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CARBON MITIGATION APPROACHES
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Approaches to linking models to assess the impacts of climate change mitigation actions on greenhouse gas emissions

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Background

The Inclusive Forum on Carbon Mitigation Approaches is the OECD's flagship initiative to help optimise the global impact of emissions reduction efforts around the world through better data and information sharing, evidence-based mutual learning, and inclusive multilateral dialogue.

By taking stock of different carbon mitigation approaches, mapping policies to the emissions they cover, and estimating their comparative impact in terms of emissions reductions, the IFCMA is enhancing understanding of the effect of the full spectrum of carbon mitigation approaches deployed around the world and their combined global impact. The IFCMA is also identifying and addressing challenges related to the calculation of sector- and product-level carbon intensity metrics, relevant to the design and evaluation of mitigation policies, and to steer firms' and consumers' decisions towards lower-emission products. This work supports better international coordination to avoid the proliferation of different standards, help minimise compliance costs for business, and avoid disruptions to trade.

To advance its technical work, the IFCMA brings together delegates from the climate, tax, and structural economic policy communities from more than 55 IFCMA members and numerous countries participating as Invitees around the world.

Inclusive Forum on Carbon Mitigation Approaches Papers

The IFCMA Papers series brings together outputs from the initiative's work to take stock of different carbon mitigation approaches, map policies to the emissions they cover, and estimate their impact on greenhouse gas emissions, as well as its work on analysing methodologies for computing the carbon intensity of goods and sectors. Comments on IFCMA Papers are welcome at IFCMA@oecd.org.

Executive Summary

This paper explores how to link different modelling approaches to enable a detailed and comprehensive assessment of the impact of climate-relevant price-based and non-price-based policies on greenhouse gas emissions. It aims to guide the development of a consistent methodological framework that combines sectoral, bottom-up models, offering a disaggregated representation of mitigation options and policies, with economy-wide models, which provide a broad coverage to assess indirect impacts on emissions. The paper reviews potential ways to link these complementary approaches and presents a framework to evaluate different methodological options based on their advantages and challenges Finally, the paper provides a blueprint for operationalising the methodological framework to assess the impacts of climate action on greenhouse gas emissions across a broad and diverse set of countries, sectors, and policy instruments.

Keywords: climate change mitigation; climate policy; impact assessment; modelling

JEL classification codes: Q48: Agricultural and Natural Resource Economics; Environmental and Ecological Economics / Energy / Energy: Government Policy; Q54: Agricultural and Natural Resource Economics; Environmental and Ecological Economics / Environmental Economics / Climate; Natural Disasters and Their Management; Global Warming; Q58: Agricultural and Natural Resource Economics; Environmental and Ecological Economics / Environmental Economics / Environmental Economics: Government Policy

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Table of contents

FIGURES

TABLES

1 Introduction

Greenhouse gas emissions from a wide range of anthropogenic activities contribute to climate change. An ambitious set of mitigation actions is required, covering a broad set of sectors, products, gases, and economic agents. A system-wide perspective on how emissions are linked to economic activities and interactions between economic sectors is therefore important to develop a comprehensive view on the direct and indirect impacts of climate change mitigation action on greenhouse gas emissions.

Countries differ significantly regarding the sources of emissions, sectoral structure of the economy, natural resource availability, infrastructure development, and technology options. Differences in the policy approaches and instruments implemented in each sector further amplify this diversity. Pricing, regulation, investments, or other types of public intervention differ in how they affect behaviours, technology choices, and the corresponding impact on greenhouse gas emissions. Given this diversity, assessments of the potential impact of policy approaches and instruments on greenhouse gas emissions can benefit from taking country- and sector-specific circumstances into account (Bataille et al., 2016[1]).

At the same time, adopting a consistent methodology to assess the effects of implemented climate-relevant policies on greenhouse gas emissions across a wide range of countries and sectors can enable insights that foster mutual learning on the effectiveness of different policy approaches (Fujimori et al., 2021[2]). In this spirit, pilot studies within the Inclusive Forum on Carbon Mitigation Approaches (IFCMA) will use quantitative modelling to explore combinations of sectoral and economy-wide models. These studies aim to integrate a broad, system-wide perspective with detailed technological insights, with the intent to capture cross-country and cross-sectoral variations in a consistent manner. The broader goal of the modelling work in IFCMA is to assess the direct and indirect impact of implemented or legislated climate-relevant policies on greenhouse gas emissions, in view of optimising the global impact of emissions reduction efforts around the world through better data and information sharing, evidence-based mutual learning and inclusive multilateral dialogue. This will require scaling up the model-based assessment to a wider set of sectors, countries, and policies after conducting the pilot studies. The focus on *implemented* policies differs from typical modelling studies, e.g. those in support of Nationally Determined Contributions (NDC) or Long-Term Strategies (LTS), offering fertile ground for novel insights while requiring careful attention to policy (implementation) details.

How to link sectoral, bottom-up models offering a disaggregated representation of mitigation options with economy-wide models (such as the OECD's ENV-Linkages Computable General Equilibrium model, see (Château, Dellink and Lanzi, 2014[3])) is the central focus of this paper. An earlier OECD report (Pisu et al., 2023[4]) presents a broader overview of methodological options for assessing and comparing climate change mitigation policies across countries, including a discussion on the advantages and limitations of *ex-ante* modelling and empirical methods in estimating the effectiveness of different policy instruments[1]. It also presents key assumptions to allow quantification based on linked sectoral and economy-wide models and illustrates existing experience with linking OECD's in-house economy-wide model to sectoral models. More generally, the merits of combining different modelling approaches to assess and inform climate policy have been described in academic work (see Weitzel et al. (2019[5]) and Geels, Berkhout and van Vuuren (2016[6])). Learning from good practice examples and identifying general challenges in linking models

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[1] For a typology of model types, see also Annex 2 of Tamminen et al. (2022[56]).

(based on past work and through pilot studies) can inform the development of a consistent methodological framework for an assessment with broad sector and country coverage.

Section 2 of this paper reviews potential ways to link complementary models to assess the impact of policies on greenhouse gas emissions. Section 3 presents an evaluation of different methodological options, developing criteria that speak to benefits and drawbacks of model-based scenarios in national and cross-country assessments. Section 4 lays out the key steps in operationalising a methodological framework tailored to a context of multi-country assessments, such as the OECD's IFCMA, drawing on examples from the literature and building on previous in-house OECD experience.

2 Methodological options

In selecting an appropriate modelling approach to estimate the impact of mitigation actions on emissions, one needs to strike a balance between achieving a minimum degree of harmonisation to ensure sufficient cross-country comparability and having to capture as best as possible country-specific features. This is in recognition that a similar policy implemented in a given sector can have different impacts in different countries, given varying country contexts.

Combining insights from technological and economic viewpoints has become common practice in quantitative assessments of climate policy. In fact, integrated assessment models (IAMs), which provide the bulk of the scenario base behind IPCC assessment reports, combine different modules that are each dedicated to specific areas, such as energy, agriculture, the macro-economy, or the biophysical world, in one encompassing framework. While this section briefly discusses IAMs as specific examples of model linking, the focus lies on the advantages and limits of dedicated, stand-alone sectoral and economy-wide models, the advantages of analysis drawing on both types of models, and the various options for linking the two types of models.

Sectoral models are highly granular models that can represent technological, behavioural and policy detail while capturing sector and country-specific context. This enables a granular assessment of emission changes associated with measures targeting specific emission sources. Sectoral models focus on specific markets for some broad activities (e.g. agriculture and food systems, energy systems, transport) or even on a specific commodity (e.g. iron and steel, plastics). Often these sectoral models are Partial Equilibrium (PE) models, which represent supply, demand, and prices in a particular sector. Some of them can model specific mitigation options, such as further integration of intermittent renewable sources in the power system, technology choices to transform vehicle or building stocks, or options to strengthen the natural carbon sink through land use change. Although they might differ in their underlying philosophy (e.g. simulation vs optimisation model, or empirical vs theoretical basis), in general sectoral models are able to deal with specific and narrowly defined policy changes because of their granular representation of sector-specific technologies and mitigation options, in addition to other details affecting production and consumption choices in specific sectors. Sectoral models can be limited in scope to cover one country in isolation or can have broader coverage of several countries. Single-country sectoral models are malleable to country-specific circumstances. Multi-country sectoral models offer a consistent treatment across countries or regions and can potentially capture interactions across countries endogenously.

However, sectoral models provide an incomplete perspective on the emission changes in other parts of the economy or resulting from economic interactions across sectors, policies, agents, countries and through macroeconomic adjustments. They do not draw a complete macroeconomic picture of the economy, as they exclude large parts of the economic system or consider key macroeconomic variables (e.g. GDP, some international prices) as exogenous. As such, they tend to preclude the analysis of second-round effects (including “rebound effects”), economic interactions, and spill-overs. These general equilibrium effects are central to any analysis that aims to identify the broader effects of mitigation actions on all sectors, including indirect and spillover effects, in order to help optimise their impact on emissions.

Economy-wide models, such as Computable General Equilibrium (CGE) models, represent a complete economy, including inter-sectoral linkages and, in the case of the OECD ENV-Linkages model, inter-country linkages. However, general equilibrium models are typically less detailed than sectoral models on technology options, definitions of goods and subsectors, and their possible interactions with policies. Furthermore, CGE models focus on market variables and often do not explicitly represent biophysical processes underlying climate change, energy system transformation, land use, crop growth or resource depletion. They provide a more generic or aggregate depiction of mitigation options than what is captured in detailed sectoral models (Delzeit et al., 2020[7]). Economy-wide models can represent emission changes resulting from policies taking into account the interactions between agents, sectors, policies, and countries.

Hybrid models aim to strike a balance between providing a complete macroeconomic picture and reflecting technological details. In most applications, hybrid models are either sectoral models extended with macroeconomic features or they are economy-wide models augmented with a detailed sectoral component (Hourcade et al., 2006[8]). A hybrid model can thus be created from different starting points: broadening sectoral models or providing more granular detail to economy-wide models. Many general equilibrium models that are used for climate and energy analysis, including the OECD ENV-Linkages model, are to some extent hybrid models. For instance, these models represent various electricity production technologies in an economy-wide model. Typically, hybrid models cannot offer the same level of technology details as dedicated sectoral models, as they generally improve the representation of one sector (in one country) while providing a more stylised view on other sectors.

Other approaches have been developed to enhance economy-wide modelling in view of estimating impacts of climate policy measures that are consistent with more granular, complementary methods. Generally, two approaches can be distinguished depending on whether the additional quantitative inputs stem from *ex-post* or *ex-ante* assessment approaches. First, the parameters of the economy-wide model can be calibrated to *ex-post* empirical evidence. Applications of this approach related to climate policy include economy-wide models with empirical foundations for production functions (van der Werf, 2008[9]) and knowledge diffusion (Bretschger et al., 2017[10]). Most economy-wide models rely on some empirical base for at least part of the parameter settings. However, models that build directly on empirical evidence derived for the specific exercise to enhance economy-wide models are not commonplace, as credibly estimating (a large set of) parameters for the model is challenging, as it requires a combination of both modelling and empirical skills. Nevertheless, a large amount of empirical evidence is being collected on climate policies (see for instance Teusch et al. (2024[11])), including under IFCMA, which could provide a fertile ground for further integration with models. Second, *ex-ante*, bottom-up modelling can provide scenario results that feed into the calibration of the economy-wide model (i.e. setting the value of parameters to reflect input data). This approach aligns responses of the economy-wide model to policy changes with outcomes of sectoral model scenarios. The aim of this approach is to run the economy-wide model as a stand-alone tool for climate policy assessment, ensuring broad alignment with detailed, sectoral models without explicitly representing underlying technological detail. An example of this approach is the IMF-World Bank Climate Policy Assessment Tool (CPAT), which builds on both *ex-ante* and *ex-post* evidence, e.g. for determining power sector responses and GDP impacts (through fiscal multipliers). In the remainder of this paper, the combination of economy-wide CGE modelling with *ex-post* evidence or *ex-ante* sectoral model outcomes are described by “empirical evidence + CGE”. This approach is sometimes referred to as calibration (first approach) or emulation (second approach) and differs from the ‘pure’ linking approaches in that the alignment of models occurs in the model development rather than in the model application stage. To offer a more comprehensive view, this paper adopts a broad definition of linking to extend the methodological discussion to “empirical evidence + CGE”.

Linking sectoral and economy-wide models offers a way to overcome their respective limitations, combining the granularity of sectoral modelling and the ability of economy-wide models to assess indirect effects of climate policy. For instance, improvements in efficiency in the energy supply sector can ‘rebound’ when other sectors expand output or energy use in response to lower energy prices, (partially) reversing the reduction in energy use due to energy efficiency gains (Lemoine, 2020[12]). Likewise, macro-economic and trade feedback effects, changes in activity levels (e.g. sectoral output or passenger-kilometres driven), income effects, price effects, interactions with overlapping and complementary policies, fiscal interactions and tax revenue use, and labour market effects are channels that can amplify or mitigate the impacts of policies on greenhouse gas emissions. Combined, these indirect effects can exert a large influence over the total effect of policy measures on greenhouse gas emissions and are therefore important to capture.

A variety of methodological approaches to linking sectoral and economy-wide models is used in various contexts both in the academic literature and in policy assessments. The choice of an appropriate framework depends on the questions at hand. This paper focuses on assessing the impact of policies on greenhouse gas emissions (for approaches to assess socio-economic outcomes, see Van Ruijven et al. (2015[13])). Some analyses in the literature focus on different policy issues, but still offer useful insights on linking models that are useful for this discussion in this paper; these are referenced as needed here.

On a technical level, several approaches exist to link sectoral and macroeconomic general equilibrium models, varying in the degree of model integration (Delzeit et al., 2020[7]). Higher integration offers higher consistency between the models, at the cost of higher data requirements, computational burden, and the need to coordinate more closely the teams maintaining the models. Table 1 provides an overview.

Table 1. Overview of linking methodologies

	Information flow	Linking procedure*	Strengths	Weaknesses
One-way linking				
Bottom-up	Sectoral→CGE	One step	More granularity in macro context	Macro feedback does not affect choices at disaggregate level
	Empirics→CGE	One step	Strong internal validity	No macro-feedback. Could lack external validity
Top-down	CGE→Sectoral	One step	Economy-wide drivers in sectoral modelling	Technological detail does not affect choices at aggregate level
Two-way linking				
Soft-linked	Sectoral↔CGE	Iterative	Consistency along selected dimensions	Resource intensive
Hard-linked	Sectoral↔CGE	Simultaneous	Consistency along selected dimensions	Resource and computationally intensive

Source: Authors.

*One-step: one model solves the mathematical problem after the other. Iterative: one model after the other, repeatedly. Simultaneous: one common solution that satisfies the equations of both models at the same time.

One-way model linking

In **one-way linking**, the output of one model is used as an exogenous parameter or variable in the other, so that information flows only in one direction. One-way linking allows results from one model to affect those of the other model but does not allow closing the loop as it does not consider feedback effects. For example, if a sectoral model predicts higher energy prices resulting from policy action in the energy sector, then the linked economy-wide (general equilibrium) model will capture the changes in consumption of non-energy products and the associated emissions. However, one-way linking does not capture further feedback from the general economy to the energy sector, such as responses to reduced energy demand due to a general slowdown of the economy or output reductions of particular sectors caused by higher energy prices. While one-way linking does not capture feedback effects, it does not preclude harmonisation of both models by using common data, such as population and GDP obtained from demographic and macroeconomic projections. One-way linking can be bottom-up when information flows from the granular sectoral model to the economy-wide model or top-down when information flows from the economy-wide to the granular model.

One-way **bottom-up linking** is used to complement scenarios generated in a sectoral model to assess the effects of mitigation actions with an economy-wide analysis of impacts on greenhouse gas emissions.

- In bottom-up linking, the parameters in the economy-wide (general equilibrium) model are adjusted so that its results (e.g. power mix and fuel use across sectors) are aligned with the predictions of the sectoral model. Parameters that are adjusted can include production (e.g. factor efficiency, elasticities), consumption (e.g. preferences for goods and services) or both (Delzeit et al., 2020[7]).
- **Empirics-to-CGE** bottom-up linking feeds results from statistical estimation, instead of results from a sectoral model to the macroeconomic analysis. Examples include substitution elasticities for trade flows, production input choices, fuel shift, and power mix, as well as price elasticities of demand for goods and services. The parameters in the economy-wide model can be calibrated to the results collected through econometric techniques. Both national and international (or cross-country) findings can in principle be accommodated in a CGE model. Statistical estimates are characterised by uncertainty even when the estimate is unbiased, i.e. the 'true' parameter falls within an interval with a certain statistical confidence. Ideally, this uncertainty is preserved after the linking. Findings from empirical analysis have the potential to maintain a strong internal validity with respect to the application of a policy in a certain country, because they are estimated on data directly relevant for the specific case. This means that they are highly informative on the parameters relevant for that case. However, they could lack external validity when linking empirics to an economy-wide model. This means that they could be difficult to generalise further to other applications, thus limiting the potential application of this approach.

One-way **top-down linking** is predominantly used to offer macroeconomic input to sectoral models. In top-down linking, the endogenous variables of the economy-wide (general equilibrium) model are taken as exogenous inputs of the sectoral model. This mostly includes aggregate variables such as GDP, employment, or international fossil fuels prices, but it can also be extended to some other features, such as trade patterns or changes in sectoral composition of the economies.

Two-way model linking

In **two-way linking**, the two models exchange information in both directions, striving to reach convergence of the common variables. Two-way linking provides a higher level of integration than one-way linking, as it aims to reach full consistency of the results, at the cost of significant additional complexity. Applications of two-way linking are motivated by an interest in variables from both models, rather than just the variables from the 'receiving' model. Two-way linking provides better estimates for these variables when the second-order effects caused by closing the loop between the two models are large.

Two-way linking can be achieved through **soft-linking**, in which the two models iterate between each other until they reach convergence, or **hard-linking**, in which the two models operate in an integrated way to find a solution that satisfies the equations of both models simultaneously. The terms “soft-linking” and “hard-linking” are used inconsistently in the literature, as the same terms could be used to denote whether the exchange of information between models is mediated by the user or computer programs (Wene, 1996[14]). “Soft-linking” is sometimes also used as a synonym of one-way linking.

In the current paper, “soft-linking” refers to running the sectoral and economy-wide models independently and exchanging information between them in between model simulations, but not during either model simulation. In theory, both iterative and simultaneous solutions are supposed to produce identical results as long as the same information is passed between the two models. However, in practice results might differ if the convergence of common variables is different, for example because the iterative process does not converge fully. Therefore, the choice between soft- and hard-linking is often determined by practical considerations and balancing trade-offs between modelling constraints and stricter convergence of the models.

Multi-model linking

Modelling frameworks with a broad coverage sometimes combine various linkages into one ‘modelling toolbox’ or ‘modelling ecosystem’. Such a framework can arise by bringing together several existing models for a particular exercise, such as developing a long-term climate strategy (Weitzel et al., 2019[5]). This approach largely employs the types of linking techniques described above but applied to more than two models to ensure in-depth treatment of multiple areas, such as energy, food and economic systems.

Integrated Assessment Models (IAMs) provide another example of linking. IAMs link geophysical modules affecting climate change with energy and economic modules, and model the feedback loops between the three. While most IAMs adopt a global or regional perspective, they differ significantly in the levels of technological disaggregation. Detailed process-IAMs offer significant technological disaggregation through the coupling of models or integration of sectoral modules. The REMIND-MAgPIE model (Bauer et al., 2020[15]), for instance, combines an energy-economy (REMIND) and a land use model (MAgPIE) through an iterative soft-link approach. The REMIND model itself hard-links a macro-economic growth model with a bottom-up energy system model via final energy demand and energy system costs. The IMAGE integrated assessment modelling framework (Doelman et al., 2018[16]) is another example where different modules are either soft-linked through an iterative data exchange (e.g. with the TIMER energy model) or hard-linked to the model core (e.g. carbon and hydrological cycles in the LPJmL model).

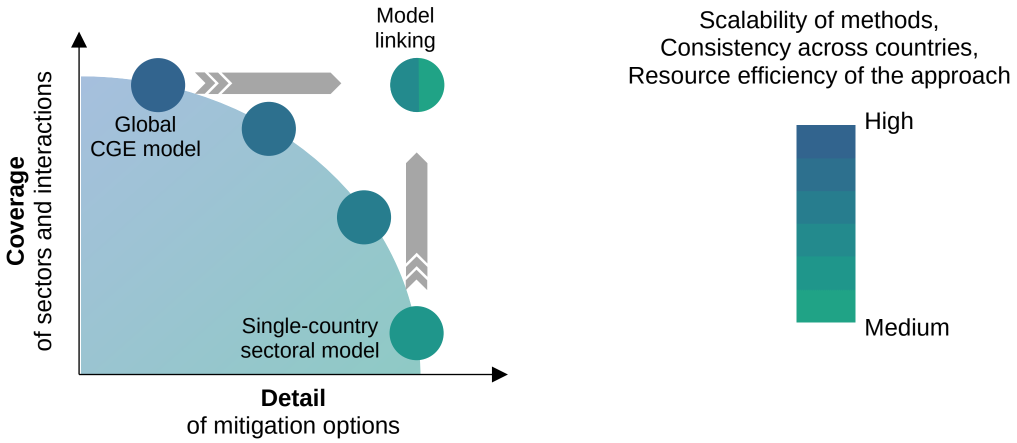
3 Evaluating methodological options

The previous section provides a broad overview of different approaches to assess the impact of policies on greenhouse gas emissions without providing guidance around methodological choices. Each of the highlighted tools, either in isolation or combined, can provide relevant answers to pertinent questions related to climate policy. The optimal methodological choice of what models to use and whether to link them depends on several factors, including the question at hand, the envisaged outcomes, the sector and policy instruments to be studied, and broader considerations such as the available time and resources.

This section zooms in on a set of methodological approaches that are particularly relevant for assessing the direct and indirect impacts of climate and climate-relevant policies on greenhouse gas emissions across a diverse set of countries, sectors, and policies. Whether and how to link models and what type of linking to pursue involves choices that will affect different dimensions of the analysis and will result in different methodological approaches. Box 1 lays out the criteria to guide the selection of the methodological approaches. These criteria are developed bearing in mind the importance of a consistent methodology in assessing the effects of implemented climate-relevant policies on greenhouse gas emissions across a wide range of countries and sectors.

The remainder of this section presents a preliminary evaluation of different methodological options based on the OECD track record on modelling and drawing on past experiences linking ENV-Linkages with sectoral models (such as the IEA World Energy Model). Any methodological choice will inevitably entail trade-offs in at least one dimension. Figure 1 visually represents this concept of trade-offs by depicting a modelling possibility frontier in two dimensions: coverage of sectors and interactions, and detail of mitigation options. Modelling approaches take different positions on this frontier, with sectoral models with a granular disaggregation of technologies on the bottom right and global CGE models on the top left. Hybrid CGE models with technology details for some sectors (e.g., power, transport, or buildings) and global energy system models can be examples of model types occupying intermediate positions.

Figure 1. Trade-offs in methodological choices



The purpose of developing the list of criteria included in Box 1 is to make these trade-offs explicit, to enable an informed consideration of the methodological options that can be used to assess the direct and indirect impacts of climate-relevant policies on greenhouse gas emissions. The evaluation presented in this paper is based on existing studies and knowledge, but can be refined by testing different approaches in pilot studies spanning a range of diverse countries, sectors, policy instruments and methodological approaches.

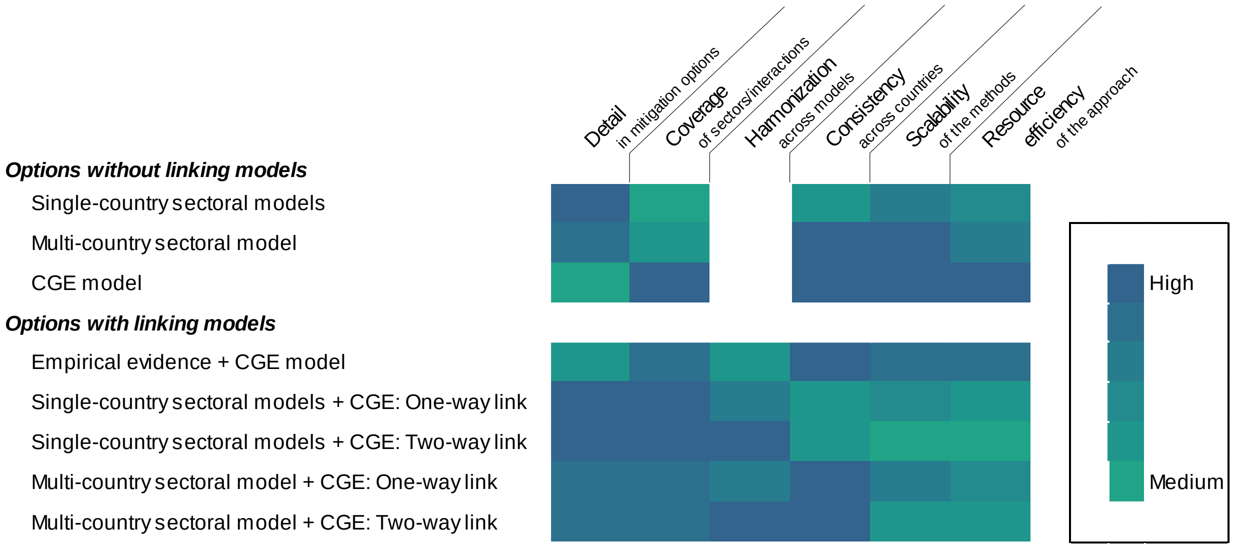
Box 1. Criteria to guide the selection of the methodological approaches for assessing the direct and indirect impact of climate-relevant policies on greenhouse gas emissions across countries

1. ***Detail*** in mitigation options that can be represented by the model: Granularity in terms of sectors, fuels, and technologies and abatement options enables capturing more implementation details of different policy instruments and allows for a more refined assessment of the impact on greenhouse gas emissions, taking country-specific information into account.
2. ***Coverage*** of sectors and interactions: Well informed discussions on optimising the global emission impact of mitigation efforts call for a methodological framework that covers a wide range of emission sources and their underlying drivers and technologies. Methodological options with extensive coverage can account for (economic) interactions across agents (households, firms, government), sectors, policies, and countries, and will therefore provide a more comprehensive view on the effects of policies on emissions across the economy.
3. ***Harmonisation*** across models: When linking different types of models, harmonising data and aligning projections for and impacts on common variables, including the strength of responses of agents to policy changes, improves the robustness of outcomes and enhances the complementarity of different assessment tools.
4. ***Consistency*** across countries: Ensuring a common methodological base and harmonised data that are consistent across sectors and countries can facilitate the international climate policy dialogue by reducing technical barriers that drive heterogeneity in the estimation of the impacts of policies on greenhouse gas emissions.
5. ***Scalability*** of the methodological approach: The ease with which a methodological approach can be applied to a wider range of countries, sectors, and instruments will be key for a quantitative, model-based assessment with a broad scope. This criterion accounts for computational and organisational complexity.
6. ***Resource efficiency***: Delivering valuable insights effectively requires considering which tools are available in associated institutions and countries and how other workflows and synergies can be leveraged. This criterion considers the resource needs associated with broadening the scope of the analysis to new sectors and countries.

As represented in Figure 2, none of the methodological approaches laid out in Section 2 dominates the other across all selection criteria. This means that favouring one option over another necessarily introduces a trade-off in at least one dimension. One general finding is that linking sectoral and economy-wide models is a way to overcome the trade-off between *detail* and *coverage*. One-way linking offers a more *scalable* and *resource efficient* way to assess multiple countries, in comparison to the theoretically superior two-way linking, which is an important consideration for practical, model-based assessments with a wide scope. Additional trade-offs may differ depending on the specific model. Figure 2 characterises general features of different methodological approaches without going into details of specific, existing models. For instance, the ease of model linking may vary upon particular characteristics of the models involved (e.g. linking static with dynamic models may introduce additional challenges). This evaluation can be refined by exploring and comparing various methodological options in a consistent way, e.g. linking different sectoral models for different countries and sectors to one economy-wide model.

Regarding the ***detail of mitigation options***, sectoral models tend to perform better than CGE models, as they focus on specific parts of the economy and do not need to balance that with the broad economy-wide view that is essential to a CGE. A CGE model linked with a bottom-up sectoral model would capture the granular representation of the latter, allowing a more detailed characterisation of the technological options than what is typically represented in a CGE model. For instance, in a stand-alone (non-linked) CGE model, energy efficiency enhancements in buildings can be represented by a shift from energy to capital in the production process, while linking it with a sectoral building stock model would allow to also assess the details of energy demand of the existing building stock. The type of the bottom-up sectoral model would affect the granularity of the linked modelling suite: whereas single-country sectoral models are flexible to being tailored to the country- and sector-specific circumstances and information, multi-country sectoral models would require harmonisation across countries and are likely to result in a less detailed representation of mitigation options and country-specific datasets.

Figure 2. Synthesis of preliminary evaluation of methodological options



Source: Authors

Note: This figure provides an *ex-ante* evaluation of different methods (described in Section 2) against the criteria laid out in Box 1. The qualitative legend indicates whether a methodological approach has benefits (High) or is likely to face more challenges (Medium) relative to the other methodological approaches for the various criteria.

Large-scale calibrated economy-wide CGE models tend to offer broader ***coverage of sectors and interactions*** compared to sectoral models. Multi-country sectoral models potentially cover more interactions than single-country sectoral models, as they might capture (endogenously) cross-border interactions such as trade of energy, food, or CO_2 emission allowances under a supra-national trading scheme. Energy trade modelling potentially captures relevant features such as network infrastructure, international oil prices, and foreign demand for hydrogen. As empirical evidence is likely available only for a subset of sector and policy instruments, the combination of empirical evidence with a CGE model has lower coverage relative to the CGE stand-alone option.

Two-way linking entails stronger ***harmonisation across models***. Nevertheless, as the challenges of linking models scale with the degree of model integration, one-way linking offers a more feasible solution than two-way linking in the context of ambitious and time-constrained assessments. Data harmonisation can be more easily implemented in one-way linking because it suffices to migrate data and definitions in one direction only (from the sectoral to the general equilibrium model). Moreover, one-way linking offers a practical solution that focuses coordination efforts between modelling teams on key interactions. This is a crucial feature when several sectoral models need to be linked in parallel to an economy-wide model. Moreover, these advantages of one-way linking would facilitate ***scalability*** to a wider set of sectors, policies, and countries. In addition, the operation of models in different institutes can create a practical disadvantage for two-way linking. One-way linking therefore facilitates effective use of resources when compared to two-way linking (***resource efficiency***).

While standalone, single-country sectoral models can capture country-specific characteristics, differences across models can raise barriers for transparency and limit ***consistency across countries***. When interpreting modelling results for different countries, it would be impossible to disentangle to what extent outcomes reflect country- or policy-specific characteristics, or whether they can be partially ascribed to the type (e.g. simulation, optimisation) or features of different sectoral models (that provide input into the economy-wide model). Multi-country (sectoral or CGE) modelling, covering a range of countries within the same methodological framework, offers a way to provide a coherent assessment across a diverse set of countries.

Similarly, linking multi-country models offers potential advantages in terms of ***scalability***, as the need to harmonise data and definitions arises only once for a set of several countries that are covered by both models. Linking different single-country models to an economy-wide model implies that information migration needs to be repeated for each of the models involved. Linking models (especially two-way linking) increases the complexity compared to stand-alone (sectoral or economy-wide) models, which complicates the scale-up to a larger set of countries. Enhancing the empirical base of a CGE model comes with scalability limitations when empirical evidence is not readily available for all countries.

While the use of multi-country (sectoral and economy-wide) models can facilitate scale-up, linking sectoral and economy-wide modelling for a large set of countries, sectors and policies, remains a resource-intensive endeavour. ***Resource efficiency*** therefore features as a separate criterion in Figure 2. Multi-country sectoral models are potentially a more resource efficient approach than a collection of single-country models, as building on the same modelling infrastructure can generate economies of scale. However, the resource efficiency argument is not clear-cut, as single-country models could have an advantage in the case that existing capacity is available and synergies can be leveraged to facilitate the work. Pilot studies can play a useful role to identify approaches to make optimal use of finite resources, to leverage available expertise, to reveal actual start-up costs and time needs in practical implementation, and to explore methods to facilitate linking while building on a diverse modelling and policy landscape (e.g. developing templates with minimal and optional data requirements for economy-wide modelling).

Summary assessment of methodological options

Overall, linking sectoral models with economy-wide CGE models can capture country- and sector-specific details while maintaining a broad coverage that includes economy-wide feedback effects. These criteria are key to provide a quantitative assessment of the impact of climate change mitigation action on greenhouse gas emissions that informs and supports an inclusive dialogue and evidence-based peer exchange. One-way bottom-up linking offers a potentially *scalable* and *resource efficient* way to deal with a large number of countries and sectors, with significant benefits on *detail* and *coverage* when compared to any of the unlinked options. Within one-way linking, single-country sectoral models are likely in a better position to accommodate local policy features, market conditions and datasets, and often form an integral part of the science-policy dialogue in the country. Using a multi-country sectoral model offers an option that is more consistent across countries than using a single-country model, with potential benefits in terms of scalability. The two approaches are alternatives and could be explored in parallel to enhance robustness of outcomes and to compare outcomes as is commonly done in model intercomparison projects in the academic literature. In addition to creating scope for robustness checks, the combination of different model types within one study can generate opportunities for collaboration and knowledge sharing, but requires additional resources.

Empirics-to-CGE linking merits exploration alongside the approaches to link economy-wide with single- and multi-country sectoral modelling described above. For example, enhancing a CGE model with empirical evidence for a particular sector or policy instrument could help substitute or complement the analysis from sectoral models if sufficient empirical evidence is available (see, for instance, D’Arcangelo et al. (2022[17]). The empirical literature already available can provide useful information on the effects of already implemented policies on emissions and could provide inputs to the *ex-ante*, forward-looking model-based analyses. In this context, the combination of empirical evidence with economy-wide modelling deserves consideration, particularly as the assessment of implemented policies can include both historical and future years. Literature reviews of *ex-post* and *ex-ante* empirical evidence on the effects of mitigation policies on emissions can support this objective.

Existing work and further pilot studies can provide illustrations of how linking models fares vis-à-vis the criteria set out in Box 1 and Figure 2, enabling a more accurate representation of the relative importance of the criteria. Identifying the weight of these criteria within particular contexts will facilitate the evaluation of methodological approaches, ensuring high value-added of the analytical work. The trade-offs between detail in the representation of mitigation options, consistency across countries and scalability of the methodological approach (among others) can be explored and tested in pilot studies. The choice of the relevant modelling framework is also conditioned by data availability or by the complexity of the policies to be explored. Testing different approaches in a variety of contexts can provide invaluable information for the discussion on these trade-offs and for developing strategies to overcome or mitigate some of the challenges underlying them. Pilot studies can furthermore serve as a testing ground to generate insights on the design of a linked modelling framework. Presenting advantages and drawbacks of one- versus two-way linking in concrete examples can help inform decisions on key variables for sectoral and economy-wide models, including defining the set of variables to be passed on between models. As different approaches build on different assumptions, particularly in sectoral interactions, pilot studies can also help revealing the sensitivity of results to these assumptions.

4

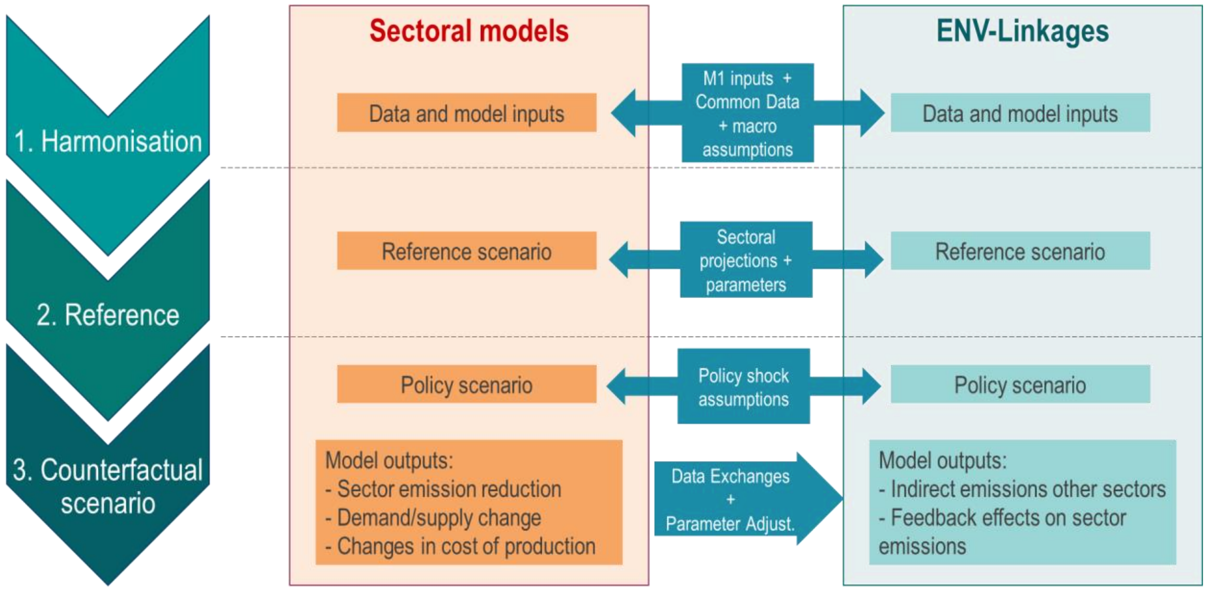
Operationalising a methodological framework

Building on the evaluation of methodological options in the previous section, this section advances one approach with strong merits: one-way linking of sectoral and CGE models. Moving from a conceptual to operational modelling framework involves a number of steps. Concretely, the modelling strategy to assess the impact of policies on greenhouse gas emissions by linking sectoral models to an economy-wide model such as ENV-Linkages (Château, Dellink and Lanzi, 2014[3]) involves three distinct steps (Figure 3), each of which is discussed in detail in the paragraphs below:

1. **Harmonisation of inputs**. The first step consists of setting up a common set of historical values (or common databases), including a stocktake of existing implemented or legislated policies, and in selecting a common set of macroeconomic projections for the main aggregate variables.
2. **Constructing a Reference scenario**. The second step of the strategy consists of building a harmonised "Reference scenario" for the models, using input from step 1 and exchanging information between different models.
3. **Developing the Counterfactual policy scenario**. The final and key step is to assess emission impacts of a policy (or a policy package) in sectoral models and use information from sectoral models to assess economy-wide impacts on emissions.

Throughout the process, interaction with national and international experts and key stakeholders can facilitate the development of a consistent methodological framework. Sufficient time must be devoted to foster a fruitful technical dialogue, as mutual understanding of the tools' operation, strengths, and weaknesses will enable informed model linkage that exploits complementarities in an optimal manner. While organisational elements are certainly important in operationalising a methodological framework that involves multiple models and teams, this section focuses on technical, model-related aspects.

Figure 3. Schematic representation of proposed approach to model linking



Step 1: Collect and harmonise databases across models

The first and preliminary step of a modelling strategy is to collect and **harmonise the data** across models for the base year and historical periods, and to harmonise socio-demographic and macroeconomic projections that will be used in Step 2. Micro- and macro-level data sources are often inconsistent. For instance, different sectoral definitions need to be harmonised. Similarly, the models might adopt different geographical disaggregation, meaning that importing and exporting countries are aggregated in regions that do not coincide. The values of capital stocks in different power sectors, when from national accounts, are difficult to reconcile with electrical capacity in volume (GW). Likewise, multiplying energy or crop volumes and prices from a bottom-up model will not automatically reproduce monetary values in input-output tables that serve as the data backbone for economy-wide models.

Data harmonisation starts from a comparison of existing data used in different models, calls for a prioritisation of key areas to harmonise and requires mapping the sectoral, geographical and time dimensions across models. This can be a time-consuming task, especially when it involves splitting of sectors when data are scarce. One important question is how to strike a balance between building on databases from national sources, leveraging internationally consistent sources, or reconciling both when feasible. At a first glance, national databases may appear to be more comprehensive in their coverage (e.g. across time and sectors), and more up to date. Using national data could furthermore facilitate linking between economy-wide and country-specific sectoral models, if both are domestic modelling teams that rely on these domestic sources of information.

On the other hand, internationally consistent databases offer an easier and more consistent treatment across countries, which is important for scalability in the context of multi-country assessments. Furthermore, building on scientific or international efforts to collect and combine, gap-fill, and update data (sometimes with proxy data or ‘satellite’ accounts) will facilitate efficient use of resources when scaling up the modelling work. Pilot studies represent a way to explore the trade-off between national and international datasets in the modelling work to better evaluate underlying challenges and opportunities, to reveal the importance of this choice in different circumstances, to identify cases where a deviation from globally harmonised datasets is valuable, and to develop strategies to reconcile advantages of different approaches. As models typically rely on various datasets, a combination of national and international datasets can also be considered.

The first key aspect to harmonise between models and potentially across countries is the historical data on greenhouse gas emissions. National sources are sometimes cumbersome to collect but are mostly compiled under the National Inventory Submissions by UNFCCC. Nevertheless, these national databases are typically incomplete in terms of year and country coverage. Using (and further harmonising) international databases like EDGAR (Crippa et al., 2022[18]), CEDS (McDuffie et al., 2020[19]), or data from US Environmental Protection Agency (EPA) or the International Energy Agency (IEA) (for CO_2 emissions) is a relevant option that deserves consideration.

The second key data inputs for economy-wide sectoral models are Social Accounting Matrices (SAM) from national accounts, including international trade. As exports from country A to country B need to match imports of country B from country A, and due to the input-output structure of the data, multi-country datasets of this type require reconciliation of different data sources. The ENV-Linkages model uses the GTAP database developed at Purdue University (Aguiar et al., 2022[20]), a unique dataset for economy-wide modelling. Therefore, a multi-country analysis with the ENV-Linkages model is bound by the sectoral definitions used in the GTAP database.

A third set of inputs is to collect and to harmonize macro-economic and socio-demographic historical data and projections. The OECD long-term (macro-economic) model (Guillemette and Turner, 2018[21]; 2021[22]) provides long-run socio-economic projections that are reviewed periodically by the OECD Economics Department committees. These projections are based on historical databases of the OECD Economic Outlook together with the UN and EUROSTAT population databases. In previous OECD reports, ENV-Linkages has already successfully relied on macro-economic variables coming from the OECD long-term model (see Annex A.1). Therefore, this approach constitutes a natural choice to build country Reference scenarios. As macro-economic data and projections could be unavailable for some non-OECD countries, the IMF World Economic Outlook or the World Bank World Development Indicators datasets could complement these.

Finally, sectoral and CGE models also rely on sectoral historical data and projections, including information on energy and agriculture sectors. National data or international databases could both be used to support the calibration of models used for assessing the impact of climate-relevant policies on greenhouse gas emissions. The IEA databases and projections are internationally consistent sources which are obvious candidates for collecting information on the energy system, and particularly for international fossil fuel prices. Likewise, the OECD-FAO database is a recognised international source for agriculture.

Regarding data collection and harmonisation of policies, a consistent policy stocktake can feed into the modelling exercise, ensuring that relevant policies from the stocktake are incorporated and represented in a consistent way in the modelling framework. For the data harmonisation and preparation for the modelling work, a protocol or template can be developed by building on commonalities across country studies, which could facilitate information sharing and enable scalability, while ensuring efficient use of resources.

Step 2: Build common Reference scenarios across models

The second step of the modelling strategy is the development of a **common Reference scenario** for the models. As different models consider different endogenous and exogenous variables, the procedure to build the Reference scenario for the sectoral and economy-wide models may differ from each other. Yet, the models ideally rely on a common set of data and projections for the variables shared by both type of models, including common assumptions and projections concerning overlapping variables like the evolution of population, GDP, fossil fuel prices, trade, consumption, and production patterns (among others), to ensure a consistent starting point for the analysis. The construction of the Reference scenario should strive to account for country-specific characteristics, e.g. emphasizing elements of particular importance for country-level economic and environmental drivers. Importantly, the Reference scenario is based on policy instruments relevant for climate change mitigation that are implemented or legislated. The representation of implemented policy instruments can be informed by policy stocktake exercises, such as the one conducted in the OECD’s IFCMA.. Some dynamic features of particular policy instruments may require further consideration, such as automatic adjustments in tax rates (e.g. indexation) or the legislated reduction of emission allowances over time in emission trading systems.

In sectoral models, population, GDP, and broad sectoral composition of the economy are generally exogenous and taken as given in the optimisation programs (for optimisation models) or in the econometric relationships (for simulation models). Economy-wide models can provide economic activity projections by sector to sectoral models. In some instances, sectoral models require calibration to exogenously determined demand values by agents (for example the projection for energy products in TIMES models), price projections (for example production prices in partial equilibrium models with infinite elasticity of supply) or projections for some production, trade flows and import prices.

Technically, calibrating an **economy-wide (CGE) model** to macro-economic projections is a straightforward exercise, routinely performed with the ENV-Linkages model in OECD reports. It involves adjusting a set of variables in the model to match (calibrate) the values of exogenous inputs when building the ‘Reference scenario’ (see detailed methodology in Annex A.1). This implies ‘inverting’ the equations of the model: otherwise, endogenous variables are fixed to match exogenous values, and parameters that take an exogenous value in simulations are adjusted to ensure that the Reference scenario matches the data. For example, to reproduce a specific exogenous GDP trend in the Reference scenario, labour productivity and total factor productivity improvements can be scaled to match the desired macroeconomic activity levels.

Refining the sectoral Reference projections and features in an economy-wide model such as ENV-Linkages using inputs from sectoral models (one-way bottom-up linking) can also follow well-established practices. Incorporating information from the sectoral model into the CGE model for the Reference scenario can facilitate the (explicit or implicit) representation of current policies. Concrete examples involve calibrating the energy system of the ENV-Linkages model to reproduce energy scenario data of the IEA World Energy Model (see examples and methods of such one-way bottom-up linking in annex A.2.) or calibrating agriculture and food systems to a partial equilibrium model (annex A.3). This procedure is slightly more complex than just inverting causality of variables in economic relationships used for aggregate variables, because it may also require adjusting some scale parameters of the CGE to match the trends provided by sectoral models. The typical scale parameters of the model that are adjusted to match sectoral trends are the share parameters in the Constant Elasticity of Substitution (CES) functions governing production and consumption decisions, the minimum subsistence levels in consumer preferences, the autonomous efficiency parameters for the primary factors or for the intermediate inputs (like energy) and the total factor productivity of the sector.

Vice versa, developing a Reference scenario in sectoral models may benefit from inputs from economy-wide models. This is particularly relevant for assumptions and features that go beyond the scope of the sectoral model, such as projections of sectoral value-added shares in the overall economy. Economy-wide models such as ENV-Linkages can provide supplementary information to sectoral models where relevant, enhancing the consistency of the “Reference scenario” across models. The typical examples include an energy model that could require projections about the value-added share of iron and steel production; an agriculture model that take as given food demand; or a transportation model that requires projections about international trade flows to calculate the corresponding international transportation costs.

Step 3: Assess impact on emissions of policies across models

The third and crucial step is the development of the Counterfactual policy scenarios, obtained excluding (or reverting) the policy that is being assessed. The procedure starts by estimating the emission impact of a specific policy (or policy packages) in the sectoral models. The second stage of the procedure is to implement the same policy (packages) in the economy-wide model. This will require some adjustments in parameters and features of the CGE model to obtain similar output as in sectoral models. The procedure ends by running the economy-wide model considering all policies together to assess the magnitude of indirect and spill-over effects of broad mitigation action (see illustration in annex A.4). The implementation in the economy-wide model of the specific policy and its resulting impact on emission extracted from the sectoral models is not as straightforward as in step 2, as two types of adjustment should be made.

Firstly, some of the structural parameters of the economy-wide model should be adjusted to align the impact of policies on emissions with the estimate of the sectoral models. In this step, it is generally not sufficient to only adjust the so-called share parameters of the CGE. To guarantee that the CGE model responses align more closely to sectoral models, some structural parameters of the CGE will likely need adjustments[2], including in the elasticities of substitution in the production function, the price-elasticity of demand, elasticities of supply, elasticities of transformation, and others (see examples provided in Annex)[3]. Alternatively, the sectoral results could also be directly imposed on the CGE model, bypassing the normal endogenous adjustment processes of the CGE model.

Secondly, implementing policies in a CGE model in line with the sectoral model (results) requires translation of the policy shock to the dimensions of the CGE model, which considers less granular definitions of commodities and lower technology details than the sectoral models. In addition to greenhouse gas emissions, extra information should therefore flow from sectoral to economy-wide models to enable a consistent treatment across models. The set of variables that are transferred from the sectoral to the economy-wide model will depend on the specific characteristics of the study (e.g. sector and policy instrument considered) and the tools used for conducting the assessment at the sectoral level. Establishing common principles for data transfer and CGE model implementation is key to facilitate the scalability of the methodological approach and the comparability across countries. The paragraphs below illustrate potential data needs and implementation options of the economy-wide modelling for different policy instrument types. This identification of data needs can be further developed at more granular typology levels to develop more detailed guidance for model-based assessments.

To evaluate the effect of **price-based** policy measures (e.g. taxes or subsidies) on emissions of a certain sector, the CGE model can apply an effective tax rate to the corresponding tax base. Additional information should be passed from the sectoral model to adjust the policy in the CGE model. If one considers fuel taxes for example, these generally differ across the various fuel (diesel, gasoline, ethanol, kerosene, etc…), but in the CGE model only one kind of refined oil product is generally considered. In this case the changes in a fuel tax policy should be aggregated for the CGE model, using detailed information about the

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[2] Sometimes the parameters adjustment is facilitated by the similarity of structural form for some economic relationship between sectoral and CGE model. For example, if in both model the system of final demand of consumers may be summarized by a matrix of cross price-elasticities and income-elasticity, the CGE model could directly use the matrix from the sectoral model.

[3] The representation of technology adoption and the associated capital investment, which are crucial drivers of emission reduction, differs in sectoral and general equilibrium models. Harmonising technology and capital investment implies a combination of adjustments in energy productivity parameters and CES elasticities, allowing vintage-differentiated capital in the macro model, or relying on marginal abatement cost curves estimates (Weitzel, Saveyn and Vandyck, 2019[38]).

different tax rates for the different refined oil products, the budget (cost) shares of each of these different oil products and the corresponding tax bases.

In the case of other **economic instruments** aiming at promoting investment in an emission-reducing technology, such as a support measure towards renewable energy production or a tax-credit to investment, the information to pass to the CGE model is different. Adjusting the tax or subsidy is not sufficient in this case; the sectoral models should also provide to the CGE model some information about the resulting amount of investment in the green technology that is driven by the change in the fiscal instrument, the expected induced changes in cost of production, and if possible, the change in required intermediate products implied by the technology shift. The latter can be considered in the economy-wide model to represent changes in emission along supply chains.

Regulatory instruments (performance standards, technology standards and other regulatory policies) **and other instruments** (government investments, information instruments and voluntary approaches) could be integrated in a sectoral model in several ways. For example, a CO_2 or fuel efficiency standard for personal vehicles can be implemented through constraints on the choice of car technologies, which is affected by costs and fuel infrastructures, for a given demand for “transportation services" (Siskos, Capros and De Vita, 2015[23]). Introducing this policy in a CGE model would require first to use the information from the sectoral model (here transport model) to assess changes in household transport demand to a level of detail that can account the different transportation mode and vehicles technologies. Then the “transportation service demands” in monetary terms in the CGE model should be derived from the detailed calculations (for instance in passenger- or tonne-kilometres) from the sectoral model. Finally, the CGE model should mimic the overall effect of the change in transport technology of households (penetration of low emission vehicles) when they are constrained by the regulation policy (possibly by adjusting substitution elasticities across transportation technology/good) as well as mimic the overall effect of the change in relative cost of different technology for transport from the sectoral model.

A final note on the implementation of the modelling framework

More generally, a number of methodological choices must be made in the model implementation phase, including with respect to which dimensions will be harmonised (fixed exogenously in the CGE model), and which elements remain to be determined endogenously by the economy-wide model. Discussing the advantages and drawbacks of these choices is important to frame the exercise and to facilitate a good understanding of the outcomes. For instance, if the economy-wide model would take sector-level greenhouse gas emissions as an exogenous input (fix exogenously as a constraint), then alignment between both models on sectoral emissions is guaranteed, but economy-wide feedback on sectoral emissions cannot be captured by the CGE model. While this approach may be adequate for a cap-and-trade system, for a carbon tax a better approach could be to align CGE inputs (instead of outputs in terms of emissions) to sectoral model outputs at a more granular level, e.g. energy mix and intensity of the sector as determined by the sectoral model.

Other modelling choices include the assumption on which policy instrument to use for recycling additional revenue (or raising lost revenue), as a consistent comparison across scenarios in a CGE model assumes no money entering or leaving the economy-wide system. Furthermore, assumptions must be made on climate action in other countries, as this would influence the cost of low-carbon technologies, the foreign demand for low-carbon goods, international fuel prices and cross-border supply chain interactions, among others. These channels can generate spillovers and interactions that affect the overall outcome on emissions. Careful consideration must therefore be given to particular modelling choices in view of the questions at hand. Abovementioned assumptions influence the estimates of the economy-wide impact on greenhouse gas emissions, in addition to sensitivity with respect to parameter settings.

Pilot studies can play a key role in informing these more refined modelling choices – including data harmonisation and model alignment – by revealing key assumptions in a transparent way and by documenting the models and the methodological options along with their potential (dis)advantages. Testing the sensitivity of CGE model outcomes to particular assumptions, approaches to overcome data gaps, and parameter values, and describing and quantifying uncertainties where possible, can provide relevant robustness checks and can inform future modelling work that aims to assess the impact of climate-relevant policies on greenhouse gas emissions across a range of sectors, policies, and countries. Finally, by exploring a broader set of modelling choices, pilot studies can reveal key channels that influence (the change in) economy-wide emissions, fostering a better understanding of policies and enabling optimisation of their impact in mitigating climate change.

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Annex A. Model linking at the OECD

The OECD has conducted a number of modelling exercises in the past, where the in-house economy-wide ENV-Linkages model is linked to other models. Leveraging this experience can facilitate the model-based work foreseen for IFCMA. ENV-Linkages is a dynamic and global CGE model, developed and run at the OECD (Château, Dellink and Lanzi, 2014[3]).

A.1. Setting-up a baseline through linking with a macro model

ENV-Linkages is linked with the OECD long-term model (Guillemette and Turner, (2018[21]), (2021[22])). This is a macroeconomic model which projects individual countries' growth paths up to 2060. It is therefore straightforward that the IFCMA modelling strategy will used these socio-economic projections as a baseline.

The linking is achieved by aligning macro-economic variables between the two models that determine the macroeconomic projections of the long-term model and play a significant role in ENV-Linkages. The link between the models is mostly one-way from the long-term model to ENV-Linkages but consistency is maintained in the sense that the CGE baseline trajectory reproduces the macroeconomic scenario from the long-term model (including GDP, investment ratio, current account, government deficit) and both models share the same exogenous population and labour force (employment) assumptions.

The following adjustments of ENV-Linkages are to reproduce the OECD long-term model baseline: i) the average growth rates of labour efficiency in ENV-Linkages model are adjusted to calibrate the GDP projections by region and year from the long-term model, ii) the investment to GDP ratio and the government expenditures ratios are calibrated by adjusting the household's saving rates and income tax rates, respectively. More details about linking macro-economic and CGE models are provided in Fouré et al. (2020[24]) while details about more calibration of projected structural changes in CGE models are found in (Chateau et al., 2020[25])

Recent effort has been made to improve the two-way linking. In (Guillemette and Chateau, December 2023[26]), emission-abatement cost curves are calculated in ENV-Linkages, aggregated at country level, and passed on to the OECD long-term model to consider in the former model the cost of mitigation on long run potential GDP.

A.2. Linking ENV-Linkages with the IEA-WEM simulation energy-model

The OECD and the International Energy Agency (IEA) have collaborated for the World Energy Outlook reports (2012, 2013, 2014, 2017, 2018). For this purpose, a strategy of linking ENV-Linkages to the energy-oriented IEA World Energy Model (WEM) has been developed by Chateau et al. (2014[27]). Despite large differences in the nature and functioning of the two models, ENV-Linkages is calibrated to reproduce energy-related patterns from the World Energy Outlook (WEO) scenarios and then to derive economic implications of IEA scenarios in its CGE framework. This link is one-way (from WEM to ENV-Linkages), although in principle it is possible to have a two-way coupling by feeding back information from ENV-Linkages to the WEM (e.g. by passing information on GDP, investments, energy prices and sectoral changes).

Calibration efforts when coupling WEM to ENV-Linkages, for the Reference scenario, are devoted to key trends in (i) energy consumption by fuel, sector, and country; (ii) fossil fuel supply by country; and (iii) changes in electricity generation mix by country and energy-related investments. After integrating ENV-Linkages into the policy from a World Energy Outlook scenario, the parameters of the model are adjusted to reproduce the key trends. In detail, the sectoral autonomous energy efficiency improvement rates by fuels of ENV-Linkages are adjusted to calibrate energy demand projections by firms, while household preferences parameters are adjusted to match projected transportation and heating fuel demands. For each fossil fuel extraction sectors, the technological progress calibrates the share of the fossil fuel production of a country in world total, while the natural resource extraction rates are adjusted to calibrate the projection of international fossil fuel price. Finally, share parameters of electricity are calibrated to reproduce the power mix of WEM.

Beyond these OECD works, linking detailed **energy** and economy-wide CGE models has become a well-established approach in the literature (Faehn et al., 2020[28]). Bottom-up linking can provide energy-related variables to the CGE model for a baseline and a policy scenario, such as total energy use by energy carrier across sectors and the electricity generation mix by year and country. Fujimori et al. (2019[29]) describe their approach of linking an energy system (AIM/Enduse), power dispatch (AIM/Power) and CGE model (AIM/CGE) to study climate policy in Japan. The information flow from the bottom-up energy model to the economy-wide model includes several variables: Power generation share by energy sources; Battery capacity; CCS installation; Final energy consumption by sectors and energy types; Investment of energy end-use sectors; Carbon prices; and Transmission losses. In the other direction, the CGE model feeds back changes in GDP, household consumption, industry and service sectors output and energy prices to the energy system model. In addition, the power dispatch model takes power capacity by technologies and electricity demand as inputs from the sectoral energy model, and feeds back detailed results on electricity generation, i.e. the curtailment rate, capacity factor by technologies and battery for short-term power fluctuation. The paper finds that linking these models results in lower estimated climate policy costs compared to a standalone CGE model, while enhancing the granularity of the energy and power sectors. This finding is echoed in recent work that iteratively links MESSAGEix-GLOBIOM and AIM/Hub models (Nishiura et al., 2024[30]).

A.3. Linking ENV-Linkages with the IMPACT partial-equilibrium model for agriculture

The ENV-Linkages model uses the output of two partial equilibrium models for the baseline calibration of its agricultural sector in a one-way bottom-up manner. While livestock feed efficiencies are obtained from the GLOBIOM model (Havlík et al., 2014[31]), the general calibration of the ENV-Linkages agriculture system is based on the agricultural and food projections from the International Food Policy Research Institute's (IFPRI's) IMPACT V.3. model (Robinson et al., 2015[32]). The core of IMPACT is a global, partial equilibrium, multimarket model focused on the agriculture sector, where demand, supply and prices on agricultural sectors are determined together via simultaneous equilibrium of the food and agricultural markets.

First, to make both models consistent, i) the country- and crop-specific land supply elasticities (in the function of land allocation across agricultural activities in ENV-Linkages) are adjusted to fit with IMPACT's elasticities of land supply by crops, and ii) the baseline scenario for macroeconomic variables used in ENV-Linkages (see Box 1) are also used to derive the IMPACT baseline projections.

Second, food and feed demands, crops and land supply are calibrated in the ENV-Linkages baseline to reproduce the IMPACT baseline projections of the agriculture system: (i) the (minimum) per capita consumption for agriculture and food products are aligned to reproduce household demand of IMPACT, (ii) exogenous land efficiency improvements are extracted from IMPACT (including an adjustment for the impact of climate change) and imposed in ENV-Linkages, (iii) the growth rate of total land supply from IMPACT is calibrated by adjusting total land supply scale parameters, (iv) for each crop modelled, the regional share of production in the world total production from IMPACT is calibrated in ENV-Linkages, through endogenous adjustment in total efficiencies of gross output.

One issue in this calibration method is that it is hard to reconcile trade flows of food and agricultural commodities between two models since IMPACT assumes perfect markets in trade flows while ENV-Linkages assumes imperfect substitution between domestic and foreign goods (Armington specification). In this case, the models do not exactly align on absolute domestic output but rather on the output share in global aggregate production.

Beyond these OECD works, CGE models have commonly been applied in combination with a more granular sectoral models is **agriculture** (or AFOLU, more broadly) (Delzeit et al., 2020[7]). For instance, the IMAGE-MAGNET modelling framework described in Stehfest et al. (2019[33]) and Fujimori et al. (2019[34]) consists of land supply, suitability, and potential (changes in) agricultural yields being aggregated from grid level in IMAGE to feed into the CGE model MAGNET, where these inputs are used to refine the representation of land as a production factor and to calibrate a land supply curve. The economy-wide model MAGNET, in turn, is able to capture international trade in determining future geographical distribution of agricultural production levels and intensity, and provides this information to IMAGE. Being a CGE model, MAGNET accounts for combinations of primary (land, labour, capital and natural resources) and intermediate production factors, and captures changes in international trade flows of agricultural products in response to (policy-induced) cost and price changes. One of the main advantages of the combination of bottom-up agricultural detail and economy-wide scope is that changes in technology and bio-physical conditions are accounted for in deriving regional production levels and the associated yields and livestock efficiencies.

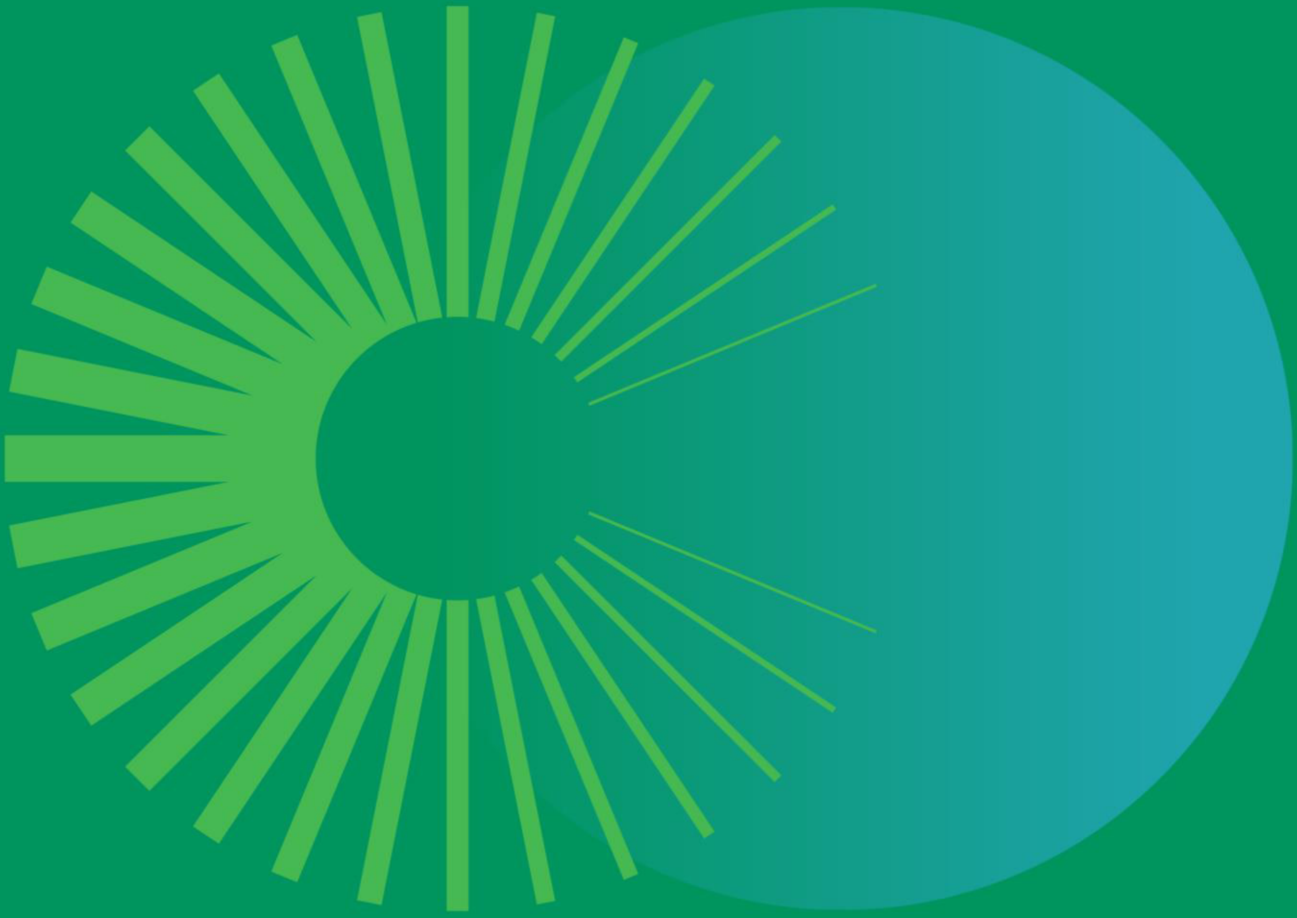
A.4. Linking ENV-Linkages with an emission abatement model

ENV-Linkages has been linked with the GAINS IIASA model (Amann et al., 2011[35]) in the context of a project on the economic consequences of air quality improvements in Arctic Council Countries (OECD, 2021[36]) to assess the costs and benefits of air pollution control. The GAINS model provides a bottom-up representation of technologies to abate emissions of air pollutants and non-CO_2 greenhouse gases. To ensure that the two models are aligned, sectoral activity levels have been harmonised. Specifically, sectoral projections in ENV-Linkages have been calibrated to ensure that key activities and emission sources (e.g. amounts of fossil fuels used in power generation and industry) matched those of the GAINS model. This was facilitated by the fact that both models were calibrated on the projections of the IEA's World Energy Outlook, as described in Section 3.1. Once the models aligned, the emission projections of the GAINS model were used also in ENV-Linkages, relying on emission coefficients (e.g. emissions per volume of energy use). For the baseline scenario, these coefficients reflected a "Current Legislations" scenario, namely the state of committed air pollution legislation assuming that the required standards can be achieved by existing technologies.

Relying on the coupling of the two models, ENV-Linkages was also used to develop policy scenarios that reflect the implementation of additional air pollution policies and their consequent wide adoption of best available techniques (BATs) to control air pollution. These technologies address technical mitigation opportunities available in the GAINS model for the key anthropogenic sources of pollution: transport, energy and industry, agriculture, residential combustion, and waste. Specifically, the technologies include (i) end-of-pipe technologies such as filters, scrubbers and catalyst (ii) capture and recovery systems (iii) cleaner and more efficient solid fuel stoves and boilers, (iv) improved waste management, and (v) measures to reduce ammonia and methane emissions in the agricultural sector.

GAINS estimates the sector- and country-specific investments necessary to achieve the maximum feasible reduction in emissions by deploying BATs. The emission coefficients in ENV-Linkages are changed following the projections of the policy scenarios in GAINS to reflect the effectiveness of the BATs. In parallel, the monetary value of the investments is included in ENV-Linkages as extra sectoral expenditures. While these expenditures constitute an initial additional sectoral cost, the investments themselves constitute an economic activity, with a positive effect on value added in the medium-long term. In parallel,

In this set up, the policy action scenarios reflect the implementation of source- and region-specific technologies aimed at reducing the emissions of several pollutants (e.g., particulate matter, nitrous oxide, sulphur dioxide) and some greenhouse gases (e.g. methane). Specifically, as a result of simulations of the IIASA's GAINS model, these scenarios reflect the maximum technically feasible reduction of emissions in each country with the best available technologies. The level of implementation of specific measures over time considers technical limitations (e.g., lifetime of installed capacities). However, there are no constraints associated with investment or operating costs. The technologies considered in the analysis are suitable for mobile, stationary, and fugitive sources.



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