therefore, it is for example not excluded that a 1.5 °C compatible scenario is simulated with global CO_2 prices that exceed the level of CO_2 prices of an alternative 1.5 °C compatible simulation.

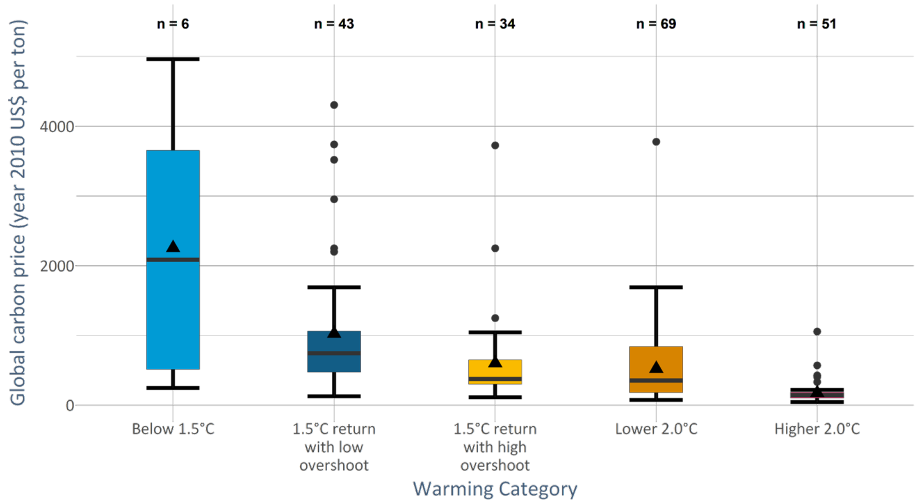
To understand individual CO_2 price dynamics, additional scenario components must be considered. For this, it is necessary to analyse the influence of additional model variables and scenario parametrisations. The IAMC 1.5 °C Scenario Explorer is capable to provide extensive data in this regard. In the database version analysed by us, the simulated dynamics for nearly 600 variables could be stored. However, this potential maximum observation range is usually not available for multivariate analyses. Not every model simulates every variable covered in the database. Consequently, available sample sizes may differ considerably among individual variables.

Figure 6: Distribution of simulated global carbon prices in the years 2030, 2050 and 2100

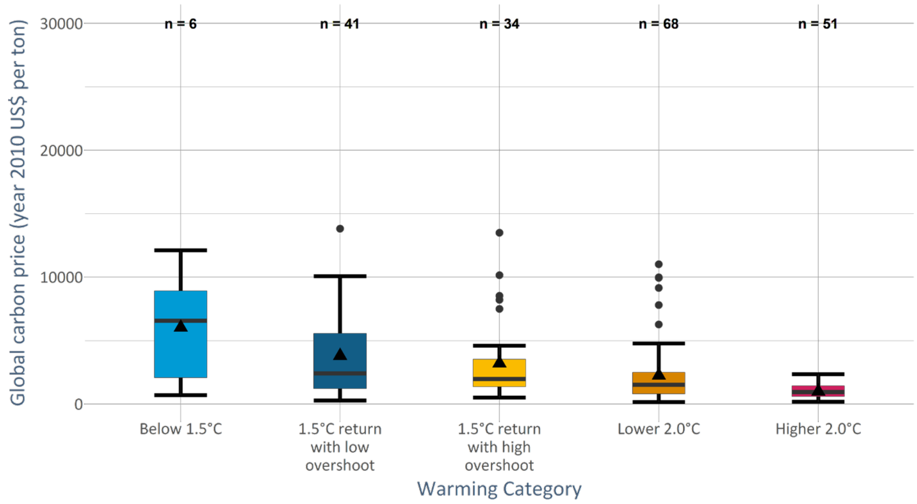
Year 2030 observations (annual outlier values removed)



Year 2050 observations (annual outlier values removed)



Year 2100 observations (annual outlier values removed)



Source: Huppmann et al. (2019). Own illustration, GWS.

In consultation with UBA and Federal Ministry of Economic Affairs and Climate Action as the clients of this research, individual variables were therefore selected for bivariate correlation studies. Applied selection criteria were UBA's analytical interests as well as individual data availabilities. The following box summarises the quantitative results from these analyses of the correlation between global carbon prices and, respectively, global GDP, global energy intensity, global emission intensity, global biomass-based primary energy supplies, global nuclear electricity supplies, global applications of carbon sequestration techniques, global per capita primary energy volumes, global freight transport volumes as well as global dietary habits.

Key findings from bivariate correlation studies

The quantitative findings illustrated in Appendix A in Meyer et al. (2021) can be summarized qualitatively as follows:

- Scenarios with relatively low GDP values tend to be characterized by relatively high CO_2 prices.
- 2 °C-compatible scenarios with low primary energy intensity tend to be characterized by relatively high CO_2 prices, at least in 2030, which seems to level off towards the end of the observed simulation period.
- Scenarios with lower initial emission intensities are characterized by lower short term CO_2 prices. In the long run, scenarios with relatively low cumulative emissions tend to be characterised by higher CO_2 prices.
- Scenarios with a relatively high primary energy supply based on biomass show higher simulated carbon prices compared to scenarios with a relatively low primary energy supply based on biomass.
- In the short term, scenarios with high electricity production based on nuclear energy tend to be characterized by higher carbon prices. But in the long run, scenarios with relatively high nuclear power production levels tend to be simulated with relatively lower carbon prices.
- In the short term, scenarios with high CCS deployment levels tend to be characterized by higher carbon prices. But in the long run, scenarios with relatively high CCS deployment levels tend to be simulated with relatively lower carbon prices.
- In scenarios with relatively low per capita primary energy consumption simulated CO_2 prices are usually higher than in scenarios with relatively high per capita primary energy consumption. But these differences between categories seem to level off over time
- In scenarios with relatively low freight transport volumes the simulated CO_2 prices are usually higher than in scenarios with relatively high freight transport volumes.
- In the short run, simulated CO_2 prices in scenarios with relatively low meat consumption are generally higher than in scenarios with relatively high meat consumption. However, these differences between categories seem to level off over time.

It should be highlighted that our analysis rests on a decidedly large dataset. Prior to the publication of the IAMC 1.5 °C Scenario Explorer, only a limited number of simulation results from 2-degree compatible (or even more ambitious) scenario projections could be analysed. Based on a much smaller set of scenarios and models, Guivarch and Rogelji (2017), for example, concluded that the largest part of the carbon price variation (90%) is due to inter-model differences and only a small fraction of carbon price differentiation can be attributed to socioeconomic variations as represented by the different SSPs.

Our empirical findings indicate that the observed price developments may be impacted much more strongly by scenario-specific influences. But these findings can only be inferred from a comparison of numerous different scenario projections for individual models. As the evidence base of previous studies appears to be relatively narrow in this respect, it is statistically plausible why predominant influence may have been previously attributed to model-specific effects.

Based on our findings, we therefore advise policy makers not to rely simply on any given Integrated Assessment study as a reference to “the” necessary CO_2 price for reaching specific climate targets. To avoid serious misunderstandings, modellers should clearly communicate whether and under which assumptions the CO_2 price paths of their simulation studies can function as reference points for concrete policy measures.

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