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IMF-ENV: Integrating Climate, Energy, and Trade Policies in a General Equilibrium Framework

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ABSTRACT: IMF-ENV is a global dynamic computable general equilibrium (CGE) model developed by the IMF's Research Department. The model features a database of 160 countries and regions, along with 76 sectors, and can be calibrated to a wide range of country-sector combinations. The model's general equilibrium structure, combined with its high level of detail, enables it to assess both direct and indirect domestic structural changes and cross-border spillover effects of policies. This makes it suitable for examining the medium- and long-term macroeconomic effects as well as structural shifts arising from national and/or global climate mitigation, energy, fiscal and trade policies. The model reports impact on macroeconomic variables, sectoral outcomes, employment and bilateral trade flows, along with detailed information for energy demand and supply, electricity generation and GHG emissions.

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WORKING PAPERS

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Prepared by Jean Chateau, Hugo Rojas-Romagosa, Sneha Thube, and Dominique van der Mensbrugghe*

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Contents

1 Introduction

This paper provides a detailed description of the IMF-ENV model, which has been developed to examine the impacts of policies inducing structural economic changes on both the overall economy and specific sectors. IMF-ENV is a global multi-region, multi-sector recursive dynamic computable general equilibrium (CGE) model. The CGE modeling framework has a long tradition in supporting evidence-based policy analysis for a broad range of issues. Policy applications range from structural adjustment policies, international trade, agriculture, public finance, income distribution, and energy and environmental policies (Devarajan and Robinson, 2005; Dixon and Jorgenson, 2013). CGE models are extensively used by international organizations such as the World Bank, OECD, WTO, and UN agencies, as well as by the European Commission, other governmental agencies, research institutes, and academia. Dellink et al. (2020) and the papers in this special issue offer a comprehensive discussion of the existing CGE models. IMF-ENV is well integrated within this established framework of economic modeling, using several standard features of global CGE frameworks and adding new improvements based on recent advancements in the field. Specifically, IMF-ENV is based on both the ENVISAGE model (van der Mensbrugghe, 2024) originally developed and used at the World Bank, and the OECD's ENV-Linkages Model (Chateau et al., 2014).[1]

The core components of IMF-ENV–production, demand, trade, factor markets and inter-temporal linkages–are all relatively standard recursive dynamic multi-sector multi-region CGE model features. The core data of the model is based on the GTAP database, which includes is a set of social accounting matrices that provide very detailed sector- and country-specific data on input-output linkages and bilateral trade flows (Aguiar et al., 2022). This database features 160 countries and regions, along with 76 sectors, and hence, the IMF-ENV model can be flexibly calibrated to a wide range of country-sector combinations.

The model uses a neo-classical framework to optimize consumption and production decisions by households and firms. It follows the circular flow of the economy based on the activities of key agents: firms, households, and markets. Firms purchase inputs (from other firms) and primary factors (from households) to produce goods and services. Households receive factor incomes and in turn demand the goods and services produced by firms. All commodity and factor markets clear simultaneously through flexible price adjustments. Countries also exchange commodities and capital on international markets.

Factors of production, excluding capital, are almost perfectly mobile across sectors but not across

[1] The current version of the ENVISAGE model is a complete re-coding of the original ENVISAGE model largely undertaken at the behest of the OECD's Environment Directorate, and thereby both the ENV-Linkages model and the IMF-ENV model share the same core codes. The ENVISAGE model can be viewed as a toolbox offering various modeling options around a central structure. Each of the three models uses different parametrization, sectoral characteristics, closure rules, and dynamic calibration choices. However, it is possible to recover one model from the codes by using the same specifications. This paper outlines the choices used in the core IMF-ENV version, but other alternative specifications can also be adopted.

countries. Capital is modeled following a putty-clay specification and therefore, exhibits different behavior based on the vintage type. *New* capital stock (i.e. net-investment) is malleable and is allocated without friction such that the return to *new* capital equalizes across sectors. Differently, *old* installed capital is fixed and cannot be reallocated without high costs.[2] Labor supply is determined by the working age population, labor participation and long-term unemployment rates, and it endogenously adjusts to changes in real wages following a reduced-form wage supply curve that accounts for decisions on leisure and work (at both the intensive and extensive margin). The model also includes land and natural resources as production factors, which constrain the expansion of agricultural and mining activities.

Production follows a series of nested constant-elasticity-of-substitution (CES) functions to capture the different substitution possibilities across all inputs and production factors. The model can also separate production activities from commodities. This distinction allows, for example, to have a single electricity commodity to be produced from multiple generation technologies. Household demand is non-homothetic and international trade is modeled using the so-called Armington specification where demand for goods is differentiated by region of origin (Armington, 1969). This specification uses a full set of bilateral trade flows, prices, transportation and trade costs by commodity. IMF-ENV is a recursive dynamic model –i.e. it is solved as a sequence of comparative static equilibria where the factors of production are exogenous for each period and linked between time periods with accumulation expressions. Agents, however, are not forward-looking and investment levels are driven by savings, which in turn is a combination of household savings, the government budget balance and the current account balance.

One of the main features of IMF-ENV is that it directly links economic activities to emissions of greenhouse gases (GHGs) from various sources like energy, agriculture, transportation, industry, waste management and buildings. The model also accounts for fugitive emissions and emissions from land use, land-use change and forestry (LULUCF). The sector-specific emission accounting GHGs enables the model to analyze GHG- and activity-specific policies.

The IMF-ENV framework evaluates the effects of new policies or shocks by comparing them to a baseline scenario where current policies stay unchanged. The differences across scenarios help quantify the impacts on macroeconomic variables like GDP, consumption, investment, sectoral production, employment, bilateral trade, energy outcomes (electricity mix and energy demand), and environmental outcomes (GHG emissions).

The model's structure and detail make it ideal for various policy applications, including climate mitigation, energy transition, fiscal and trade policies. Various combinations of these policies can be implemented concurrently or independently in different countries and regions. It can be used to simulate

[2] The distinction of capital vintages can also be important as new capital becomes more energy and emission efficient (see Capelle et al., 2024).

a wide range of mitigation and energy policies such as different carbon pricing schemes like carbon taxes (on a flexible combination of activities, emission sources, and GHGs), national and regional emission trading schemes (ETS), feed-in tariffs, feebates, regulations for improving energy efficiency, and incentives and programs that encourage the adoption of certain technologies, such as heat pumps for consumers and production or investment incentives for producers. Some of the climate and energy policies are implemented as fiscal policies, like carbon taxes and production and investment subsidies, while the model can also analyze broader fiscal policy packages. IMF-ENV can also be used to assess the macroeconomic and sectoral impacts of trade policies like free trade agreements (FTAs), changes in trade barriers like tariffs, non-tariff measures (NTMs), and import quotas. It can also be used to model trade restrictions such as sanctions and disruptions for specific countries, trading blocks, or globally. The model's detailed data on energy and emissions allows to analyze the link between trade, energy, and mitigation policies, such as carbon border adjustment mechanisms (CBAM). Finally, the IMF-ENV model is continuously evolving with regular updates, and upcoming new features are presented in Section 8.

Several modeling frameworks can be used to assess the ex-ante economic costs of climate, energy and trade policies and shocks. Among these models, dynamic CGE models like IMF-ENV remain a standard economic tool to analyze medium- and long-term structural changes in the economy triggered by sectoral or economy wide policy changes. Next, we summarize the main features of these approaches and highlight the distinct advantages provided by CGE models like IMF-ENV, while also identifying cases when other models are more suitable.

One of the main advantages of CGE models like IMF-ENV is their granularity, allowing detailed analyses of policy packages and generating a rich set of results across countries and regions, economic activities, production factors and energy sources, both at the macro and sectoral level. Another key advantage is that the modeling framework maintains consistency by respecting resource constraints and macroeconomic and fiscal balances. Additionally, CGE models can be linked with partial equilibrium sectoral models for energy, agriculture and land use or be linked to gravity trade models, or be combined with poverty and income distribution data through micro-simulations.[3] Lastly, CGE models can incorporate climate change damage functions from other studies to estimate the macroeconomic impacts of climate physical risks.

IMF-ENV differs from the class of New-Keynesian dynamic general equilibrium models, which include both traditional dynamic stochastic general equilibrium (DSGE) models (see Sbordone et al., 2010) and non-stochastic models (see Carton et al., 2023). DSGE models capture business cycle dynamics and short-

[3]For instance, many of the Country Climate and Development Reports (CCDRs) by the World Bank feature a CGE model at their core, which uses and consolidates detailed information and outputs from other models and country teams' analyses on specific topics like agriculture, land use, energy, transportation, waste, health, education, poverty, and risk management.

term price and wage rigidities when factors of production and intermediate inputs are reallocated across economic activities. The IMF-ENV model is not designed to analyze short-term transition dynamics as nominal rigidities are not adequately represented and the model swiftly shifts from one general equilibrium to another. Moreover, IMF-ENV does not model business cycles, inflation dynamics or interest rate fluctuations, whereas DSGE models are better placed to deal with these topics. DSGE models often incorporate forward-looking agents, although it comes at a cost to regional and sectoral granularity. Consequently, DSGE models generally focus on one or few countries and a small number of sectors making them less suitable for assessing structural changes, cross-country spillover of policies and competitiveness effects. Furthermore, for medium- to long-term policies with political and technological uncertainties, such as climate and energy policies, the benefits of using forward-looking dynamic optimization are unclear. Though useful for some issues, the recursive dynamic model offers similar behavior in the energy sector and carbon price estimates with more flexibility and granularity.[4]

There are two other distinct frameworks that are used to model energy and climate policies - partial equilibrium models (PE) and Integrated Assessment Models (IAMs). Partial equilibrium models are based on bottom-up sectoral specifications and are dedicated to the analysis of a particular sector of the economy such as energy, transport, or agriculture. These models provide a more detailed representation of the specific sector than CGE models. For example, the power system representation in IMF-ENV captures a broad range of regional variations in capital and operational expenses across generation technologies, investment in transmission and distribution ($T\&D$) technologies, and the aging of capital stock through the capital vintage structure. In addition to these considerations, bottom-up PE energy models represent other elements such as early-stage generation technologies for various energy carriers and usages, account for daily and seasonal variations in load demand and may include precise plant-level details. Sectoral details at this level of granularity can be useful and necessary for certain applications. However, PE models are limited in that they cannot assess impacts beyond the specified sector, such as macroeconomic effects, cross-sectoral interactions, or feedback (general equilibrium) effects from the rest of the economy. To leverage the strengths of both PE models and CGE models, CGE models are often linked to partial equilibrium models (see Delzeit et al., 2020). Following this approach, IMF-ENV also uses data from bottom-up models like PE energy models to guide the evolution of electricity generation.[5]

Integrated Assessment Models (IAM) are designed to assess the interactions between human and en-

[4] Babiker et al. (2009) find that the recursive dynamic assumption and forward-looking optimization yields comparable results in the energy sector impacts and CO_2 prices. While forward-looking dynamic optimization can generate lower macroeconomic costs by shifting consumption in response to carbon pricing, this approach may lead to underestimation of costs as several important model features like capital vintages and technology options need to be removed for the model to solve the intertemporal optimization problem.

[5] In the past, these included the World Bank's Electricity Planning Model (EPM), the EU's Price-induced market equilibrium system (PRIMES) model or the European Commission's Prospective Outlook on Long-term Energy Systems (POLES) model.

vironmental systems. They integrate economic, social, and environmental factors to evaluate the impacts of climate change and policy responses and have been extensively featured in the Intergovernmental Panel of Climate Change (IPCC) assessment reports. IAMs primarily focus on environmental impacts and analyze the dynamics of physical variables, incorporating environmental feedback such as climate extreme events on economic activities. Typically, IAMs present a cost-benefit assessment framework and therefore can be used to simulate optimal policy pathways. (cf. Barrage and Nordhaus, 2024). Although CGEs models have be integrated within IAM models (cf. Fujimori et al., 2024), it is computationally expensive and usually results in reduced model dimensionality, less detailed economic behaviors and fewer policy options.

Finally, CGE models are closely related to the so-called New Quantitative Trade (NQT) models (for example Caliendo and Parro, 2015; Baqaee and Farhi, 2019). These NQT models, in essence, are stylized forms of CGE models. They use very similar demand, supply and general equilibrium mechanisms, based on neoclassical optimization theory. Both use multi-country and multi-sector input-output data that is complemented with bilateral trade data. The advantage of NQT models is that they are parsimonious models, which has the advantage of making them analytically tractable and require less parametrization and hence, assumptions. This also allows them to structurally estimate the main parameters of interest (e.g., the trade elasticities).[6] CGE models, on the other hand, are more comprehensive and include several additional features that are useful for detailed policy analysis. They include several production factors (instead of only labor used by NQTs), use non-homothetic demand systems, add institutional details (government balance with detailed tax options, investment and capital accumulation, non-balanced current accounts) and can incorporate energy and environmental features. Besides the differences in model dimensions, both modeling frameworks are based on different underlying trade models and solution methods.[7] In recent years, hybrid models based on elements from both approaches have been developed. Some CGE models incorporate the Eaton and Kortum (2002) model (cf. Bekkers et al., 2023) and structurally estimate the trade elasticities using the same underlying data used in the simulations, while some of the more recent NQT models are becoming more complex by including unbalanced trade, capital, sub-national and climate features.

The rest of the paper is organized as follows. Section 2 describes the core components of IMF-ENV, including the energy and environmental features of the model. Section 3 explains the data and baseline calibration process. Section 4 discusses the model outputs and the IMF-ENV dashboard. Section 5 presents modeling uncertainties while Section 6 reviews the policies that can be simulated using the

[6] While the structure of CGE models require some exogenous parameter choices, NQT models also set many nests at Cobb-Douglas, which is methodologically equivalent to assuming the value of the elasticity exogenously.

[7] NQT models are based on the Eaton and Kortum (2002) trade model, while CGE models generally use the Armington assumption (Armington, 1969).

model. Section 7 provides an overview of recent model applications, Section 8 previews ongoing model developments and Section 9 concludes.

2 Core blocks of IMF-ENV

This section describes the main components of IMF-ENV through the lens of the traditional circular flow scheme of economics, i.e. starting with production and factor incomes, then moving to final demand, trade, and ending with macroeconomic closures and model dynamics. The section concludes with an explanation of how greenhouse gas (GHG) emissions are measured and integrated with economic activity within the model.

2.1 Production

In IMF-ENV separate production functions are defined for each economic sector or activity (denoted by a).[8] Sector-specific representative firms minimize their production costs under the assumption of constant returns to scale. This implicitly assumes that each sector has perfectly competitive markets.[9]

The production function in each sector is structured as a series of nested constant-elasticity-of-substitution (CES) functions, designed to capture various substitution possibilities between different pairs of input bundles. This production framework is anchored in the traditional CES function (see Box 1), and the decision-making process regarding input pairs is "nested" in a "tree"-like structure. The nested CES system captures the optimization process faced by each representative firm in activity a, where it minimizes the cost of purchasing intermediate inputs and production factors subject to the production function that describes the available production technology.

[8] The rest of the paper uses economic activity and economic sector interchangeably and both are denoted by a.

[9] These assumptions can be relaxed, usually using a monopolistic competition specification, if sector- and country-specific data on fixed costs are available (cf. Balistreri and Rutherford, 2013; Francois et al., 2013). For example, see Chateau et al. (2022a) for an application where deviations from perfectly competitive markets are modeled in the power sector owing to state ownership and regulations.

Box 1: Generic CES production function.

In generic terms the optimization problem entails the minimization of aggregated production costs, given by the objective function:

$$\min_{V_i} \sum_i P_i V_i$$

and subject to the constraint:

$$X = A\left[\sum_i a_i(\lambda_i V_i)^{\rho}\right]^{1/\rho}$$

where P_i is the price of input i and V_i is the input quantity purchased for a given level of production X. The constraint is referred to as the CES primal function, where A is an aggregate technological parameter that can be used to shift the overall production function and a_i are the primal share coefficients. Each input V_i is multiplied by an input-specific shifter (λ_i) that can be used to implement input-specific productivity increases (e.g., biased technological change or labor productivity changes). The parameter (ρ) is linked to the curvature of the CES function and is defined by the elasticity of substitution σ, such that: $\rho = \frac{\sigma-1}{\sigma}$. For given input prices P_i, and a given level of production X_a, solving the optimization problem –which is described in Annex A– yields optimal demand functions for production inputs:

$$V_i = \alpha_i^{\sigma}(A\lambda_i)^{\sigma-1}\left(\frac{P}{P_i}\right)^{\sigma} X_a$$

where α_i are the dual share parameters that are typically fixed and calibrated to the base year data. P is a composite price of all inputs, which is expressed by the following formula:

$$P = \frac{1}{A}\left[\sum_i \alpha_i \left(\frac{P_i}{\lambda_i}\right)^{1-\sigma}\right]^{1/(1-\sigma)}$$

In general, the demand for intermediate inputs and production factors is mainly determined in the model by changes in relative prices (P/P_i), conditional on the elasticity of substitution (σ). There are two special cases within the CES specification: when $\sigma = 0$, the function becomes Leontief (fixed proportions), and when $\sigma = 1$, it becomes a Cobb-Douglas function.

2.1.1 Production factors

The production function for each sector a requires factors of production and intermediate inputs from other sectors as inputs. While factors of production are provided strictly from domestic resource pools, the intermediate inputs may be sourced from either domestic or international origins (refer to Section 2.5 for a discussion on international trade). IMF-ENV incorporates four types of production factors: capital, labor, land, and natural resources.

IMF-ENV incorporates two types of capital inputs by employing a vintage capital modeling approach. The use of vintage capital is a unique feature of IMF-ENV among the IMF's climate modeling tools. There are two types of capital in the vintage specification, *Old* and *New* capital. The *Old* capital stock is the cumulative sum of the net (i.e. considering capital depreciation) capital allocated to the sector by the end of the previous year. Differently, the *New* capital is determined by regional investments and is allocated across sectors so as to equalize rates of returns.[10] As a result of capital vintages, sectoral production is identified by capital vintages, i.e. divided into *old* and *new* following a putty-clay specification. The implication of this is that for each sector, production takes place using two distinct technologies differentiated by the use of *old* or *new* capital vintages. Substitution elasticities among factors are lower when production is done with *old* capital relative to *new* capital i.e. *old* capital is sticky. This translates into slower changes in sectoral quantities in response to changes in prices. Therefore, such a formulation imposes an adjustment cost that reflects the real-world frictions of reallocating capital away from a sector once an investment has been made.

IMF-ENV uses one type of labor input that can move freely across production activities within a region.[11] The model has a single type of land input that is necessary for production of agricultural activities only.[12] Lastly, natural resource is a factor input in fossil and mineral extractive sectors, fisheries and forestry sectors. This input captures the natural capital like fossil-fuel and mineral reserves, forests and fisheries, that is necessary for production from these sectors.

[10] Most commonly in the literature, CGE models have a single type of capital. Additionally, several models allocate capital (either total or new when they have vintages) across sectors using a CET transformation function (Chateau et al., 2020) which is a less dynamic assumption compared to the *new* capital allocation approach used in IMF-ENV.

[11] Upcoming developments in the model will allow for the differentiation between skilled and unskilled labor types, leveraging the GTAP database that provides information on five distinct labor occupation categories (see Section 8.3). Furthermore, if additional country-specific data on the geographic distribution of the labor market (rural vs. urban) is available then it could also be integrated on an ad-hoc basis.

[12] IMF-ENV could be extended to include different land use types by using GTAP's satellite data on Land Use and Land Cover and this extension can allow the model to be used for applications aimed at examining the land-environment-energy nexus. With this model extension, land endowment can be represented by 18 agro-ecological zones (AEZs) for each model region or country.

Box 2: Notation used in production trees

The main paper discusses each of the nested CES production functions through the use of production trees, while the technical annex (see Annex B) offers a complete set of underlying equations that determine each production function. These equations include the full dimensions of the model, which has r regions (or individual countries), a economic activities (sectors), i commodities and v capital vintages.

In the production trees all nodes are color coded.

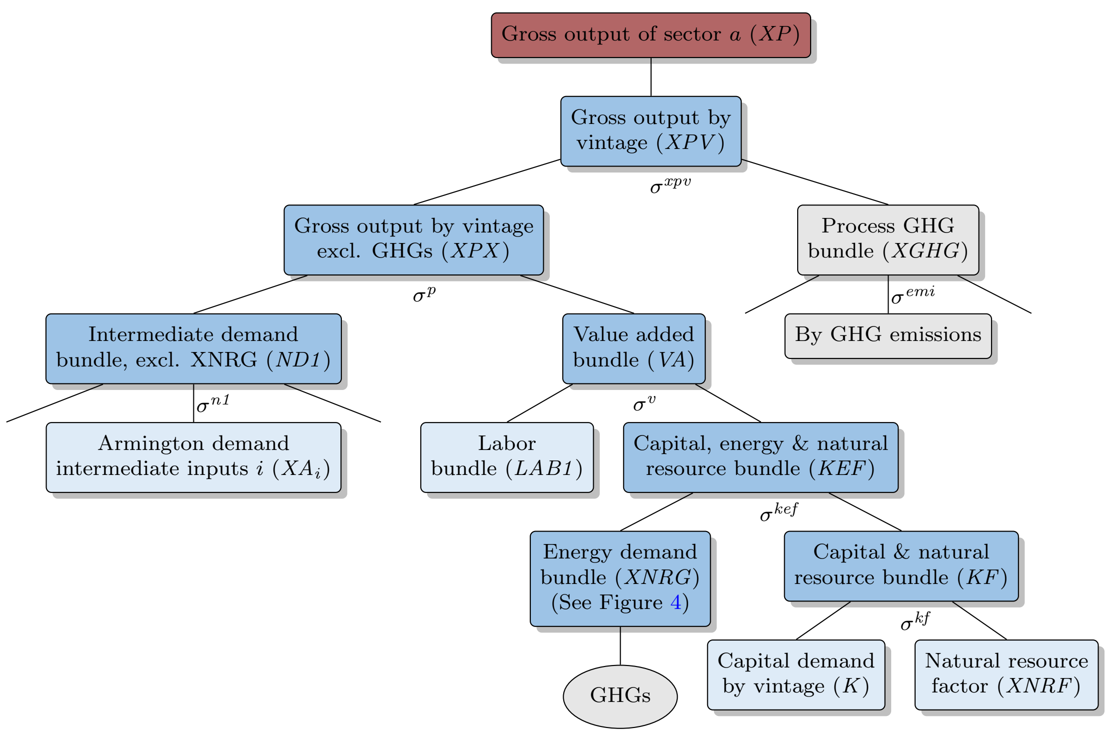
- Maroon nodes represent the total sectoral output summed across capital vintages.
- Dark blue nodes indicate CES functions. The corresponding substitution elasticity between inputs (shown by σ parameters) is shown at each of these nodes. The specific elasticities values are shown in Tables 2 and 3. CES nodes that have more than two branches for example, at the ND1 node or XGHG node, indicate that more than two inputs or GHGs are part of the CES nesting at this node. For example, in the case of *XGHG* it implies emissions of different GHGs - CO_2, N_2O and CH_4), while for *ND1* it reflects the large number of intermediate inputs from all commodities.
- Light blue nodes show either (Armington) demand for intermediate inputs or demand for primary production factors namely land, labor, capital and natural resources.
- Green nodes show the zero-emission production activities which in IMF-ENV refer to the renewable power generation sources.
- Gray nodes indicate sources of GHG emissions at different levels of production along with the underlying drivers. If only a single type of greenhouse gas (GHG) is emitted, the label will specify this; otherwise, the use of the label GHG at this node indicates that multiple types of GHGs are emitted from the associated emission driver.

2.1.2 Default production structure

We begin by discussing the default production structure that is common across all production activities excluding crops and livestock. The production nesting is modified to model agricultural activities, which include crop and livestock sectors, by including land as a production factor coupled with fertilizer inputs and the features of this adjusted production function are discussed in Section 2.1.3.

Figure 1 shows the default nested CES production structure in IMF-ENV. In the top nest, gross output of sector a is simply the sum of the gross output by capital vintage (XPV). The following node combines gross output by vintage excluding GHG emissions (XPX) with these process-related GHG emissions ($XGHG$) using a CES function. Gross output (XPX) is in turn a CES function between intermediate goods (bundle of domestically produced versus imports, $ND1$) and domestic value-added (including energy, VA). Value-added is a CES function between labor ($LAB1$) and a capital, energy, and natural resource bundle ($VA1$). The next node represents this bundle as a CES function between energy demand ($XNRG$) and a bundle of capital (K) and the natural resource factor ($XNRF$).

Figure 1: Default nested CES production structure



This nested-CES structure allows the model to have different substitution possibilities (denoted by the *sigma* parameters) at each node, which can be also differentiated across regions. The specific elasticities values are shown in Tables 2 and 3. All the technological shifters in production –i.e. the full set of A and λ parameters– are exogenous in the model. Therefore, at each production node, the overall technological shifter (A) and/or the input-specific shifters (λ_i) can be changed to reflect structural change driven by technological changes (e.g., renewable generation becoming cheaper or capital becoming less energy intensive) or explicit policies (for example, labor productivity increases associated with education policies).

Initial production levels are calibrated using the input-output information from the GTAP database, that fully reflect the cost structure of production by activity and country, and different factor intensities of production. The full calibration process is explained in Section 3.2.

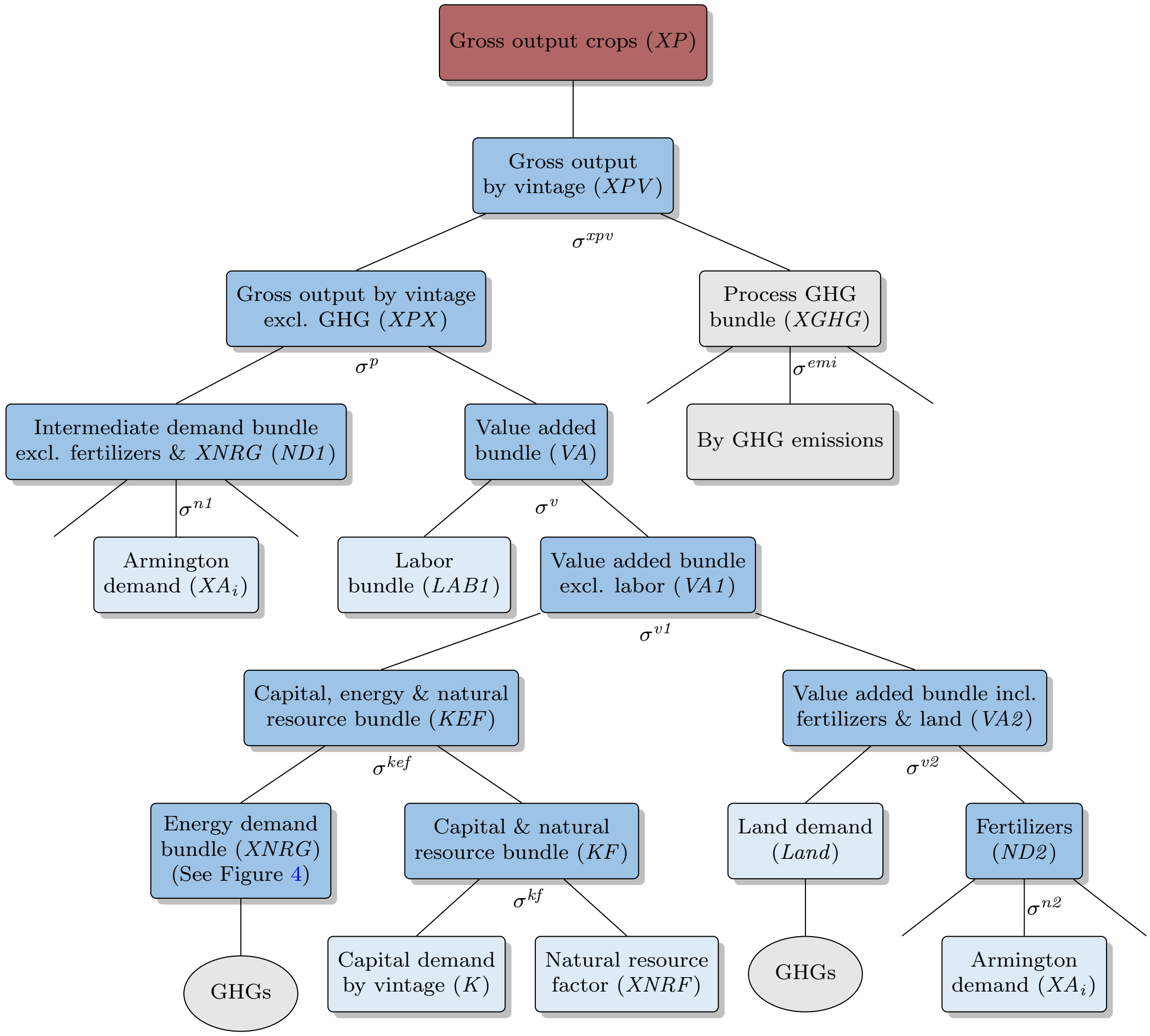
The specific equations for each of the production nodes in Figure 1 are presented in Annex B. Moreover, the equations also specify particular price wedges between producers and consumers, which include different types of taxes (including carbon taxes), transport margins and international trade costs.

2.1.3 Production structure for crops and livestock sectors

We now present the modifications made to the default production structure to model crops and livestock activities. There are two main distinction from the default production function, first these two sectors incorporate land as a factor of production and second, intermediate inputs of fertilizers is removed from *ND1* node and coupled with land demand in a newly defined node *VA2*. The implies that both production functions permit differentiation between land use intensification (by increasing sectoral output by increasing application of fertilizer or feed inputs) and extensification (by increasing the land input). This provides a richer and more nuanced response of the agricultural sectors when faced with policy shocks.

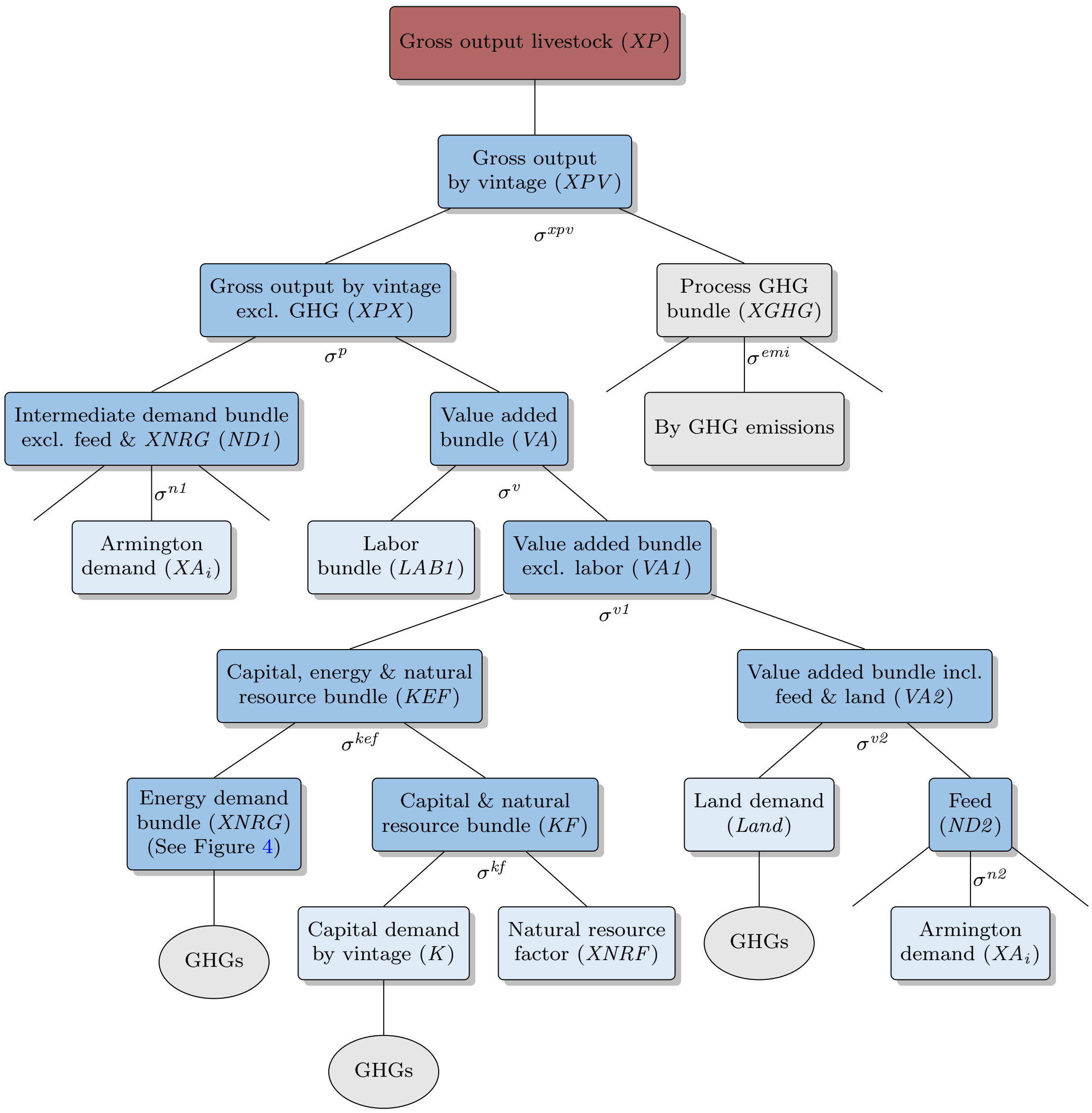
The production structure for crops is shown in Figure 2. Here we see that land and fertilizers are added to a new node (*VA2*), which represents the extensive use of land and the intensified use of land by employing fertilizers. As with all intermediate inputs, the demand for fertilizers can be domestically or internationally sourced. GHG emissions of CH_4 and N_2O are linked with land input and cover direct soil emissions and emissions from application of fertilizers. The rest of the production structure follows the same specification as the default structure.

Figure 2: Production structure for crops



In the case of livestock production (shown in Figure 3), it also has the additional node ($VA2$) though the intensified use of land can be achieved by the use of livestock feed rather than fertilizers. GHG emissions of CH_4 and N_2O are linked with land input and cover direct soil emissions and emissions from manure management. The other key difference relative to the crop production structure is that in the livestock sector capital (i.e., the livestock itself) generates GHG emissions and this chiefly primarily refers to the CH_4 emissions from livestock.

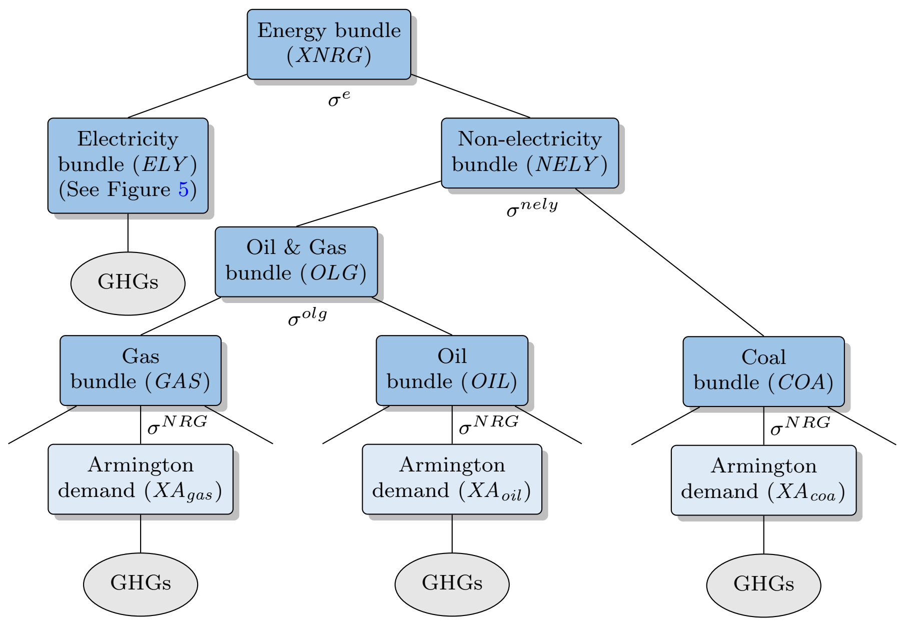
Figure 3: Production Function: Livestock



2.1.4 Energy bundle

The energy sector in IMF-ENV is defined by a distinct structure that is granular because it accommodates various production technologies. This section explains how the energy bundle ($XNRG$) node is determined in the default production structure and the corresponding production tree is shown in Figure 4. The energy bundle is characterized as a nested CES function that is a composite of the electricity commodity bundle (ELY) and the non-electricity energy commodity bundle ($NELY$). The supply of electricity (ELY) has a very detailed structure because it is produced by eight electricity generation sectors in conjunction with the transmission and distribution sector. Section 2.2.2 provides a detailed description on how electricity supply is determined in the model. The non-electricity bundle includes all fossil fuel inputs in a production structure where coal (COA) is nested with a CES function between natural gas and oil (OLG). Coal and oil are assumed to be easily traded internationally, whereas natural gas is less tradable, as it requires pipelines or liquefied natural gas (LNG) facilities. Total supply of these energy commodities is determined using the Armington specification. Finally, the gray nodes in Figure 4 indicate the GHG emissions that are directly generated by burning these fossil fuels.

Figure 4: Energy bundle



2.2 Domestic commodity supply

In the model, domestic production activities (a) are transformed into commodities (i). These commodities can be used as intermediate inputs for production or final consumption and can either be used domestically or traded internationally. The transformation from activities to commodities can be characterized in more than one way, depending on the production process. For example, one activity can produce many commodities (e.g. an agricultural activity producing both crops and bio-fuels), many activities can produce a single commodity (e.g., electricity generated using different power sources) or one activity produces one commodity. IMF-ENV can capture each of these production transformations, which are defined by the commodity transformation matrix (denoted by *mapi*), which specifies which activities are responsible for producing which commodities.

The default setting in IMF-ENV is that each economic activity produces a single commodity. The exception is the electricity generation sector. An important feature of IMF-ENV is that it distinguishes between eight electricity generation technologies: coal, gas, oil (diesel), nuclear, hydro, solar, wind and others (including geothermal, bio-fuels, tidal and waste technologies). Hence, electricity generation activities follow a many-to-one mapping, i.e. all power generation activities produce a single electricity commodity.[13] The mapping from GTAP data to IMF-ENV commodities and activities is shown in Tables 4-5 in the Annex. Next, we discuss the supply functions for non-electricity activities and electricity supply separately.

[13]This means that *mapi* is a diagonal matrix for all a x i values except for the electricity activities.

2.2.1 Non-electricity goods and services

This section describes the commodity transformation matrix for all commodities indexed by i except for the electricity commodity ($ely-c$). We first describe the general *transformation* from activities to commodities, where there is the option for a single economic activity to produce one or more commodities. Then we describe the general *supply* of commodities, where one or more activities are used to produce a single commodity.

Equation (1) describes the standard constant elasticity of transformation (CET) supply allocation expression, where the allocation of output ($XP_{r,a}$) in region r from activity a is linked to the transformation of commodities ($X_{r,a,i}$).[14] Here $P_{r,a,i}$ is the price of commodity i produced by activity a, $PX_{r,a}$ is the producer price before taxes, and $\gamma^p_{r,a,i}$ is the CET share parameter in the transformation matrix. For all non-electricity commodities $\gamma^p_{r,a,i} = 1$. The CET expression incorporates an efficiency parameter ($\lambda^s_{r,a,i}$) that allows for changes between the quantity produced and the quantity that reaches the market.[15]

The transformation elasticity is given by $\omega^s_{r,a}$ and it measures how easily firms can switch between producing different commodities in response to changes in relative prices. In the special cases where a single activity produces several commodities, a higher elasticity indicates how easily firms can shift production from one commodity to another. At the extreme, where $\omega^s_{r,a} = \infty$, there is perfect transformation from each economic activity to a single commodity.[16] However, the default option in IMF-ENV is that $\omega^s_{r,a} = \mathit{0}$, where $X_{r,a,i} = XP_{r,a}$ and there is a one-to-one matching between activity a and commodity i. Equation (2) determines the total gross output of activity a ($XP_{r,a}$) needed to produce the set of commodities i using activity a ($X_{r,a,i}$). In the standard case where each activity produces a single commodity, equation (2) becomes an equilibrium condition that determines aggregate gross output ($XP_{r,a}$).

$$\begin{cases} X_{r,a,i} = \gamma^p_{r,a,i} \left(\dfrac{1}{\lambda^s_{r,a,i}} \right)^{1+\omega^s_{r,a}} \left(\dfrac{P_{r,a,i}}{PX_{r,a}} \right)^{\omega^s_{r,a}} XP_{r,a} & \text{if } \omega^s_{r,a} \neq \infty \\ P_{r,a,i} = \lambda^s_{r,a,i} PX_{r,a} & \text{if } \omega^s_{r,a} = \infty \end{cases} \tag{1}$$

$$PX_{r,a} XP_{r,a} = \sum_i P_{r,a,i} X_{r,a,i} \tag{2}$$

Next, the general *supply* of commodity i is determined using a CES aggregation of output of one or more activities a. Equation (3) determines the demand for output a to compose commodity i in region r ($X_{r,a,i}$). Here PS_{ri} is the market price of commodity i in region r and $PP_{r,a,i}$ is the producer price that includes output taxes ($ptax_{r,a,i}$), which is defined in equation (5). $\alpha^s_{r,a,i}$ is the CES share parameter in the transformation matrix. For all non-electricity commodities $\alpha^s_{r,a,i} = \mathit{1}$. The substitution elasticity is given by σ^s_{ri} and the default value in the model, where all activities produce a single commodity, is for $\sigma^s_{ri} = \mathit{0}$, with the exception of electricity generation.[17] Finally, equation (4) determines the market price

[14] A CET function is very similar to the CES function (see Box 1). The main difference is that CES focuses on substitution between inputs, while CET focuses on the transformation between different outputs. In other words, the variable V in the CES function in Box 1 refers to inputs, but will refer to outputs in the CET formulation.

[15] This feature can be used to simulate, for example, post-harvest losses. The default value, however, is one.

[16] In this special case firms can shift all their resources to produce the commodity with the highest price without any loss in efficiency or productivity. This is also referred as the law-of-one-price, where the price of the activity is determined by the highest commodity price.

[17] Again, the model allows for perfect substitution ($\sigma^s_{ri} = \infty$), where the law-of-one-price determines that only the cheapest activity output is used to produce the single commodity.

of commodity i (PS_{ri}), and in the standard case this is given by the producer price including output taxes of the single activity a.

$$\begin{cases} X_{r,a,i} = \alpha^s_{r,a,i} \left(\dfrac{PS_{ri}}{PP_{r,a,i}} \right)^{\sigma^s_{ri}} XS_{ri} & \text{if } \sigma^s_{ri} \neq \infty \\ PP_{r,a,i} = PS_{ri} & \text{if } \sigma^s_{ri} = \infty \end{cases} \tag{3}$$

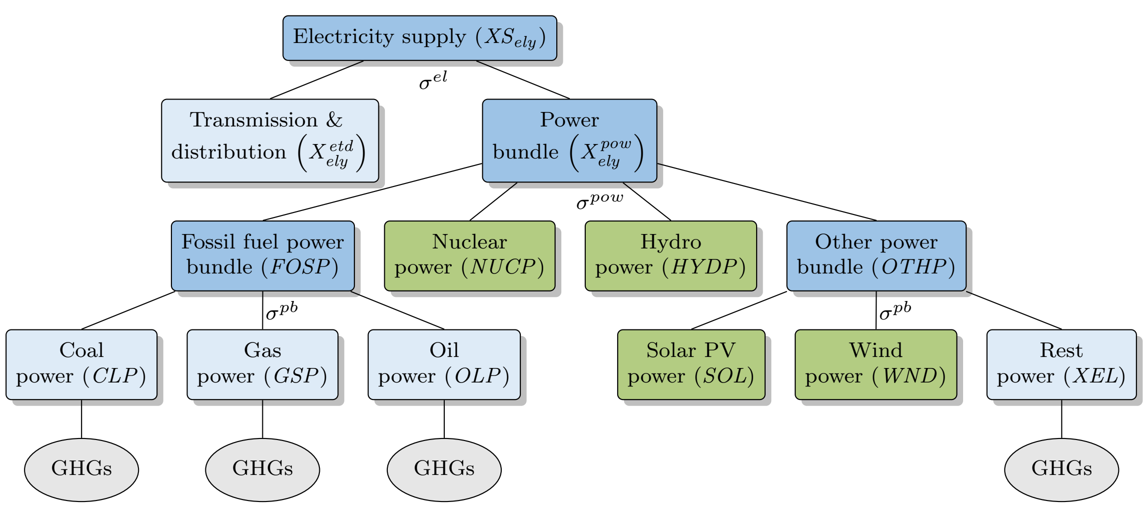
$$PS_{r,i} XS_{ri} = \sum_a PP_{r,a,i} X_{r,a,i} \tag{4}$$

$$PP_{r,a,i} = (1 + ptax_{r,a,i})\, P_{r,a,i} \tag{5}$$

2.2.2 Domestic supply of electricity

The standard representation of electricity supply in each region r in the IMF-ENV model assumes that a representative electricity provider chooses an optimal mix of electricity generation across electricity generation technologies. Electricity production uses a nested CES structure instead of a single nest (see Figure 5). The top node shows the substitution possibilities between electricity transmission and distribution (X^{etd}) with the power bundle (X^{pow}). Power can be generated directly using several user-determined power bundles (indexed by pb). The default classification in IMF-ENV has four different power bundles: the fossil fuel power bundle ($FOSP$), which includes coal, gas and oil (diesel) generation; the nuclear ($NUCP$) and hydro ($HYDP$) power bundles; and the "other" power bundle ($OTHP$), which includes renewable generation using solar and wind power, and the remaining power generation sources: bio-fuels, geothermal, waste, and tidal technologies. The gray nodes represent the GHG emissions from electricity generation using fossil fuels.

Figure 5: Electricity bundle



The top nest in Figure 5 is a CES function between electricity transmission and distribution (T&D) services (X^{etd}_{ely}) and the electricity power bundle (X^{pow}_{ely}), used to produce the single electricity commodity (indexed by ely), and it is defined by equations (6 to 8). Equation (6) determines the demand for T&D services (X^{etd}_{ely}), where $PS_{r,ely}$ is the supply price of electricity in region r, $PP^{etd}_{r,ely}$ is the producer price (including output taxes) of the (T&D) services, $\alpha^{etd}_{r,ely}$ is the CES share parameter of (T&D) services, and $\sigma^{el}_{r,ely}$ is the elasticity of substitution. The default specification assumes a Leontief technology, i.e. $\sigma^{el}_{r,ely} = 0$ and this means that T&D is a necessary input and scales up in proportion to increase in total electricity output. Similarly, equation (7) determines the demand for the power bundle ($X^{pow}_{r,ely}$). Equation (8) determines the supply price of aggregate electricity.

$$X^{etd}_{r,ely} = \alpha^{etd}_{r,ely} \left(\frac{PS_{r,ely}}{PP^{etd}_{r,ely}} \right)^{\sigma^{el}_{r,ely}} XS_{r,ely} \tag{6}$$

$$X^{pow}_{r,ely} = \alpha^{pow}_{r,ely} \left(\frac{PS_{r,ely}}{PP^{pow}_{r,ely}} \right)^{\sigma^{el}_{r,ely}} XS_{r,ely} \tag{7}$$

$$PS_{r,ely} = \left[\alpha^{etd}_{r,ely} \left(PP^{etd}_{r,ely} \right)^{1-\sigma^{el}_{r,ely}} + \alpha^{pow}_{r,ely} \left(PP^{pow}_{r,ely} \right)^{1-\sigma^{el}_{r,ely}} \right]^{1/\left(1-\sigma^{el}_{r,ely}\right)} \tag{8}$$

The fact that electricity generated using different technologies is aggregated as a single commodity implies that end-users cannot identify the generation technology for electricity commodity. This assumption reflects the fact that consumers usually do not have the option to choose the source of the electricity they use. However, with the large expansion of renewable generation, this assumption can be relaxed to allow for consumers to choose electricity generated from renewable or fossil fuel sources.[18]

The following nest decomposes aggregate demand for power into the four power bundles (pb): fossil fuels ($FOSP$), nuclear ($NUCP$), hydro ($HYDP$) and others ($OTHP$). The CES function for this nest is defined by equations (9 - 10). For simplicity, in what follows we drop the r and ely indexes that should be attached to all variables and parameters in these equations. Equation (9) determines the demand for each of the four power bundles (XPB), where PP^{pow} is the producer price for aggregate power, PPB_{pb} is the aggregate producer price for each power bundle, α^{pb}_{pb} are the CES share parameters, λ^{pow}_{pb} is a power-specific efficiency parameter[19], and σ^{pow} is the elasticity of substitution between power bundles. Equation 10 defines the producer price for aggregate power (PP^{pow}).

$$XPB_{pb} = \alpha^{pb}_{pb} (\lambda^{pow}_{pb})^{-\sigma^{pow}} \left(\frac{PP^{pow}}{PPB_{pb}} \right)^{\sigma^{pow}} X^{pow} \tag{9}$$

$$PP^{pow} = \left[\sum_{pb} \alpha^{pb}_{pb} \left(\lambda^{pow}_{pb} PPB_{pb} \right)^{1-\sigma^{pow}} \right]^{1/(1-\sigma^{pow})} \tag{10}$$

The bottom nests decompose the various power bundles into component power activities. Each of the eight electricity generation technologies (indexed by $elya$) is mapped to a power bundle (pb). Equation (11) determines the demand power activity $elya$ (X_{elya}) that is mapped to power bundle pb. Here PP_{elya} is the producer price for the power technology ($elya$), PPB^{pb} is the aggregate producer price of the power bundle (pb), α^{s}_{elya} are the CES share parameters and σ^{pb} is the elasticity of substitution between power bundles pb. Equation (12) determines the price index for the power bundle PPB_{pb}.

[18]This can be achieved by expanding the set ely to include more than one electricity commodity, which in turn will require to alter the production structure in Figure 5.

[19]This parameter can be used to adjust the electricity mix in certain policy applications.

$$X_{elya} = \alpha^s_{elya} \left(\frac{PPB_{pb}}{\lambda^{pb}_{elya} PP_{elya}} \right)^{\sigma^{pb}} XPB_{pb} \quad \text{if } elya \in pb \tag{11}$$

$$PPB_{pb} = \left[\sum_{elya \in pb} \alpha^s_{elya} \left(\lambda^{pb}_{elya} PP_{elya} \right)^{1-\sigma^{pb}} \right]^{1/(1-\sigma^{pb})} \tag{12}$$

The modeling of electricity explained above provides detailed information on how electricity is generated and at the same time, allows the use of several policy instruments and technology levers (i.e., the λ parameters). For instance, output taxes and subsidies can be included in any of the producer prices in each of the nests, and these can be used to model feebates and other mitigation policies, which are further explained in Section 6.1.2. Nevertheless, the modeling of electricity generation in IMF-ENV still misses several technical and legal aspects that are important to assess how different policies and technology shocks change electricity generation. Many of these are country-specific, such as the potential for renewable generation, political decisions regarding the deployment of nuclear and hydro plants, the legal and technical hurdles to electricity trade, technical issues related to integrating a large share of renewable generation into grids that were designed for traditional power sources, and how to deal with renewable intermittency, among others.

2.3 Factor supply

We now present how the supply of each production factor is determined in the model.

2.3.1 Labor

The total (economy-wide) labor supply (LS) is determined by demographic and labor market characteristics:

$$LS_{r,t} = POP^{wa}_{r,t} \times LFPR_{r,t} \times (1 - \mu_{r,t}) \tag{13}$$

where $POP^{wa}_{r,t}$ is the working age population (15 to 64 years old) in region r and year t, $LFPR_{r,t}$ is the labor force participation rates and $\mu_{r,t}$ is the long-term unemployment rate. Labor can freely move across sectors in a model region and in equilibrium wages clear in each regional market across all economic activities. The standard approach is to assume that $LFPR$ and μ are fixed, and hence, labor supply changes are driven by the working age population changes. However, it is possible to allow $LFPR$ and unr to change over time if country circumstances require this, for example in the case of higher female participation is associated with expanded daycare policies or cultural shifts. For instance, IMF-ENV has the option to incorporate a simplified decision-making process for individuals, balancing the choice between additional work (at both the extensive and intensive margins) and leisure. This leads to an endogenous adjustment of the labor participation rate, which is modeled through a real wage-labor supply curve (equation 14).

$$LFPR_{r,t} = LFPR_{bau,r,t} \left[\frac{W_{r,t}}{W_{bau,r,t}} \right]^{\eta^{wl}_r} \tag{14}$$

where $LFPR_{bau,r,t}$ is the initial labor force participation rate in the baseline (bau), W_{bau} refers to the real wage in the baseline, and W in the policy simulation. As real wages rise, individuals perceive work as more appealing compared to leisure, resulting in an increase in their labor participation and in overall labor supply (following equation 13). The extent of these adjustments in labor supply is determined by the elasticity of the wage curve (denoted by η_r^{wl}). The standard values of this elasticity range from 0.05 to 0.2, which aligns with established literature (cf. Evers et al., 2008).[20] The model also accounts for the reverse effect: lower real wages reduce labor supply as leisure becomes relatively more attractive than work.

It is important to clarify a prevalent misconception that CGE models operate under the assumption of full employment. In practice, there are several labor adjustment margins, including the endogenous wage-labor supply adjustment and exogenous changes to the long-term unemployment rate, both of which differ across countries. Additionally, the CGE framework offers multiple options to directly endogenize unemployment (see for example, Boeters and Savard, 2013).

2.3.2 Capital

There are two types of capital in the vintage specification, *Old* (i.e. installed capital) and *New* capital. Initial installed capital is set at the beginning of the current year and is equal to the depreciated level of the total capital (sum of old and new capital) at the end of previous year. During the current year the *New* capital is allocated across sectors so as to equalize capital rates of returns.

For a given sector there are two configurations. First, the sector is in expansion, and therefore there is a need for new capacity of production and demand for *New* capital exceeds the initial installed capital. Second, the sector is declining, the actual capacity of production (initial installed capital) is too high and therefore there is no demand for *New* capital. A declining sector may release some of its *Old* capital and sell it (on secondary markets) to be used in other expanding sectors, but only partially and at a lower price than the rate of return of capital in expanding sectors. It is assumed that *Old* capital of a declining sector can be sold following an upward sloping (finite) supply curve to capture i) the restricted mobility of installed capital across the economy in the short-run and ii) a lower rate of return than in expanding sectors.

2.3.3 Land

IMF-ENV has one type of land and aggregate land supply is specified using a supply curve. Typically, the supply curve is determined either through a logistic (with an upward asymptote) or an iso-elastic (constant elasticity) function.[21]

1. The aggregate land supply curve, represented by a logistic function in a simplified form, is given by the following equation:

$$S = \frac{\overline{S}}{1 + \chi e^{-\gamma P}} \tag{15}$$

[20] For an elasticity of 0.1, this indicates that a 1 percent increase in real wages results in a 0.1 percent increase in total labor supply. If $\eta_{wl}(r)$ is set to zero then labor supply of the region remains fixed across scenarios.

[21] The model also allows two additional specifications: a generalized hyperbola (with an upward asymptote) and fixed supply (perfectly horizontal).

where total land supply ($TLand_{r,lnd}$) is given by S, which has an upper bound or maximum value of $\overline{S}$. The real price of land using the GDP price deflator ($PTLand_{r,lnd}/P_r^{GDP}$), is given by P. The gamma coefficient (γ_r^{tl}) is calibrated using the initial land supply values and real land price, such that:

$$\gamma = \frac{\eta_r^t}{P}\left(\frac{\overline{S}}{\overline{S} - S}\right) \tag{16}$$

where η_r^t is the aggregate supply elasticity of land by region r. The chi parameter ($\chi_{r,lnd}^t$) is calibrated using equation 17, but requires first calibrating the gamma parameter.

$$\chi = e^{\gamma P}\left(\frac{\overline{S} - S}{\overline{S}}\right) \tag{17}$$

2. The iso-elastic function in simplified form can be described by the following equations:

$$S = \chi P^{\eta} \tag{18}$$

where all the variables are defined as above, except for the calibration of the chi parameter, which is given by:

$$\chi_{r,lnd}^t = \left(\frac{P_r^{GDP}}{PTLand_{r,lnd}}\right)^{\eta_r^t} \tag{19}$$

After determining the total land supply in the economy, land is distributed among agricultural activities using a nested CET specification based on their relative rates of returns.

2.3.4 Natural resources

Natural resources are supplied to extraction activities –forestry, fisheries and mining– in a fixed proportion (Leontief specification). Moreover, this natural resource factor constrains the possibility of extraction activities to expand, as the quantity of the fixed natural resource factor employs an iso-elastic supply function with an elasticity that is usually below one.[22] The country- and region-specific values of this elasticity are taken from the OECD's ENV-Linkages model. However, a future planned expansion of IMF-ENV is to incorporate the depletion module from the ENVISAGE model, which calculates the values of these elasticities using detailed data on natural resource reserves and production costs (see Section 8.4).

2.3.5 Factor taxes

Producers pay the market price for factors adjusted by factor taxes. Equation (20) determines the producers purchase price of factors for all factors of production. Equation (21) is the relevant equation for the price of capital across vintages.

$$PF_{r,f,a}^{p} = \left(1 + \tau_{r,f,a}^{f}\right) PF_{r,f,a} \tag{20}$$

[22] The standard values of the supply elasticity are 0.25 for fisheries, 0.5 for forestry, 0.9 for coal extraction and 1 for natural gas extraction. Coal and other extraction activities, on the other hand, have elasticities above one, reflecting that production of these extraction activities can increase more easily.

$$PK^{p}_{r,a,v} = \left(1 + \tau^{f}_{r,cap,a}\right) PK_{r,a,v} \tag{21}$$

2.4 Final demand

IMF-ENV has three types of final demand: private consumption (by households), public expenditure (government) and investment. Household demand for goods and services is constrained by the income generated by production factors (labor, capital, land and natural resources). In IMF-ENV household consumption demand is the result of static maximization behavior which is formally implemented as an Extended Linear Expenditure System (ELES)[23]. The model assumes a price-taking representative household in each region that optimally allocates disposable income (Y) among set of consumption commodities (C_k) and savings (S). IMF-ENV employs non-homothetic private demand functions, as this is consistent with considerable empirical evidence on household preferences (cf. Dowrick et al., 2003).

The ELES integrates the savings decision together with demand for goods and services.(Lluch, 1973; Howe, 1975). It is based on consumers maximizing their utility between a bundle of current consumption and an expected future consumption bundle represented by savings. This consumption and saving decisions are made in each year (i.e., it is not a fully inter-temporal optimization process). This means that consumers save a constant proportion of their income and do not adjust their behavior to reflect future events that may impact their income. Formally, a representative consumer maximizes utility U subject to resource constraints:

$$\begin{aligned} Max \quad U &= \sum_k \mu_k ln(C_k - \theta_k) + \mu_s ln\left(\frac{S}{P_s}\right) \\ \text{subject to:} \quad YH^d &= \sum_k P^c_k C_k + S \quad \text{and} \quad \sum_k \mu_k + \mu_s = 1 \end{aligned} \tag{22}$$

where C is a vector of k consumer goods, P^c_k is the vector of consumer prices (market prices plus any consumer excise or *ad valorem* tax and subsidies), μ_k are the marginal propensities to consume and μ_s is the marginal propensity to save. Parameter θ_k is the subsistence level of consumption of vector k of commodities and this feature is needed to make the utility function non-homothetic. S represents the value of saving, P_s the relevant price of saving which is set arbitrarily equal to the average price of consumer goods, and YH^d represents household disposable income (net-of-taxes) and this is assumed to be completely allocated between consumption and savings.[24]

In IMF-ENV investment is savings driven and equal to domestic saving adjusted by net international capital flows and changes in the government balance. This is the standard saving/investment closure rule of the model. As an alternative closure rule, the model can target a predetermined level of investment (as a share of GDP for example) and endogenize the μ_s parameter that will find a level of savings consistent with targeted investment.

[23] Other consumer preferences, such as the Linear Expenditure System (LES), Constant Difference of Elasticity (CDE) or An Implicit Directly Additive Demand System (AIDADS) can also be implemented instead of the ELES demand system (see van der Mensbrugghe (2024)).

[24] Since the model is dynamic, the absence of forward-looking households makes it necessary to exogenously specify a savings rate of households.

A transition matrix approach is used to convert the household commodities into the produced commodities. In the core version of IMF-ENV the set of consumer goods k is lower than the set of produced commodities i (see Table 7 in the Annex). This approach has the advantage that it provides a more accurate picture of consumer demand, as many raw agricultural and manufacturing commodities are mainly used as intermediate inputs, and not for final consumption. In addition, it makes it easier to link demand with consumer taxes.[25]. A final advantage is that using this transition matrix makes it easier to link the model with household surveys, which can be used to assess distributional and poverty impacts.

For each country, the consumer's objective function thus gives rise to household private consumption (equation 23) and savings (equation 24).

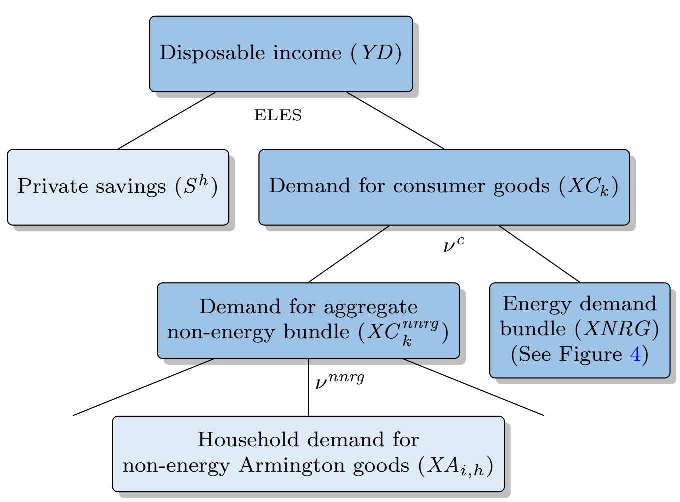
$$C_k = Pop\,\theta_k + \frac{\mu_k}{P^c_k} Y^*, \quad \text{where} \quad Y^* = Y^d - Pop \sum_k P^c_k \theta_k \tag{23}$$

$$S = Y^d - \sum_k P^c_k C_k \tag{24}$$

where Pop represents population, Y^* is a supernumerary income –i.e. income above the subsistence level. Households derive income from supplying factors of production (labor, capital, land, natural resources) to firms and Y^d is this net-of-taxes income. There are also direct transfers between households and governments. Hence, Y^d is the sum of factor income across all activities at market prices, minus households' income taxes plus direct public transfers.

The graphic representation of the demand system is shown in Figure 6. The main feature is that consumer goods are initially separated between energy and non-energy bundles. The energy bundle follows the structure depicted in Figure 4, but the elasticities of substitution are different, as they refer to final consumption instead of intermediate consumption.

Figure 6: Consumer demand structure



In addition to final demand by households, there are two more types of final demand in the model-

[25] For example, it is possible to connect taxes on different energy bundles with different sources of demand. The demand for transport is likely to be dominated by liquid fuels, whereas the demand for energy in households is likely to be a mix of electricity, gas and coal.

the investment sector and the government. Both these sectors consume a bundle of final goods, with a CES specification, reflecting a simplified version of household demand (excluding savings and excluding the subsistence consumption bundle). This leads to the total demand of a good in the economy being equal to the sum of consumer demand, intermediary demands from firms, the government and investment expenditures of this good.

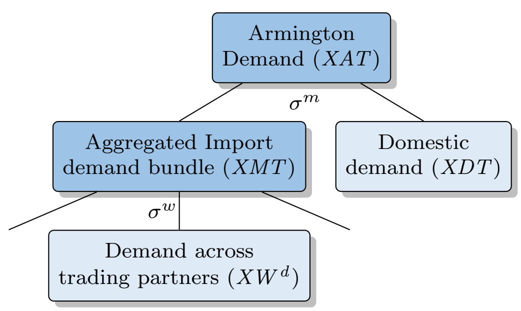
2.5 International trade

In this section we explain how international trade is modeled using the Armington assumption for import demand and perfect transformation for export supply. In addition, we describe the different price margins (e.g., international transport and trade costs) between exported and imported goods.

2.5.1 Import Demand

International trade is modeled assuming that imports are differentiated by country of origin and hence are imperfect substitutes. This specification is based on Armington (1969) and is implemented via a two level nested-CES function (see Figure 7). In the top nest, domestic agents choose an optimal combination of domestically produced goods (XD) and aggregated import goods (XM). At the second level nest, agents optimally allocate demand for the aggregate imported good across different trading partners d (XW^d) based on their relative export prices.[26].

Figure 7: Import demand function: Armington good



The national sourcing of aggregate inputs is defined in equation (25), which adds up Armington demand (or domestic absorption for the Armington good XA) across all Armington agents (aa) to measure aggregate Armington demand, XAT.[27]

$$XAT_{r,i} = \sum_{aa} \gamma^{eda}_{r,i,aa} XA_{r,i,aa} \tag{25}$$

where γ^{eda} is a price wedge that is explained below. The aggregate Armington demand (XAT) is then decomposed into aggregate demand for domestically produced goods, XDT^d (equation 26) and aggregate

[26]It is possible to consider an enhanced version of the trade system, where the top nest Armington choice, i.e. between domestic and aggregate imports is considered at the individual agent level. In this case, import demand is differentiated between firms and households (cf. van der Mensbrugghe, 2024). Though this represents perhaps a more realistic modeling of trade preferences, it significantly increases the model size and computation time.

[27]The model allows for the domestic/import split to be done at either the agent level or the national level. Herein, the choice is the latter. To source at the agent level, the GTAP MRIO specification and database needs to be used.

import demand, XMT (equation 27).

$$XDT_{r,i} = \alpha^d_{r,i} \left(\frac{PAT_{r,i}}{PD_{r,i}} \right)^{\sigma^m_{r,i}} XAT_{r,i} + XTT_{r,i} \tag{26}$$

$$XMT_{r,i} = \alpha^m_{r,i} \left(\frac{PAT_{r,i}}{PMT_{r,i}} \right)^{\sigma^m_{r,i}} XAT_{r,i} \tag{27}$$

where α^d and α^m are, respectively, the share parameters of domestic and imports goods in total Armington demand. The parameter σ^m represents the key trade substitution elasticity and is often referred to as the (first-level) Armington elasticity. Each region in the model provides international trade and transport services (XTT), which are described below. It is assumed that these services are only provided using domestically produced goods. Hence, equation (26) also includes the region's provision of these services, in addition to the demand for domestic goods coming from the other agents in the economy.

Equation (28) determines the Armington price aggregator (PAT), which is a CES combination of the domestic aggregate price (PDT) and the aggregate import price (PMT).

$$PAT_{r,i} = \left[\alpha^d_{r,i} \left(PDT_{r,i} \right)^{1-\sigma^m_{r,i}} + \alpha^m_{r,i} \left(PMT_{r,i} \right)^{1-\sigma^m_{r,i}} \right]^{1/(1-\sigma^m_{r,i})} \tag{28}$$

The market clearing condition for the aggregate Armington good is given by:

$$PAT_{r,i} XAT_{r,i} = PDT_{r,i} \left(XDT_{r,i} - XTT_{r,i} \right) + PMT_{r,i} XMT_{r,i} \tag{29}$$

The Armington price paid by agent aa (PA_{aa}) is defined by equation (30). Here τ^a is the agent specific tax on Armington consumption. The economy-wide Armington price (PAT) is allowed to vary across end-users using a price wedge represented by γ^{eda}. The carbon tax is treated as a Pigouvian tax that is added to the after-tax Armington price, where τ^{emi} is the carbon tax rate and Emi are the emission levels by GHG (em):[28]

$$PA_{r,i,aa} = \left(1 + \tau^a_{r,i,aa} \right) \gamma^{eda}_{r,i,aa} PAT_{r,i} + \sum_{em} \tau^{emi}_{r,em,i,aa} Emi_{r,em,i,aa} \tag{30}$$

The second CES nest (see Figure 7) decomposes the aggregate demand for imports (XMT) into demand for imports by source region (XW^d).[29] Equation (31) describes demand for imports by region r for imports from region s for good i, where α^w is the CES share parameter of imports by source region s. The variable PDM represents the end-user price of imports –i.e. it includes bilateral tariffs and other trade costs (see Section 2.5.3 below). The key substitution elasticity is given by σ^w, which is the second-level Armington elasticity. The aggregate import price, PMT, is the CES aggregation of the tariff-inclusive bilateral prices as described in equation (32).

$$XW^d_{s,i,r} = \alpha^w_{s,i,r} \left(\frac{PMT_{r,i}}{PDM_{s,i,r}} \right)^{\sigma^w_{r,i}} XMT_{r,i} \tag{31}$$

[28] Emission accounting is explained in Section 2.9.

[29] As mentioned above, the XW^d is substituted out and thus this expression carries the iceberg parameter in the model implementation.

$$PMT_{r,i} = \left[\sum_s \alpha^w_{s,i,r} \left(PDM_{s,i,r}\right)^{1-\sigma^w_{r,i}} \right]^{1/(1-\sigma^w_{r,i})} \tag{32}$$

Finally, the market clearing condition for aggregate imports is:

$$PMT_{r,i} XMT_{r,i} = \sum_s PDM_{s,i,r} XW^d_{s,i,r} \tag{33}$$

2.5.2 Export supply

In the standard version of IMF-ENV, it is assumed that domestic producers are indifferent between the destination of their goods (between domestic and export markets). This assumption is made to limit model dimensions, but IMF-ENV also has the option to implement an allocation of domestic supply analogously to the Armington assumption from the demand side using a nested constant-elasticity-of-transformation (CET) specification. In this alternative case, the domestic supply of each commodity (XDT) is then supplied to the domestic market by an aggregate export bundle (XS) using a top-level CET function. The latter is allocated across regions of destination using a second-level CET function (see for example, van der Mensbrugghe, 2024).[30]

In the standard case of perfect transformation, the market price of goods sold domestically (PDT) is equal to the average supply price (PS) adjusted by an exogenous price wedge (γ^{esd}):

$$PDT_{r,i} = \gamma^{eds}_{r,i} PS_{r,i} \tag{34}$$

Equation (35) determines that the price of aggregate exports (PET) equals the average supply price adjusted by the price wedge γ^{ese}:

$$PET_{r,i} = \gamma^{ese}_{r,i} PS_{r,i} \tag{35}$$

while the market clearing condition is:

$$PS_{r,i} XS_{r,i} = PDT_{r,i} XDT_{r,i} + PET_{r,i} XET_{r,i} \tag{36}$$

The second level nest is represented by equation (37), where the export price by destination region d (PE_d) is equal to the aggregate export price and there is again the option to introduce an exogenous price wedge (γ^{ew}):

$$PE_{r,i,d} = \gamma^{ew}_{r,i,d} PET_{r,i} \tag{37}$$

Finally, the market clearing conditions for total exports (XET) is the sum over the value of exports allocated to each of the destination markets (d) (XW^s_d):

$$PET_{r,i} XET_{r,i} = \sum_d PE_{r,i,d} XW^s_{r,i,d} \tag{38}$$

[30] Technically, the standard version assumes perfect transformation between domestic production and export supply by setting the transformation parameters to: $\omega^x = \infty$ and $\omega^w = \infty$; and not infinity otherwise.

2.5.3 Bilateral trade prices

Each bilateral trade node is associated with four prices: i) the domestic producer price (PE); ii) the export border price, also referred to as the free-on-board (FOB) price (PWE); iii) the import border price, also referred to as the cost, insurance and freight (CIF) price (PWM); and iv) the end-user import price that includes all applicable trade taxes and costs (PM).

The price wedge between the producer price and the FOB price is represented by the export tax (or subsidy) τ^e:

$$PWE_{r,i,d} = \left(1 + \tau^e_{r,i,d}\right) PE_{r,i,d} \tag{39}$$

The wedge between the CIF and FOB prices is provided by two costs: international trade margins and "iceberg" trade costs: [31]

$$PWM_{r,i,d} = \left(PWE_{r,i,d} + \zeta^{mg}_{r,i,d} PWMG_{r,i,d}\right) \Big/ \lambda^w_{r,i,d} \tag{40}$$

where ζ^{mg} represents the per unit transportation margin that is valued at the average price of port-to-port shipping ($PWMG$). The CIF import price is adjusted by the iceberg parameter, λ^w. Both these margins represent the use of real resources that are supplied by each region. The global international trade and transport sector purchases these services from each region so as to minimize the aggregate cost, as explained in the following section.

The final price wedge between the CIF and end-user import prices is determined by any bilateral import tariff (τ^m) and other import related policy distortions, such as import quotas and non-tariff measures (NTMs) represented by τ^{ntm}:

$$PM_{r,i,d} = \left(1 + \tau^m_{r,i,d} + \tau^{ntm}_{r,i,d}\right) PWM_{r,i,d} \tag{41}$$

2.5.4 International trade margins

International trade is associated with transport margins that capture the wedge between the price at the source port and the price at the destination port, i.e. the CIF/FOB price wedge. These transport services include insurance and transport-related services. The supply of these services is assumed to be provided by a global supplier that chooses the lowest cost supply subject to a CES preference function.

Equation (42) determines the demand for international trade and transport services per bilateral node ($XWMG$), as a simple linear technology:

$$XWMG_{r,i,d} = \zeta^{mg}_{r,i,d} XW^s_{r,i,d} \tag{42}$$

The bilateral demand for trade and transport services is allocated across margin commodities (m) using a similar linear technology (equation 43). These margin commodities are usually associated with the different transport services in the data: land, water and air transportation, and their shares are given by α^{mg}. There is the option to include exogenous technological change in international transport services

[31] The concept of iceberg trade costs is used to denote the value of imports that is "melted away" or lost during transit, but which does not accrue to any domestic or foreign agent. This includes several costs and administrative burdens, such as compliance with customs and safety procedures, delays at ports and customs, among others. These costs, therefore, exclude tariffs and transportation costs that are paid to governments and transport companies, respectively.

using the parameter λ^{mg}.

$$XMG^{m}_{m,r,i,d} = \alpha^{mg}_{m,r,i,d} \frac{XWMG_{r,i,d}}{\lambda^{mg}_{m,r,i,d}} \tag{43}$$

The average price of transportation per bilateral node ($PWMG$) is a function of the global average transportation price by margin commodity ($PTMG$):

$$PWMG_{r,i,d} = \sum_{m} \alpha^{mg}_{m,r,i,d} \frac{PTMG_{m}}{\lambda^{mg}_{m,r,i,d}} \tag{44}$$

Total global demand (and therefore supply) for trade and transport margins ($XTMG$) for each margin commodity m, is the sum across all potential bilateral nodes:

$$XTMG_{m} = \sum_{r} \sum_{i} \sum_{d} XMG^{m}_{m,r,i,d} \tag{45}$$

The global supplier allocates this demand across potential suppliers using a CES preference function. Equation (46) determines region r's supply of trade and transport services (XTT) for commodity m:

$$XTT_{r,m} = \alpha^{tt}_{r,m} \left(\frac{PTMG_{m}}{PDT_{r,m}} \right)^{\sigma^{mg}_{m}} XTMG_{m} \tag{46}$$

where σ^{mg} is the elasticity of substitution between different margin commodities, and α^{tt} is the share of each margin commodity in the CES function.

Finally, the market clearing condition for international transport services in each margin commodity is given by:

$$PTMG_{m} XTMG_{m} = \sum_{m} PDT_{r,m} XTT_{r,m} \tag{47}$$

2.6 Income block

This section describes how income is assigned to different agents and how the model keeps track of macroeconomic balances.

2.6.1 Household income

The income of the representative household in region r (YH_r) is defined in equation (48). It includes the income from all production factors employed in all activities ($XF_{r,f,a}$) at market prices ($PF_{r,f,a}$). This income is net of factor taxes and depreciation (κ_f).

$$YH_{r} \quad = \quad \sum_{f} \sum_{a} \left(1 - \kappa^{f}_{r,f,a} \right) PF_{r,f,a} XF_{r,f,a} \tag{48}$$

Equation (49) describes disposable income, YD, where κ^{h} is the marginal (and average) tax rate on household income and TRG_r are direct transfers from the government to households.

$$YD_{r} = \left(1 - \kappa^{h}_{r} \right) YH_{r} + TRG_{r} \tag{49}$$

2.6.2 Government income

Government revenues, contained in the variable $YGOV$, are indexed by the set gy, which contains eight different tax revenue sources and are described in the following equations.

1. Production and unit cost taxes (ptx). These are a combination of the production tax rate (τ^p) on the pre-tax production value ($P * X$) applied on commodity i produced by activity a, and the unit cost tax rate (τ^{uc}) applied to the unit cost production value ($UC * XP$) applied on capital vintage v and economic activity a:

$$YGOV_{r,ptx} = \sum_a \left[\sum_i \tau^p_{r,a,i} P_{r,a,i} X_{r,a,i} + \sum_v \tau^{uc}_{r,a,v} UC_{r,a,v} XPv_{r,a,v} \right] \tag{50}$$

2. Taxes on production factors used by firms (vtx). Applied to all production factors indexed by the set f that includes labor, capital, land and natural resources. This consists of a region-, factor- and activity-specific tax rate ($\tau^{vt}_{r,f,a}$) applied on the firm's factor costs ($PF * XF$):

$$YGOV_{r,vtx} = \sum_a \sum_f \tau^{vt}_{r,f,a} PF_{r,f,a} XF_{r,f,a} \tag{51}$$

3. Subsidies on production factors used by firms ($vsub$). This includes support received by production factors and therefore has a negative value. The subsidy rate is provided by τ^{vs}, which can vary by region, factor and activity:

$$YGOV_{r,vsub} = \sum_a \sum_f -\tau^{vs}_{r,f,a} PF_{r,f,a} XF_{r,f,a} \tag{52}$$

4. Consumption (sales) taxes (itx). This tax is applied to all domestic agents, indexed by aa, which include domestic firms in activity a in addition to households. The standard approach in IMF-ENV is that the sourcing of goods is made at the national (aggregate) level and thus all users face a common Armington price (PAT). The end-user sales tax rate τ^a is then applied to this Armington price times the consumption volume by agent aa ($XA_{i,aa}$). Goods at this level are assumed to be additive. However, allowances are made for different prices and this is captured by the γ^{eda} coefficients.

$$YGOV_{r,itx} = \sum_{aa} \sum_i \tau^a_{r,i,aa} \gamma^{eda}_{r,i,aa} PAT_{r,i} XA_{r,i,aa} \tag{53}$$

5. Import tariffs (mtx). In the standard specification, tariffs are uniform across all agents and the tax collection is done at the border relative to the aggregate level of bilateral tariffs and summed across all source countries (s), where the first regional index is always the exporting region, and the second regional index is always the destination (d or importing) region. The tariff rates τ^m are applied to the border (or CIF) price of imports (PWM) times the trade volumes (XW). The model allows for

iceberg trade costs on imports and exports, using the parameters λ^w and λ^x, respectively.[32]

$$YGOV_{r,mtx} = \sum_s \sum_i \tau^m_{s,i,r} PWM_{s,i,r} \lambda^w_{s,i,r} \lambda^x_{s,i,r} XW^d_{s,i,r} \tag{54}$$

6. Export taxes (etx). The export tax rate τ^e is applied to the producer price of exports (PE) times the trade volumes (XW):

$$YGOV_{r,etx} = \sum_d \sum_i \tau^e_{r,i,d} PE_{r,i,d} XW^s_{r,i,d} \tag{55}$$

7. Carbon taxes (ctx). The carbon tax rate τ_{emi} is applied to emissions (Emi) in region r by GHG (em), emission source β and by all economic agents aa:[33]

$$YGOV_{r,ctx} = \sum_{em} \sum_\beta \sum_{aa} \tau^{emi}_{r,em,\beta,aa} Emi_{r,em,\beta,aa} \tag{56}$$

   A detailed description on how emissions are accounted for in the model is provided in Section 2.9, while Section 2.6.3 describes alternatives to the standard fiscal closure that allows for targeted recycling of carbon tax revenues.

8. Direct (income) taxes (dtx). These taxes are imposed on two sources: household factor incomes and on total household income after factor taxes. The factor income tax rate κ^f is applied on factor income ($PF * XF$). The net direct tax rate κ^h is applied to total household income after factor taxes (as defined in equation 48). Direct transfers to households (TRG_r) are deducted from these income tax revenues.

$$YGOV_{r,dtx} = \left(\sum_f \sum_a \kappa^f_{r,f,a} PF_{r,f,a} XF_{r,f,a} \right) + \kappa^h_r YH_r - TRG_r \tag{57}$$

In the standard closure rule, the government balance (for a given deficit level) is calibrated using the net direct tax rate (κ^h). In other words, all tax rates are fixed, except κ^h, which is endogenously determined to calibrate the targeted government budget balance. As explained above, this standard closure rule can be changed, and for instance, this is common when recycling carbon tax revenues.

Note that all tax rates can be determined at a very detailed level. These rates can vary by region, by activity and/or commodity, by production factor, and by bilateral trade partner. This allows the model to simulate very specific fiscal policies. For example, carbon taxes can be differentiated by region, by GHG, by emission source, economic activity and agent –i.e., firms in specific activities and/or final consumers. Moreover, production and consumption subsidies can also be simulated either as a reduction

[32]The iceberg trade cost parameter generates a wedge between the volume of imports by source-destination country pairs. The import volume is given by XW^d and the export volume by XW^s. At equilibrium, the following expression holds: $XW^d = \lambda^w \lambda^x XW^s$ and this expression is used to substitute out XW^d. Thus, in the model implementation, the import tax revenue expression also contains the iceberg parameters as the model only carries the variable XW without a superscript and it represents pre-border export supply.

[33]This equation holds for both Armington specifications.

in the production and sales tax rates (τ^p and τ^s, respectively) or directly as negative values that yield pure subsidies.

2.6.3 Carbon tax and fossil fuel subsidy revenue recycling options

Mitigation policies based on price mechanisms, namely fossil fuel subsidy phaseouts and carbon pricing, have the advantage that they generate additional fiscal revenues for the government. The decision on how to spend these additional funds, however, is usually a political decision based on country-specific circumstances. Under these conditions, IMF-ENV provides a menu of recycling options that can be used to tailor the expected government response. In the current setting of the model, there are four main options. The first three assume that the revenue recycling is budget neutral:

- Direct household transfers. TRG_r is endogenized to reduce the direct income tax revenue ($YGOV_{dtx}$) by the same amount as the increase in carbon tax revenues ($YGOV_{ctx}$). Note that with a single representative household, this recycling rule is equivalent to a budget-neutral reduction in direct income tax rates.

- Reduce taxes on wages (or capital income). In this case the factor tax rate (κ^f) for labor (or capital) is endogenized to exactly match the reduction in government revenue from factor taxes ($YGOV_{vtx}$) to the increase in $YGOV_{ctx}$. Alternatively, in the case of fossil fuel removals, the factor tax revenue decrease is endogenized to be same as the increase in production and/or consumption tax revenue ($YGOV_{ptx}$ and/or $YGOV_{itx}$).

- Increase government expenditures. This approach assumes that all carbon tax revenues are allocated in a budget-neutral manner to expand government spending on goods and services.

- Increase government savings. This option is not budget-neutral, as it assumes that the additional carbon tax revenue (or savings from fossil fuel subsidy removals) is entirely used to increase government savings (S^g). This is equivalent to a reduction in the government budget deficit. Importantly, this option also implies that total savings are increased, and as explained in the section below, total investment will increase proportionally.[34]

The model also allows to employ a combination of these recycling instruments. For instance, by assuming that 50% of the carbon tax revenue is recycled towards direct household transfers and 50% is used to reduce labor taxes. In recent work done using IMF-ENV for Article IV and FSAP country support, the predominant recycling rule is to increase direct household transfers. Governments often prefer this approach because they can provide partial compensation to households facing rising fossil fuel and heating costs, which typically encounter significant political opposition.[35]

[34] As the model does not distinguish between public and private investment, this option implies that the government savings are directly translated to an overall investment increase. In reality, the additional government savings could also be used to increase public investment, in which case, it needs to be determined the degree of crowding-out of private investment and the overall change in total investments.

[35] These transfers are usually targeted towards lower-income groups. However, in the current setting of the model, with a single representative household, the distributional implications of this policy feature cannot be assessed.

2.6.4 Investment and savings balance

The recursive-dynamic nature of IMF-ENV implies that on a year-on-year basis, total investment is determined by total savings by region. Equation (58) describes the financing of gross investment, where the variable YFD represents final demand expenditures, in value terms, for the final demand agents, indexed by fd that takes on values of h, gov and inv respectively for households, government and investment.[36] Gross investment is equated to the sum of all savings. This includes domestic savings from households (S^h) and government (S^g), and foreign savings (S^f), where the latter is evaluated using a global price index, PW^{sav}:

$$YFD_{r,inv} = S_r^h + S_r^g + PW^{sav} S_r^f + DeprY_r \tag{58}$$

The depreciation allowance ($DeprY_r$) is calculated as the replacement cost of the estimated depreciation:

$$DeprY_r = \delta_r^f PFD_{r,inv} K_r^s \tag{59}$$

where the parameter δ^f is allowed to differ from the physical rate of depreciation, δ, though in most cases it will be identical. The variable PFD_{inv} is the unit cost of investment and K^s is the non-normalized level of the aggregate capital stock.[37]

Foreign savings (S^f), moreover, represent the net inflow of capital to each region and is inversely related to the current account balance (CAB). The global nature of the model also implies that all foreign savings need to cancel out, such that:

$$\sum_r PW^{sav} S_r^f = 0 \tag{60}$$

Equation 58 reflects the default closure in IMF-ENV where investment is savings driven and therefore this equation determines the nominal level of investment.[38] Equation (58) is defined for all regions, except one region called as the residual region ($rres$) to maintain Walras' Law.[39] In practical terms, this indicates that one of the equations in the model is unnecessary for solving the general equilibrium system. The final equation, known as Walras' equation, is employed to verify that all sources of income are included and that the model is functioning correctly.

Finally, future model development will aim at providing a richer and more flexible interaction between savings and investment (see Section 8.6).

2.7 Macroeconomic balances and closures

For each simulation period, all macroeconomic balances must hold: all commodity (domestic and traded) and factor markets are cleared, meaning that demand must equal supply. In addition, all income flows must balance, and households receive all payments to factors of production, receive government transfers

[36] With the introduction of the R&D module, it will also include r_d for R&D expenditures.

[37] The normalized level of the capital stock is scaled to the initial aggregate remuneration of capital – i.e., its price in the base year is one. The non-normalized level is needed for calculating the depreciation allowance and in the dynamic equation for updating the aggregate capital stock.

[38] If an alternate closure is implemented that fixes investment, then this equation could determine either the household or public savings.

[39] This is a fundamental principle in economics that states that in a general equilibrium model, if all but one market are in equilibrium (where supply equals demand), then the last market must also be in equilibrium.

and pay direct taxes. The government accrues all net tax payments, purchases goods and services (i.e. public consumption) and pays direct transfers to households. Firms' net-of-tax income is equal to factor payments plus purchases of intermediate goods and services (i.e. there are no profits in the model).

As explained above, the production and private consumption decisions are modeled using endogenous behavioral equations, where firms and households optimize their production and consumption decisions. On the other hand, the behavior of other agents (i.e., government) and institutional accounts (i.e. current account and the saving-investment account) is more difficult to endogenize. For these cases, IMF-ENV employs "closure rules", which are exogenous assumptions on how certain markets are cleared. For instance, the decision of governments on how to close their budget and/or change expenditures and revenues depends on several factors that are not easy to anticipate and which can diverge substantially between countries. Similar complexity is involved in the clearance of the current account balance, which implicitly also requires that domestic investment equals overall savings (private, public and foreign). The use of these closure rules has the limitation that important macroeconomic features are exogenously determined. Conversely, it also provides flexibility to model different government behaviors (i.e., recycling rules of carbon tax revenues) and different policy and international decisions (e.g., financing the green transition using domestic or foreign savings).

The following are the default closure rules employed in IMF-ENV:

1. The government budget balance is assumed to follow exogenous projections.[40] The default is that government expenditures are kept fixed to baseline values, either in levels (standard option) or as a share of GDP. This implies that tax revenues adjust so the budget balance is fixed to its projected values. This is done by keeping all tax rates fixed, except for the direct tax rate, which is endogenously determined by the model to keep the predetermined budget balance level (see Section 2.6.2).

2. The current account balance (CAB) is kept fixed to baseline values, either in levels or as a share of GDP. This implicitly assumes that the real exchange rate is adjusting to ensure this is the case.

3. Domestic investment is determined by total savings in each year. Total country-specific investments are the sum of household savings (determined by the ELES demand system), government savings (which are fixed to follow exogenous projections) and foreign savings (determined by the CAB closure rule).

However, the model is not limited to these specific closure rules. For instance, there are many options to change the government balance closure rules. First, the direct (income) tax rate can be swapped with another tax to provide the adjustment in total revenues, but also government expenditures and savings can be adjusted to follow a predetermined budget balance. In the case of policy scenarios that result in increased government revenues (e.g., from carbon taxes and/or removal of fossil fuel subsidies) the model has the flexibility to recycle these additional revenues through several mechanisms: keep overall revenues fixed by reducing another tax rate (sales, direct or labor taxes), increase subsidies (on renewable electricity

[40] The standard approach is to use the budget balance projections from the most recent IMF World Economic Outlook (WEO), and for years beyond the WEO projections we assume that the balance, as a share of GDP, remains the same as the last available year.

or electrical vehicles), increase direct government transfers to household and/or increase government savings.[41]

Accordingly, other CAB closure rules can be implemented. For example, a planned extension for IMF-ENV is to endogenize the CAB (see Section 8.5). On an ad-hoc basis IMF-ENV has been extended to include other regional income streams like international income flows from profits, income for non-tariff measures (NTMs), or intergovernmental transfers like official development aid or other grants (Cai et al., 2024; Black et al., 2022).

Finally, the investment-saving closure rule can also be modified to accommodate different policy scenarios and assumptions regarding savings (see Section 8.6), for example, when green investment projects in developing countries are assumed to be financed by international capital and when savings are changing over time to reflect demographic shifts (i.e., aging, migration). Note that the CAB and the investment-saving closure are intertwined, and hence, modifying one affects the other. For example, in the case when the CAB is endogenously determined, the investment-savings closure will also be endogenously changed, even if public and private savings are fixed. The main limitation of the standard investment-saving closure rule, however, is that households are not forward-looking and they do not optimize their savings and consumption decisions over time. As highlighted in the introduction, this modeling caveat is less critical when modeling policies, which are plagued with high political and technology uncertainty or are gradually implemented over several years like climate and energy policies. Moreover, implementing intertemporal optimization comes at a cost to other key features of the model like capital vintages and model dimensionality, the absence of which could contrarily lead to underestimation of macroeconomic costs. Therefore, if deemed necessary for an application, the preferred option in IMF-ENV is to use the optimal investment path from a model with forward-looking agents to adjust private (or public) savings accordingly in IMF-ENV as this approach allows the model to incorporate the changes in savings behavior without loosing key features or dimensionality.

2.8 Model dynamics

IMF-ENV has a recursive dynamic structure, and the model dynamics are driven by three elements:

- Total labor supply (LS) growth is determined by equation 13. As explained above, labor supply is changing mainly through the shifts in the working age population, but also through the endogenous adjustment to the labor force participation rates through the real wage-labor supply curve (when this feature is active).

- The aggregate capital supply evolves according to the standard stock/flow motion equation:

$$K_t = K_{t-1}(1-\delta) + I_{t-1} \tag{61}$$

  i.e., the capital stock at the beginning of each period (K_t) is equal to the previous period's capital stock, less depreciation (δ), plus investment in the previous period (I_{t-1}).

- The standard version of the model assumes labor augmenting technological change—calibrated to baseline GDP growth pathway and inter-sectoral productivity differences. There is also a standard

[41]The model can also combine all these mechanisms in different proportions. For instance, by allowing that half the additional revenues are transferred back to households and half are used to subsidize renewable electricity generation.

assumption about a 1 percent annual improvement in energy efficiency across all regions and sectors. In policy simulations, technology parameters are typically assumed to be fixed at the calibrated or assumed baseline levels.

2.9 Emissions accounting

The different sources and types of greenhouse gases (GHG) have distinct impacts on the degree of global warming. GHGs are comprised of CO_2 and non-CO_2 gases. Over the last few decades non-CO_2 emissions consist of about a quarter of the total global GHG emissions and therefore, remain an important source of total GHG emissions.[42]

In IMF-ENV, the link between GHG emissions to economic activity is calculated using the GTAP emissions database. The input data for carbon is in millions of metric tons of $\mathrm{CO_2}$ and the data for the other GHGs is available both in physical units (metric tons) as well as in CO_2-equivalent.[43] The standard GTAP database includes carbon emissions ($\mathrm{CO_2}$) and three types of non-CO_2 GHGs: methane (CH_4), nitrous oxide ($\mathrm{N_2O}$) and fluorinated gases (F-gases) (Chepeliev, 2020). There are several drivers of GHG emissions by activities and Table 8 in the Annex provides the mapping of the emission drivers, by greenhouse gas across economic activities.

- **$\mathbf{CO_2}$ (fossil)** from burning fossil fuels for any economic activity and fugitive emissions;
- **$\mathbf{CO_2}$ (non-fossil)** from industrial process emissions, and land-use, land-use change and forestry sector (LULUCF);
- **$\mathbf{CH_4}$** from rice cultivation, livestock production (enteric fermentation and manure management), fugitive methane emissions from coal mining, crude oil extraction, natural gas and services (landfills and water sewage);
- **$\mathbf{N_2O}$** from crops (nitrogenous fertilizers), livestock (manure management), chemicals (non-combustion industrial processes) and services (landfills);
- **Fluorinated gases ($\mathbf{SF_6}$, PFCs and HFCs)** from chemicals industry (foams, adipic acid, solvents), aluminum, magnesium and semiconductor production

In the IMF-ENV model, emissions gradually become relatively decoupled from underlying economic activity due to the autonomous energy efficiency parameter ($aeei$). This suggests that over time, advancements in energy-saving technologies will enable emissions to increase at a slower rate than economic activity. For calibrating non-CO_2 emission trajectories, sectors that generate non-CO_2 emissions have emission prices set to a small value based on a chosen carbon price. In contrast, in sectors that do not produce any non-CO_2 emissions, the emission rate is maintained at zero.

Emissions (Emi) in region r by GHG (em) are a combination of emissions from different sources (B) in sector a, emission intensity (ρ^{Emi}) and an emission shifter (χ^{Emi}), such that:

[42] Source: Greenhouse gas emissions - Our World in Data

[43] The conversion from tons to CO_2-equivalent uses the standard global warming potential (GWP) coefficients defined by the Intergovernmental Panel on Climate Change (IPCC). The higher the GWP the larger is the warming effect of the GHG compared to CO_2 over a given time period. Commonly GWPs are calculated for 100 years. IPCC's AR6 report estimates the 100-year GWP of CH_4 (fossil and non-fossil) and $\mathrm{N_2O}$ to be about 29.8, 27 and 273.

$$Emi_{r,em,\beta,a} = \chi_{em}^{Emi} \rho_{r,em,\beta,aa}^{Emi} B_{r,\beta,a} \tag{62}$$

where the set aa includes all activities a plus final demand by households, government and investment. B represents the matrix of emission sources (indexed by β). This matrix is shown in Table 8 in the Annex, and it links emission sources to GHGs and the economic activities in the model. Emission sources come from direct consumption of a commodity, factor-based emissions, and industrial processes or fugitive emissions. Emissions from consumption include emissions that are generated by directly burning fossil fuels (*coalcomb*, *coilcomb*, *roilcomb* and *gascomb*). Factor-based emissions refer to emissions that are linked to land (*land*) or capital (*capital*) endowments (e.g., the capital endowment of herds in the livestock sector or land endowments in the crops sectors associated with burning crop residues). Lastly, industrial processes and fugitive emissions cover process emissions ($chemUse$ and act), fugitive emissions in extraction activities ($fugitive$) and waste related emissions ($wasteld$).[44]

$$EmiTot_{r,em} = \sum_{i} \sum_{aa} Emi_{r,em,\beta,aa} + EmiOth_{r,em} \tag{63}$$

$$EmiGbl_{em} = \sum_{r} EmiTot_{r,em} \tag{64}$$

The aggregate level of emissions $EmiTot$ for region r and GHG (em) is then defined in equation (63) where $EmiOth$ represents the LULUCF emissions which could either be calculated based on marginal abatement cost curves in the model when mitigation policies are active (see section 6.1.6) or could follow an exogenously defined pathway. Lastly, equation (64) defines the global level of emissions that is a sum of regional emissions from all drivers.

[44] For example, CO_2 process emissions from cement production or methane from waste landfills.

3 Data and model calibration

This section describes the main data sources of the model and how the model dimensions are defined. We then explain the baseline calibration process.

3.1 Data sources and model dimensions

IMF-ENV is built primarily on a database of multi-regional input-output tables, combined with national accounts and bilateral trade flows. The primary input for the model is the GTAP Power database, and the model is regularly updated to incorporate new versions of the database. IMF-ENV currently uses version 11 of the GTAP Power data with 2017 as the base year (Aguiar et al., 2022; Chepeliev, 2023). This database includes country-specific input-output tables for 143 countries, 18 regions, 65 commodities, and 76 economic activities. It differentiates between four fossil fuel sectors, 12 electricity generation technologies, and an electricity transmission and distribution activity. Unlike the standard GTAP database, which has a single electricity sector, GTAP Power separates activities into coal, gas (base and peak load), oil (base and peak load), nuclear, hydro, wind, solar, other power technologies, and electricity transmission and distribution. As explained in Section 2.2, except for the electricity sector, each economic activity maps one-to-one to commodities (see Tables 4-5) and therefore, there are more activities than commodities in the database. The GTAP Power database also represents global trade flows in 2017 and includes all main greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases – hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6).(Chepeliev, 2020) Regional and fuel-based GHG emission coefficients are based on the base year data from the GTAP Power database.

Presently, the most commonly used version of IMF-ENV is calibrated for all G20 countries along with 5 regional groups to represent the remaining countries, resulting in a total of 25 regions. It differentiates between 36 economic activities and 28 commodities. The mapping of the GTAP regions to the IMF-ENV for the G20 version is shown in Table 6 in the Annex. Nonetheless, the choice of the regional and sectoral mapping that is needed varies across projects. The model aggregation can be flexibly changed to accommodate different regional and sectoral mappings, and most recently, two new regional aggregations have been created for Sub-Saharan African countries (Cai et al., 2024) and Middle Eastern and Central Asian countries.

IMF-ENV is coded and solved in the General Algebraic Modeling System (GAMS) software, which is specialized in solving high-dimensional non-linear optimization problems. Several CGE models are coded in GAMS as the software environment allows variables and equations to be specified using set-based indices that are defined at run-time when the data is read in.

3.2 Calibration

The calibration process involves two steps. The first step is the static calibration, where the model is adjusted to match the base year data from the GTAP Power database. The second step is dynamic calibration, which creates a baseline scenario (without new policy changes or business-as-usual) and projects the model dynamics several years into the future. Currently, the model is calibrated until 2040.

3.2.1 Static calibration

During the process of static calibration, primary model elasticities and technological parameters are defined using empirical studies and data sources. The key elasticities used in the current model version are documented in Tables 2 and 3 in the Annex. The GTAP database provides the income elasticities of household demand and Armington trade elasticities.

However, these parameters alone are not adequate for the model to accurately replicate the base year data. Some model parameters need to be calculated to align with the base year data, contingent on the chosen modeling assumptions for behavioral and structural technical relationships. The main parameters to calibrate are the share parameters of CES functions (α's), while scale parameters (λ's) are usually not calibrated and only used for policy experiments. The calibration procedure for a generic CES function is explained in Section A.2 in the Annex.

3.2.2 Dynamic calibration

The dynamics of the baseline scenario are determined by macroeconomic and sectoral drivers in the model. The dynamic calibration component involves calibrating model parameters to match the progression of these drivers between 2017 and 2040. Within the CGE literature, different approaches are used by modeling teams to calibrate model dynamics (Dellink et al., 2020), and in several aspects our choices are aligned with the literature.

The calibration of baseline dynamics requires historical data and projections for different model outputs. The historical time series and medium-term macroeconomic projections for real GDP, current account balance, government budget balance, and investment shares are sourced from the IMF's World Economic Outlook (WEO), while long-term projections use the shared socioeconomic pathways (SSPs), specifically the SSP-2 scenario (Dellink et al., 2017), and are calibrated until 2040. Historical energy and emissions data is taken from the IMF Climate Indicators database (IMF, 2022) and electricity sector data is based on the International Renewable Energy Agency (IRENA). Medium- and long-term projections related to the energy sector are taken from several sources that are summarized below. Importantly, while we present the commonly used data sources for projections, the model baseline can be flexibly calibrated to other projections. The dynamics of the model are predominantly influenced by assumptions about factor productivity, population growth, saving rates, and energy efficiency. The following section explains how these drivers are determined and how structural shifts are modeled in the baseline.

- **Real GDP projections:** The external GDP growth rate and population projections are used to target the growth rates of real GDP per capita by endogenizing economy-wide labor productivity. In the policy simulations, real GDP is endogenous and overall labor productivity is kept fixed to the calibrated levels.

- **Labor supply:** Projections on working age population growth by countries, which are also consistent with the SSP2 scenario. In the baseline scenario labor supply growth is exogenously determined using the growth rate of the working age population. Country-specific labor supply growth projections can also be used if available and/or combined with separate assumption on changes in the labor force participation rates (LFPR) and long-term unemployment. In the policy scenarios, labor supply is endogenously determined by the real wage-labor supply curve (see Section 2.3.1).

- **Government budget balance:** External projections are used to target the government balance as a share of real GDP in the baseline by endogenizing the direct tax rate. In the policy scenarios, unless the policy shock specifically incorporates changes in government savings, the budget balance is assumed to remain fixed at baseline levels and as in the baseline, this is done by endogenizing the direct tax rate for each country.

- **Current account balance (CAB):** Projections are used to exogenously determine the CAB as a share of GDP in the baseline. This is done by changing the inflow of foreign savings and making sure that global net savings are zero (i.e., that regions with positive foreign savings are exactly matched by negative foreign savings in the remaining regions). In the policy scenarios the CAB remains fixed as a share of GDP and there is a residual region for which foreign savings adjusts to balance global savings.

- **Electricity generation by technologies:** In the baseline scenario, IMF-ENV uses the Leontief specification, which targets the shares of production for various electricity technologies, to calibrate the generation shares of each electricity technology. In the policy simulations, dynamics of the power sector can be modeled in two ways. Firstly, the model specification can be set to a CES production function for aggregating electricity supply across sources in equation 9. This allows endogenous adjustments in generation levels across various technologies, influenced by costs, prices, as well as predefined exogenous constraints such as investment and utilization assumptions. Secondly, depending on the availability of data by policy and research objectives, policy simulations may use external projections from bottom-up energy system models. These models capture detailed country-specific constraints within the energy systems and incorporate these projections into IMF-ENV by adjusting exogenous share parameters using the Leontief specification as indicated in equation 9. In the past, commonly used energy models include PRIMES[45], POLES[46], NGFS (NGFS, 2024), EPM[47], or authorities' projections. Importantly, electricity prices and electricity demand are endogenously determined in both CES and Leontief specifications. Furthermore, each electricity technology has its own cost structure, resulting in different production prices. These production prices affect the overall price of the electricity commodity by region depending on the mix of supply sources.

- **GHG emissions:** In the baseline scenario external projections on overall emissions are targeted by calibrating the emission-intensity parameters, which are differentiated by region and type of GHG. These external emission projections are taken from national sources, or from global projections generated by the NGFS scenarios (NGFS, 2024).[48] The exception are LULUCF emissions, which are fixed to base year levels in the absence of projections. In the policy simulations, all GHG emissions are endogenously determined (expect when a policy instrument is designed to target a certain reduction in emissions like an emissions trading scheme).

- **Energy efficiency:** We assume a 1% annual growth rate in energy efficiency across all fuel types used in intermediate and final consumption.

[45] https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-primes.
[46] https://joint-research-centre.ec.europa.eu/poles_en.
[47] https://www.worldbank.org/en/programs/power-system-decarbonization-pathways/methodology.
[48] When data is available these overall emissions are separately projected for CO_2, non-CO_2, and LULUCF emissions.

- **Economic structure:** When recent input-output (IO) tables are available for the country of interest, we can target the production values of different economic activities to replicate the new economic structure from the IO table. This is done by endogenizing sector-specific TFP values in the baseline scenario to obtain the desired gross production shares by broad economic activities. In the policy scenarios these sectoral TFP values are kept fixed at baseline levels and sectoral gross production is endogenous.

- **Trade patterns:** When conducting trade-related analysis, the bilateral trade patterns of interest can be updated using the most recent trade data. The most commonly used data source is the UN COMTRADE database. There are different methods to update bilateral trade flows. For instance, for relatively small sectoral trade adjustments, the iceberg trade costs can be endogenized to target the desired trade values in the baseline scenario.

In addition to the above drivers, the model also has the option to calibrate other drivers depending on data availability. These include:

- Consumer preference convergence in developing countries toward OECD averages

- Autonomous efficiency gains for capital, land and specific natural resources

- Autonomous efficiency gains of fertilizers in crops sectors and of the food bundle in livestock rearing

- Supply of land and natural resources (except for fossil fuels sectors)

- Aggregate average and sectoral labor productivity growth, determined by calibration of technical progress coefficients embodied in labor

- Energy demands (projected by using elasticities of demands to GDP), for all kind of fuels demands excepted crude oil, determined by calibration of the Autonomous Energy Efficiency Improvements (named AEEIs) in energy use, by sector and type of fuel

- International prices of fossil fuels, determined by calibration of the potential supply of fossil fuels resources

- Investment to GDP ratios, determined by calibration of the household marginal propensity to save.

4 Model outputs and visualizations

For each simulation using IMF-ENV, the output files include numerous variables for all regions and sectors. Presenting key simulation results clearly is crucial to understanding the main drivers and impacts. To streamline this process, the team has created a series of standardized panel charts and the IMF-ENV dashboard. The IMF-ENV dashboard (see Box 3) is available to IMF staff. It functions as a repository for model results and includes interactive visualization capabilities. Users can customize charts according to various specifications of regions, years, activities, and commodities.

A set of six standardized chart panels can be generated by country. The baseline drivers panel (Figure 8) provides an overview of the main drivers of the baseline dynamics, which include projections on overall GHG emissions, real GDP, labor supply, value-added by sector, government finances and the current account balance. The remaining panels show key results from the different policy scenarios. The emissions panel shows changes to GHG emissions by source, gas and other emission-related results (Figure 9). The energy and prices panel shows the changes in electricity generation, energy use, energy-related indicators, together with producer and consumer price changes (Figure 10). The macroeconomic effects on real GDP, its demand components (consumption, investment and net exports) and supply components (by changes in value-added by broad activity groups), and sectoral changes in employment, value-added and gross investments are included in the Real Sector panel (Figure 11).[49] The impacts on the external sector includes changes in sectoral exports and imports, changes in international commodity prices, market shares of key sectors, terms of trade and the real effective exchange rate (Figure 12). Lastly, the fiscal sector panel (Figure 13) shows impacts on government finances and revenue sources, including carbon taxes and their associated revenue.

Depending on the focus of the analytical work, specific outputs may hold greater relevance than others. Consequently, additional model outputs are made available to teams on a project-by-project basis. For example, when bilateral support is provided using IMF-ENV, country teams receive highly detailed results. An example of these panels is shown in Figures 8 to 13. These panel charts depict three illustrative decarbonization scenarios for a sample country, using a combination of supply (production subsidies to renewable power) and demand side (carbon pricing) policies.

[49] The model can also estimate different welfare indicators, such as equivalent variation.

Box 3: An overview of the IMF-ENV Dashboard

Purpose of the dashboard. The IMF-ENV dashboard provides interactive features to display macroeconomic and sectoral charts based on IMF-ENV model results.
Technological background. The dashboard is built using an R-shiny app. Unlike typical R-programming, R-shiny utilizes reactive programming techniques, enabling the app to dynamically adjust visual outputs in response to user inputs. With this technology, the IMF-ENV dashboard offers interactive features, such as data filters, which users can customize to tailor the displayed results.
Accessing the dashboard. The dashboard is available to IMF staff only. The dashboard webpage includes a read me section that explains how to operate it.

How to use the dashboard?

- Uploading Data: The dashboard requires model results created in the form of GDX files, generated by GAMS in which the IMF-ENV model is coded. Users must upload at least two files via the "Input data" tab at the top of the interface: one file for the baseline scenario and the rest of the files for the policy scenarios. After uploading the files, users can rename scenario labels and create customized regional groups within the same tab.

- Generating Charts: Once the setup is complete, the app generates visualized charts available under two main tabs:

  - "Summary charts" Tab: Displays a predefined set of charts for user selected country and scenario.
  - "Detailed charts" Tab: Offers more granular details for each economic indicator. For instance, users can explore real GDP impacts for selected countries, scenarios and years.

  The displayed charts dynamically update in response to user inputs. After adjusting inputs, users must click the "Update" button for the changes to take effect.

- Exporting Data and Charts: The dashboard includes features to download the underlying data and charts:

  - To download individual charts, users can click "Save as png" and "Save data file" at the bottom of the respective chart.
  - For convenience, the "Export" tab enables users to download all underlying data or charts simultaneously.

- Saving and Restoring Configurations: Users can save their current configuration such as input filters, customized regional groups, and scenario names using the "Export" tab. To restore these configurations, users can upload the saved configuration file via the "Input Data" tab.
  Important Note: Users must first upload the required GDX files before restoring a saved configuration. Additionally, configurations incompatible with the uploaded GDX files (e.g., customized regional groups referencing countries not included in the GDX files) will not function correctly.

The IMF-ENV dashboard and this box have been prepared by Jaden Kim.

Figure 8: Baseline drivers

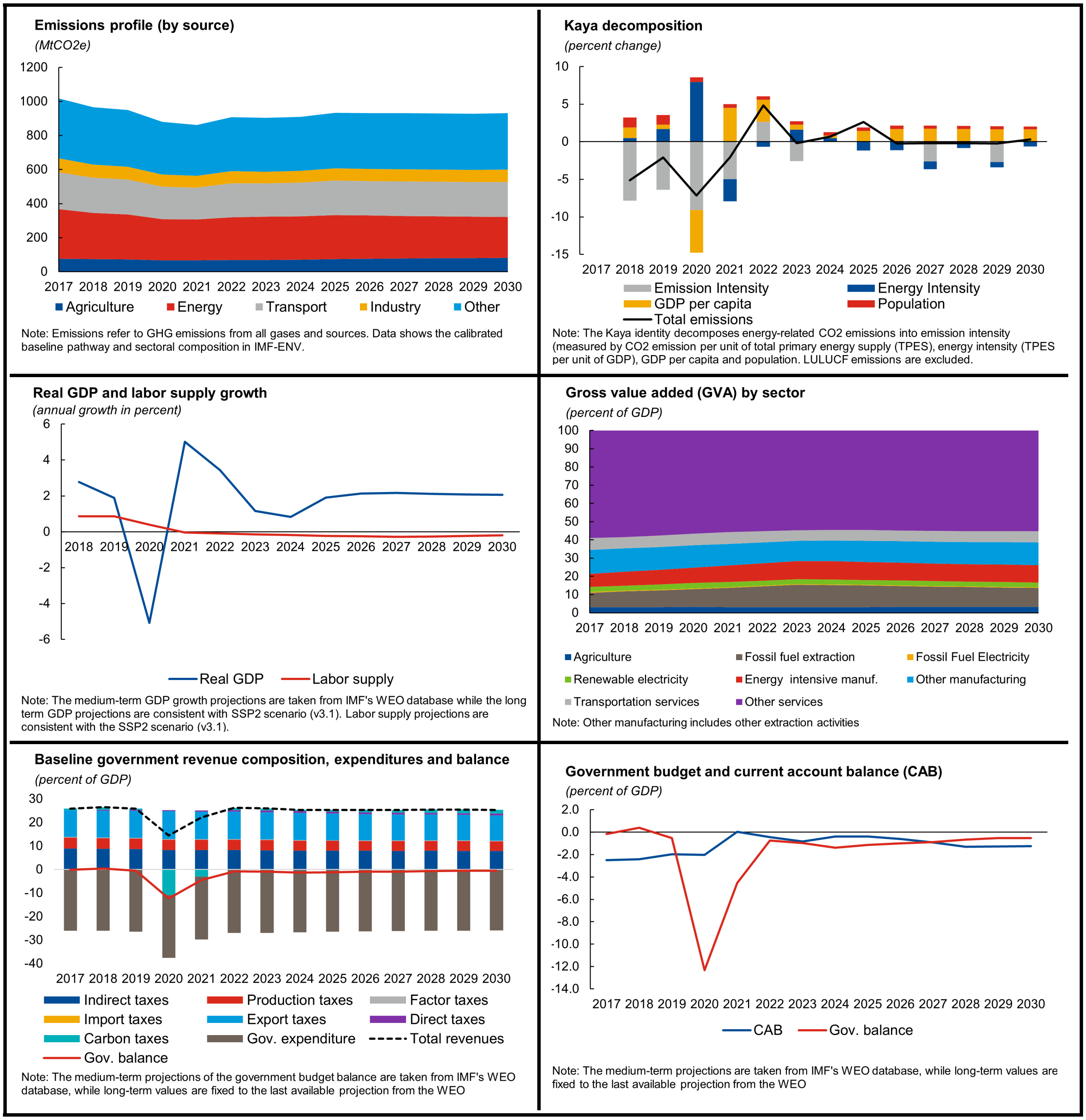


Figure 9: Policy scenario results: Emissions

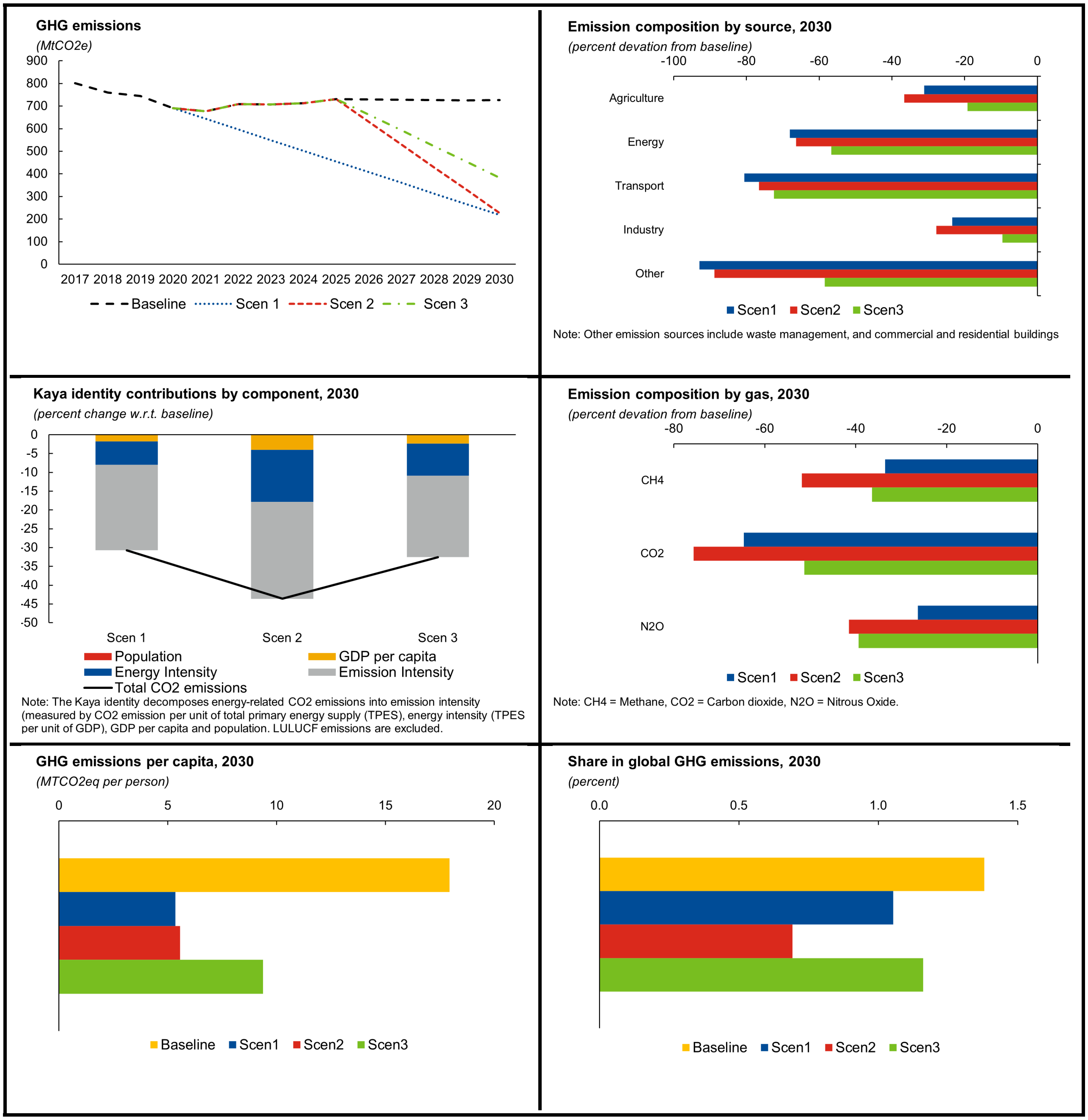


Figure 10: Policy scenario results: Energy and prices

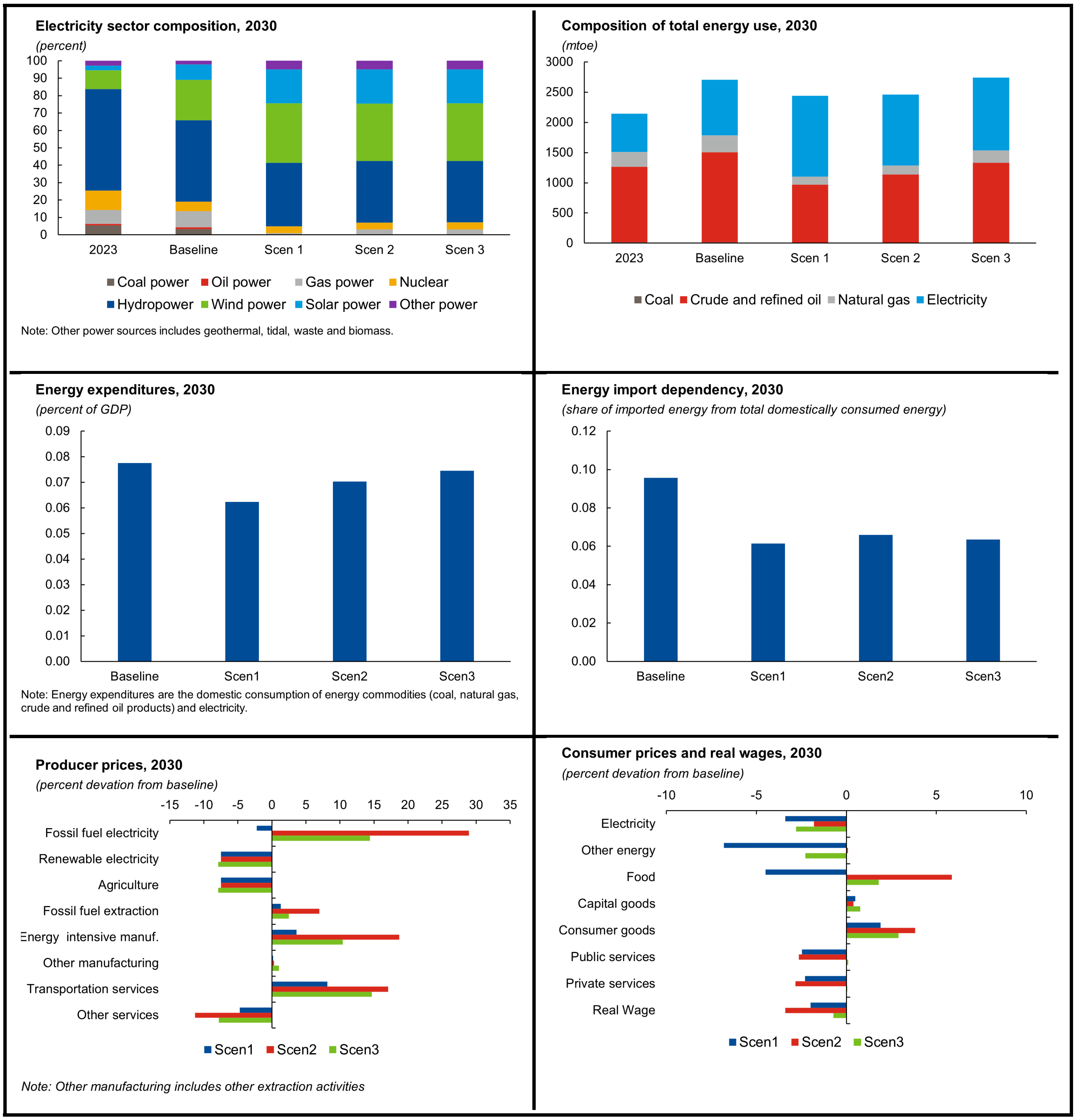


Figure 11: Policy scenario results: Real sector

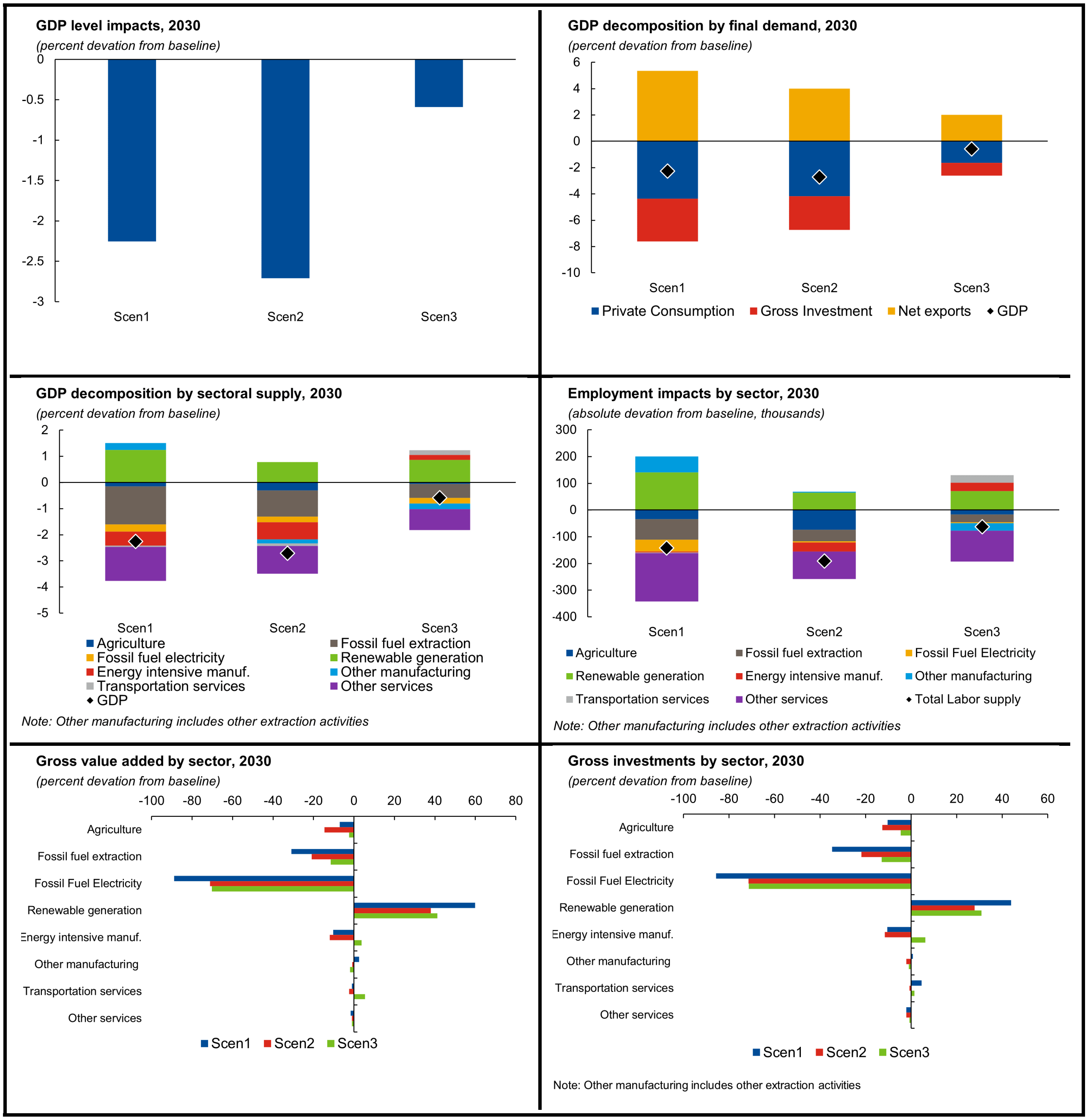


Figure 12: Policy scenario results: External sector

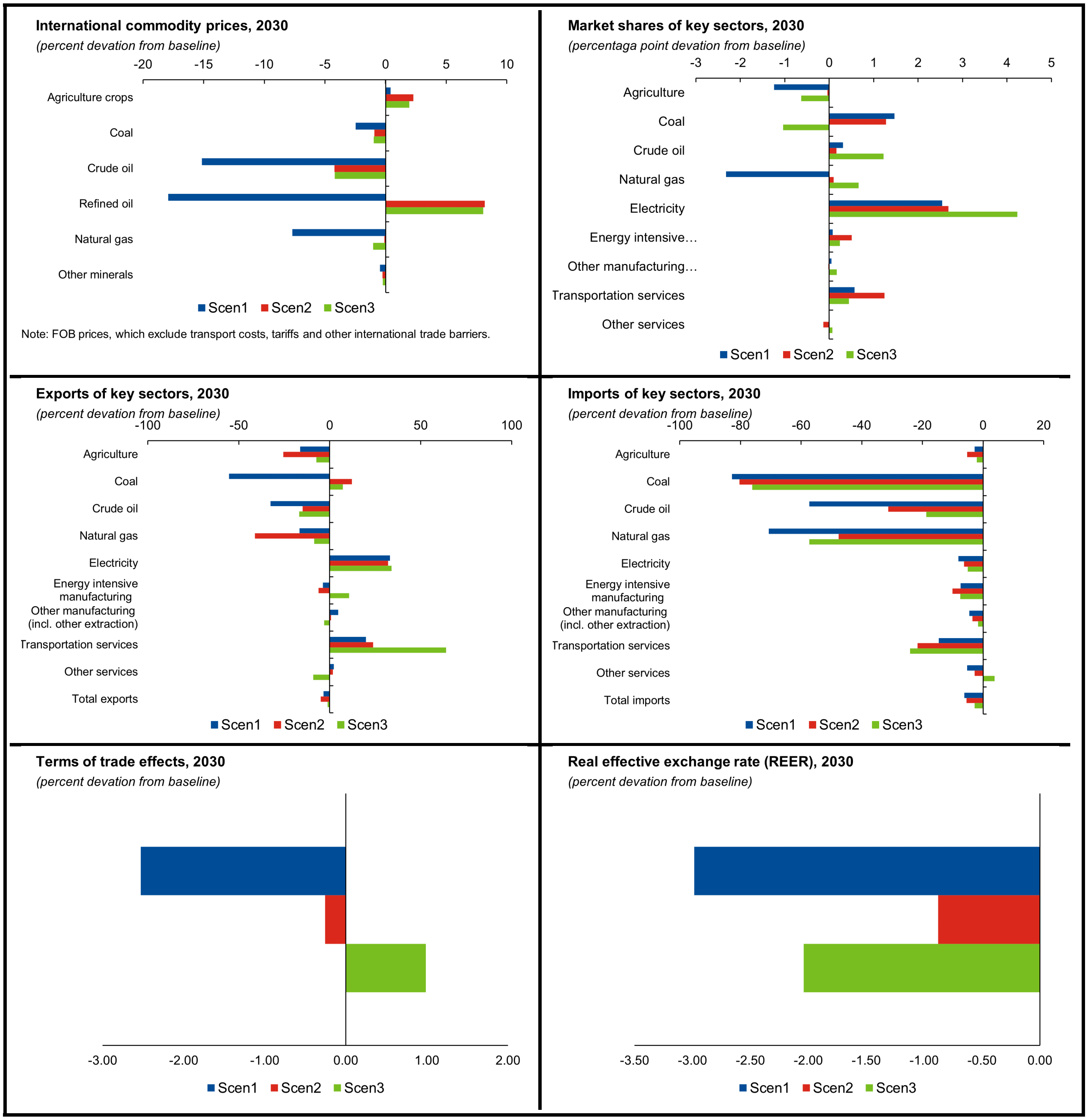
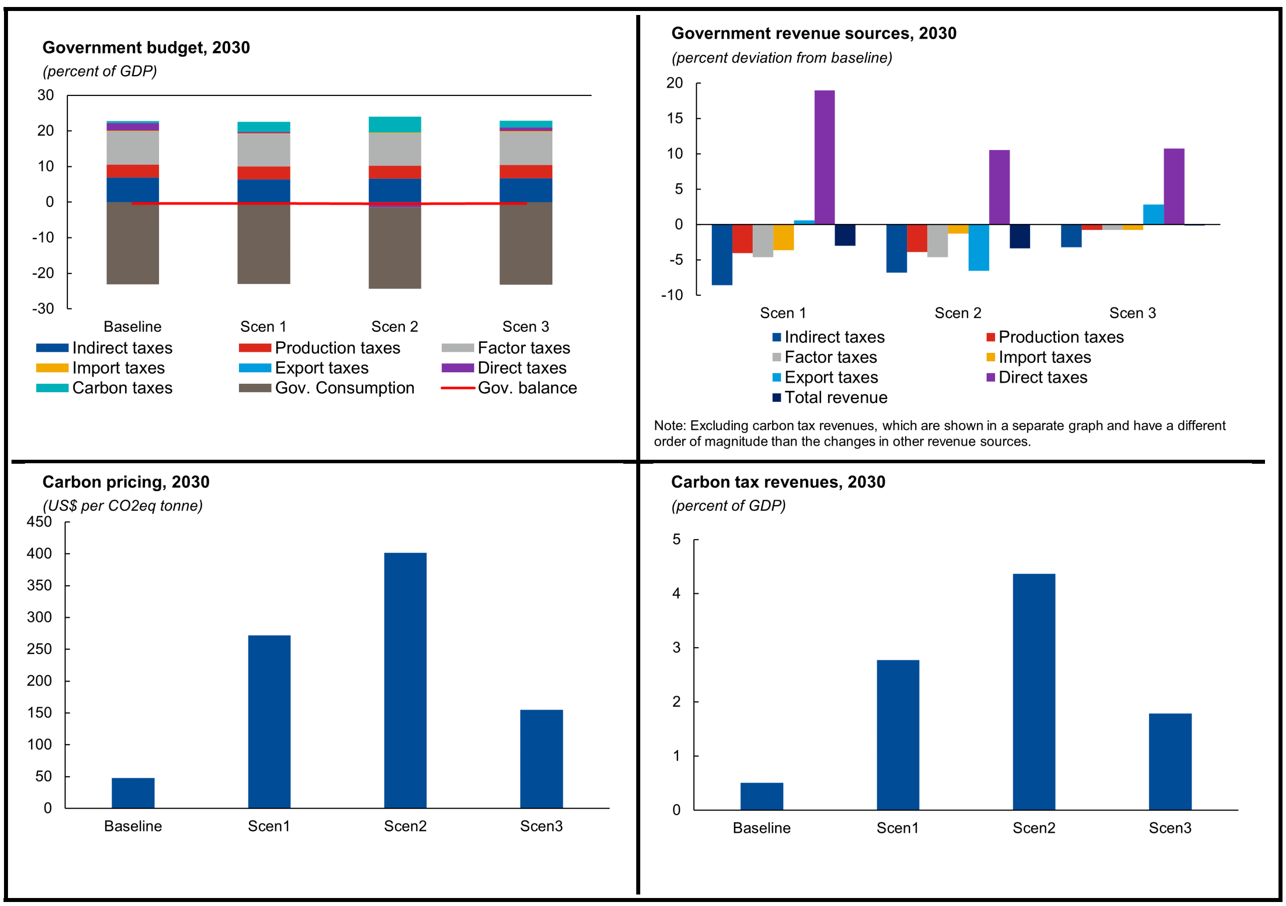


Figure 13: Policy scenario results: Fiscal sector



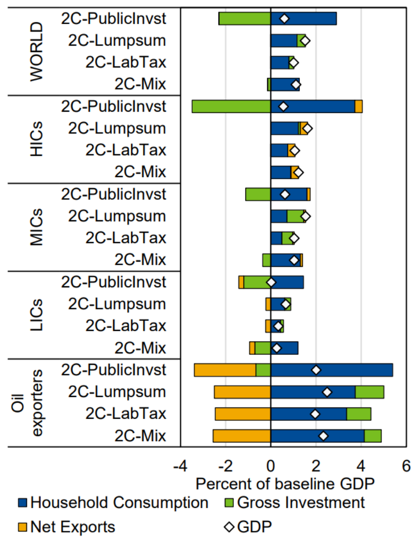
5 Sensitivity analysis

Performing sensitivity analysis on results from economic models concerning parametric and structural assumptions is a standard practice. Parametric uncertainty stems from assumptions about (1) behavioral parameters like substitution elasticities between primary production factors, energy commodities and trade elasticities, (2) autonomous efficiency assumptions for capital, land and natural resource, (3) autonomous energy efficiency gains, or (4) parametrization of costs for new and emerging technologies. Evaluating the sensitivity of key elasticity values and energy efficiency assumptions are the simplest tests that can be conducted in IMF-ENV, and these values are regularly compared with existing literature and other CGE applications.

On the other hand, structural uncertainty comes from various model features such as static versus dynamic approaches, differences in regional and sectoral aggregation, trade specification, inclusion of non-carbon technology and closure rule assumptions. For instance, there are several studies in the literature that estimate the impact of structural assumptions on measures of abatement costs of emissions (see Antimiani et al., 2015; Fischer and Morgenstern, 2006; Kuik et al., 2009; Lanz and Rausch, 2011; Thube and Peterson, 2022), impact of trade elasticities on free trade agreement evaluations (Bekkers and Rojas-Romagosa, 2019), influence of behavioral parameters on the carbon leakage rates (Carbone, 2013; Burniaux and Oliveira Martins, 2012) and the scale of rebound effects (Turner, 2009).

In addition to parametric and structural assumptions, results are also sensitive to the way policies are designed. For example, in IMF-ENV the impact of carbon taxes on GDP is sensitive to the assumption on how carbon revenues are recycled by governments (see Black et al. (2022) for GDP impacts on country groups by income level and Fournier et al. (2024) for results in Canada). Among the recycling options presented in Figure 14, the global GDP costs are the least when revenues are used to fund productive investments, while costs are largest when revenues are recycled as lump sum transfers to households. The same pattern is also seen across country groups.

Figure 14: GDP costs under different revenue recycling rules



Source: Black et al. (2022). Notes: HIC = high-income countries; LIC = low-income countries; MIC = middle-income countries. All scenarios limit emissions to reach the target of a global temperature increase below 2°C, where carbon revenues are recycled as productive investments (*2C-PublicInvst*), lump sum transfers to households (*2C-Lumpsum*), or as labor tax reductions (*2C-LabTax*). In *2C-Mix* all countries allocate 30 percent of carbon tax revenues toward lump sum transfers to households. The remaining 70 percent is used to reduce labor taxes in HICs, while MICs and LICs use it to increase productive investments.

6 Designing Policies in IMF-ENV

A comprehensive range of policies can be evaluated using IMF-ENV. This section outlines the policies that have been implemented in recent applications of the model. Generally, within the neo-classical framework of the model, the primary transmission mechanism for policy shocks operates through changes in relative prices and the substitution possibilities within consumption, production, and trade. The extent of behavioral responses to these changes is determined by the relevant elasticities. For instance, implementing a carbon tax will raise the price of emission-intensive inputs and final goods relative to those with low or no emissions. Consequently, the ultimate behavioral response depends on the production, consumption, and trade elasticities, as well as the substitution possibilities associated with the affected inputs and goods.

6.1 Climate and energy policies

Greenhouse gas (GHG) emissions are produced by a variety of human activities across different economic sectors. Globally, approximately three-quarters of these emissions originate from energy use in industry, transport, and buildings, while the remaining emissions come from agriculture, forestry, and land-use, as well as process emissions from industry and waste. Additionally, there are significant differences in the sources of emissions between different economies. As a result, domestic mitigation policy instruments, the sectors they cover, and the gases they regulate vary across economies. The IMF-ENV model captures the major sources of emissions, for all major GHGs (i.e., CO_2, CH_4 and N_2O) by economic activity. Thus, the model has the flexibility to model several mitigation policy instruments.

6.1.1 Carbon and fossil fuel pricing

- **Carbon pricing**
  These policies can be structured in two ways: as direct price-based measures, such as carbon taxation, or as quantity-based measures that indirectly impose carbon pricing, like an emission trading scheme (ETS). In the first case, producers are taxed for each ton of $CO_2 - eq$ emissions from fossil fuel combustion. The carbon content varies among coal, oil and gas, resulting in differing tax costs for one unit of production depending on fuel type. In the second case, there is a cap on the total $CO_2 - eq$ emissions from fossil fuel generation, which results in an implicit carbon price on emissions. Since IMF-ENV has a detailed specification of emissions by source, GHG and economic activity (see Section 2.9), carbon pricing can be applied for different combinations of sectors, regions and GHG gases. Examples of carbon pricing policies include a carbon tax on $CO_2 - eq$ emissions on transportation services, methane emissions in agricultural activities, or broadly as an overall carbon tax for all GHGs in all economic activities.

- **Fossil fuel subsidy reforms**
  In many countries, in particular those that are fossil fuel producers, it is common to subsidize the consumption of fossil fuels, either for use in production or consumption. This can be viewed as a negative carbon tax that incentivizes the use of fossil fuels. Therefore, removing these subsidies can yield substantial reductions in energy demand and emissions. To model fossil fuel subsidy reforms, the first step is to update the values of these subsidy rates in the baseline.[50] The policy scenario is then simply to remove these subsidies and to determine how the associated savings are employed by the government, which usually implies assumptions on different revenue recycling options (see Section 2.6.3).

6.1.2 Power sector

Decarbonization policies in the power sector can be achieved by reducing the emission intensity of the sector either by providing incentives to switch to renewable-based generation sources or to tax emission-intensive fossil generation sources.

- **Regulation on clean energy standards**
  The regulation policy could be designed such that a minimum share of electricity needs to be generated from renewable sources. It is modeled as an additional constraint to the production optimization process described in Section 2.1, which imposes a minimum share of non-fossil power generation ϕ in total electricity generation by imposing a shadow price of fossil power generation sources:

$$\phi X_{pow} < F\left[X_{solar} + X_{wind} + X_{hydro} + X_{nuclear} + X_{other}\right] \tag{65}$$

[50] This is usually a challenging task, as the exact values of these subsidies are not publicly available. This is can be the case when the subsidies are part of complicated energy and electricity pricing schemes, and/or applied by State-owned firms that do not publicly report their finances nor the amount subsidized.

- **Feed-in tariff policy**

  Under this policy, the producers of renewable power, usually wind and solar PV, receive a subsidy per unit of electricity, such that they sell electricity above their unit cost of production (PP). The representative electricity provider for eligible sectors pays only:

$$PP_a \times (1 - subs_a) \tag{66}$$

  The subsidy rate ($subs$) could be different by generation technologies and could vary over time.

- **Feebates**

  The system of fees and rebates in the power sector is used to expand renewable generation and reduce fossil fuel electricity generation. The key feature is that the system is self-financing: the rebate expenses on renewable generation are exactly compensated by the revenue fees on fossil fuel generation. This assures that the policy is revenue neutral for the government. Technically, it implies that electricity generation which emits more than a given target of CO_2 emissions per kWh (emi^{ely}) will pay a fee ($\tilde{p} > 0$), and those that emit less receive a rebate ($\tilde{p} < 0$). The system can be summed up as follows:

$$PP_a + \tilde{p}\left(\frac{emi_a^{ely}}{X_a^{ely}} - \frac{\sum_a emi_a^{ely}}{\sum_a X_a^{ely}}\right) \tag{67}$$

  where X_a^{ely} is the output by activity generation a and PP_a is its producer price, which is adjusted by $\tilde{p}$. The value of $\tilde{p}$ is endogenously determined in the model to reach the total emission target: $\frac{\sum_a emi_a^{ely}}{\sum_a X_a^{ely}}$. The impact of $\tilde{p}$ is determined by the difference between this target and the individual emissions from each generation source: $\frac{emi_a^{ely}}{X_a^{ely}}$.

  In the policy simulations, $\tilde{p}$ is year and country-specific, depending on the exact specification of the feebate policy.

6.1.3 Energy-intensive sectors

Regulations in the energy-intensive sectors usually imply emission caps or activity reduction paths for these sectors. The regulations are implemented in the model as an additional constraint on θ, defined as the CO_2 intensity or total CO_2 emissions to gross output, for each sector a. The new constraint is given by:

$$emi_{CO_{2,a}}^{proc} + \sum_f x_a(f).c_a(f) = CO_{2,a} < \theta_a \sum_v X_{a,v} \tag{68}$$

where total CO_2 emissions from sector a are the sum of process CO_2 emissions ($emi_{CO_{2,a}}^{proc}$) and CO_2 emissions from fossil fuel combustion, where $c(f)$ is a fixed coefficient of emission associated to the use by fossil fuel f.

6.1.4 Green Industrial Policies

The green transition is increasingly being driven by green industrial policies that are designed to incentivize the development of certain activities by introducing a subsidy to production or investments in these sectors.

These policies are designed by implementing an output subsidy for specific economic activities by altering the tax rate in equation 5. Differently, a subsidy on new investments is modeled by subsidizing new capital vintages in the targeted sectors in equation 21.

6.1.5 Energy efficiency regulations

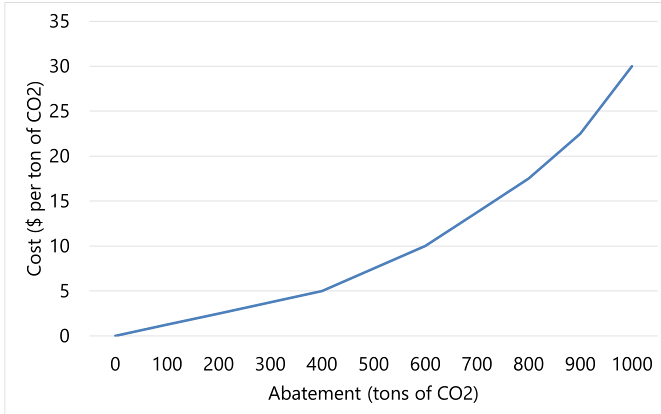
Some mitigation policies aim at reducing the energy-use of different activities. These can be related to emission standards for internal-combustion (IC) vehicles, reduced energy use for heating commercial and residential buildings, or the replacement of gas boilers with more energy-efficient heat pumps, among others. To implement these policies in IMF-ENV detailed information is required on the associated energy savings and the costs of implementing the policies. The precise modeling depends on the exact policy characteristics. For instance, the increase in the share of heat pumps for domestic heating is implemented as a shift in the share parameters of the CES function (the α values in Box 1) from household demand (shifting from gas to electricity), complemented by a reduction in the overall energy demand by households. The associated costs, on the other hand, are modeled using an investment-loss function, which is explained below (see equation 69).

6.1.6 Agriculture, Forestry and LULUCF

Land, capital, fossil fuel use, and fertilizers drive GHG emissions in agriculture (Table 8). These drivers are tied to economic activity, and targeting them with specific policies provides the endogenous impact within the model's general equilibrium framework. On the contrary, the land-use change and forestry emissions changes are estimated using predefined marginal abatement cost (MAC) curves, as IMF-ENV does not model changes in land-use and forest cover. This is because the current version of IMF-ENV has only one type of land and therefore we do not model land transformation for different activities. Figure 15 presents an illustrative Marginal Abatement Cost (MAC) curve that helps to understand the emission reductions attainable at a specific carbon price level. Regional MAC curves for the LULUCF sector are calibrated using estimates from the MAGNET (Modular Applied GeNeral Equilibrium Tool) which has a detailed land module that models land use change (Woltjer and Kuiper, 2014).[51] Using an explicit MAC curve for LULUCF emissions allows the model to consider emission reductions from the LULUCF sector for a given carbon price. However, it does not fully account for the general equilibrium impacts of these emission changes. For example, when land-use change involves reforesting agricultural land, the emission impacts are accounted for with this approach, but the economic consequences of reduced agricultural output are not captured.

[51] The MAGNET consortium, includes Wageningen University and Research Centre (lead), the European Commission's Joint Research Centre (JRC) and the Thünen-Institute (TI).

Figure 15: Marginal abatement cost curve



Notes: This is an illustrative MAC and will vary across regions based on the abatement options. In IMF-ENV explicit MAC curve is only provided for calculating CO_2 mitigation from land-use change and forestry sector while the rest of the activities reduce emissions based on structural and policy assumptions.

6.1.7 Emerging green technologies

Ideally, new technologies and their related economic activities (e.g. electrical vehicle production, and carbon capture technologies) can be included in the model when included in national accounts and input-output tables. However, these tables are not frequently updated and hence, there is an inevitable delay in how new technologies and activities are recorded.[52]

Nevertheless, the model can be used to provide broad estimations of the effects of emerging green technologies, even when these are not explicitly incorporated into the underlying input-output structure of the model. These estimations, however, usually require detailed information on the expected impacts measures via emission reductions or changes in energy demand and the costs of expanding the use of these technologies. We describe below how some of these new green technologies have been modeled in recent IMF-ENV applications.

- **Electrical vehicles (EVs)**
  The main environmental effect of the increased penetration of EVs is to switch the demand from diesel and gasoline to electricity. In so far as electricity is mainly generated using renewable sources, this will reduce overall GHG emissions. This switch in energy demand is modeled as a change in the share parameters of the CES function (the α values in Box 1) of household demand. Using economy-wide estimations of EV penetration data and projections, these share parameters are calibrated to reflect the switch in private demand from non-electricity energy to electricity.[53] This yields an overall increase in electricity demand and a proportional reduction in fossil fuel demand. Associated costs from increased EV penetration are the costs of setting the network of charging stations, which can

[52]The GTAP database, which is the underlying database of the model, has made recent progress in disaggregating sectors that are key to green transition for example through in the GTAP-CE database. Future versions of the database are expected to include several green technologies like electrical vehicles, batteries, solar panels, wind turbines. Once these new economic sectors are included in the database, it will ease the modeling of policies related to the green transition.

[53]A similar calibration can be done for the land transportation sector, if adequate country-specific data is available.

be privately or publicly financed.[54]

- **Carbon capture, utilization and storage (CCUS)** These set of technologies aim at reducing CO_2 emissions from industrial processes and electricity generation. These are modeled in IMF-ENV if projections of the share of economy-wide emission reductions that would be captured are available, together with their associated costs in terms of investment needs (capex).[55]

  The estimated emission reductions by year are directly deducted from total overall emissions and the costs are modeled using an investment-loss function, where the overall costs of CCUS (or other technologies) are estimated as a yearly share in total investment and then deducted from the capital accumulation function in the following year, such that:

  $$K_{t+1} = K_t(1-\delta) + (1 - IL_t)I_t \tag{69}$$

  where IL_t is the share of total investment in year t associated with CCUS technologies. This specification implies that to apply CCUS new capital has to be built, but this capital will not expand the stock of (productive) capital in the next period. In other words, the CCUS investment reduces GHG emissions, but does not expand the productive capacity of the economy.

6.2 Trade policies

IMF-ENV has detailed sector- and country-specific data on bilateral trade and different trade costs (i.e. international transportation, tariffs) and hence, is well suited to analyze the impacts of trade policies at different levels of detail. In fact, the CGE modeling framework was initially developed to analyze trade policies and therefore, these models can assess the macroeconomic and sectoral impact of free trade agreements (FTAs), and changes in specific trade barriers, such as tariffs, non-tariff measures (NTMs), and import quotas. IMF-ENV can also be used to model trade restrictions, for example, trade sanctions and other trade disruptions –e.g. the war in Ukraine (Rojas-Romagosa, 2024). These trade policies can be modeled for specific countries, by trading blocks and/or at the global scale. The combination of bilateral trade at the sectoral level and the input-output data also allows to analyze global supply chains (GSCs).

Finally, as the model has detailed information on energy and emissions, it can capture inter-linkages between trade, energy, and mitigation policies.[56] For example, the detailed information on bilateral trade and the emission-content of production (and exports) allows the assessment of carbon border adjustment mechanisms (CBAM) and changes to energy security indicators (Dolphin et al., 2024). However, if policies are aimed at particular products (instead of sectors), the model needs to be adjusted. For instance, the EU-CBAM is aimed at five products: fertilizers, aluminum, iron and steel, cement, and electricity. While electricity and iron and steel are separate sectors in the GTAP database, the remaining products are integrated into larger economic sectors (e.g., aluminum is included in the non-ferrous metals sector). Thus, a modeling limitation arises when policies focus on a narrow set of products that are components

[54] Projections on these costs are difficult to obtain, and need to be balanced against reduced costs of replacing existing gas stations for IC vehicles. When the additional costs for EV charging networks is available, they can be accounted for in the model using the investment-loss function explained below in equation 69.

[55] These data are available, for instance, from the NGFS phase IV scenarios.

[56] As explained in the introduction, CGE models like IMF-ENV are closely related to new quantitative trade (NQT) models, such as Caliendo and Parro (2015) and Baqaee and Farhi (2019). Thus, IMF-ENV is capable of evaluating the same trade policies as these models, but it offers the advantage of greater detail on energy and emissions.

of broader economic activities within the model. In these cases, additional data on the production and exports shares of these products is required.[57]

When modeling any trade policies, IMF-ENV baseline assumptions are updated to the latest available trade and trade barriers data, which can be taken from several sources.[58] The policy scenario will then change these trade barriers (i.e., tariffs, NTMs) or other trade policies according to the policy package.

7 Applications of IMF-ENV

IMF-ENV has been employed to examine a range of topics including domestic and global mitigation policies, the spillover effects of policies on competitiveness, energy security, transition risks within the financial sector, as well as the growth potential from increased energy supply and the implications of heightened electricity demand due to the advancement of artificial intelligence. Table 1 provides a list of these studies and below we provide a brief description of some of these applications.

7.1 Domestic climate and energy policies

IMF-ENV has been extensively used for modeling the macroeconomic assessment of country-specific climate and energy policies in Article IV reports for several G20 and other countries (see Table 1). In such analytical work, IMF-ENV is customized and extended to include salient country specific features. Within the country applications a variety of policy instruments have been studied like carbon pricing, green production and investment subsidies, feebates, green regulations, carbon border adjustment mechanisms (CBAM), among others. The choice of policy scenarios is determined by the country context and particular circumstances.

7.2 Global and regional climate and energy policies

A fragmented or uncoordinated approach to climate policies may result in competitiveness issues and the potential for carbon leakage. The model has been applied to develop varying degrees of coordination across regions and sectors and assess the economic impacts of these policy designs. Chateau et al. (2022c) systematically compares the economic performance of feebates, feed-in subsidies and carbon taxes in the power sector and in energy intensive and trade exposed (EITE) sectors. Fournier et al. (2024) studied regional spillovers of climate policies and competitiveness impacts within North America, particularly in the context of the Inflation Reduction Act and the Canadian carbon tax.

7.3 Transition risks

7.3.1 Financial Sector Assessment

The model is routinely used in Financial Sector Assessment Programs (FSAP) reports pertaining to transition risks of climate mitigation policies. In this context, the IMF-ENV model is linked to a micro simulation module that includes individual non-financial firms and banks for the country analyzed (Gross

[57] The current best alternative is to use the GTAP-CE database, which has these products disaggregated as individual economic activities.

[58] For example: UN Comtrade, WTO, OECD and/or national statistics, depending on the country and commodities of interest.

et al., 2025). More recently, IMF-ENV has been used to provide standardized scenarios that are aligned with the NGFS (phase IV) scenarios: NDC, Below 2°C, Delayed Transition and Net Zero by 2050. These scenarios were initially used in the forthcoming FSAPs for India and Canada, and are available for future FSAPs in other G20 countries.[59]

7.3.2 Fossil Fuel Exporters

While global demand for fossil fuels is expected to fall in the upcoming decades, the speed of this transition remains highly uncertain. With coal demand expected to drop faster than crude oil and natural gas due to its high carbon intensity, coal exporters were a focus of the work in the application for Australia (Spray and Thube, 2024).

7.4 Energy security

Russia's invasion of Ukraine in 2022 sparked an energy crisis in Europe that revived the interest in energy security issues. The IMF-ENV model provides outputs on energy demand, supply and trade by fuel type that have been used to assess the effects of mitigation policies on different energy security indicators at the global level (Kim et al., 2025) and on Europe (Rojas-Romagosa, 2024; Dolphin et al., 2024).

7.5 Climate finance

Meaningful climate action in several developing economies would require the flow of climate finance flows from advanced economies. The model has been used to develop global (Black et al., 2022) and regional (Cai et al., 2024) scenarios that explore the different normative rules based on which climate finance can be pooled by advanced economies and redistributed to emerging and developing economies and the resulting macroeconomic impacts.

7.6 Climate damages

The model's granularity enables the inclusion of various estimates of future climate change damages, commonly referred to as climate physical risks. These can be assessed at the economy-wide level, for instance, using estimations provided by the NGFS scenarios (NGFS, 2024) as expected reductions in real GDP (i.e., chronic physical risks).[60] More detailed damage estimations can also be included by using climate damage functions that link changes in temperature and precipitation patterns to productivity and other economic losses. These include for example labor productivity reductions from worker exposure to extreme heat, reduced agricultural productivity and lower yields for certain agricultural crops, increased energy demand for air conditioning, loss of arable land from rising sea levels, and capital losses from flooding, hurricanes and other extreme weather events, among others. These damage functions can be taken from global reports (Roson and Sartori, 2016) or from country- or region-specific studies.[61]

[59] Work is underway to update these scenarios to the NGFS phase V.

[60] An IMF-ENV applications using the methodology is explain in the Technical Note from Japan's FSAP.

[61] For instance, several World Bank Country Climate and Development Reports (CCDRs) employ detailed country-specific damage functions in their CGE assessments.

7.7 Growth opportunities from the green transition

Expansion of energy infrastructure and improving energy access remains a challenge in several economies. The IMF-ENV model version for sub-Saharan African countries was recently developed to assess the macroeconomic gains of increasing deployment of renewable electricity in the region (Cai et al., 2024) assuming different sources of financing, namely: domestic sources, external sources and a mix of the two. The role of complementary investments in transmission and distribution grid (T&D) and energy efficiency measures was also modeled.

7.8 AI and energy demand

Increased electricity demand from several drivers including artificial intelligence (AI) is an emerging topic of interest. IMF-ENV has been applied to study the impact of increasing electricity demand from expansion in data centers on electricity prices and emissions in the U.S., China and Europe.

Table 1: Selected IMF Applications of the IMF-ENV model

Reports	**Year**	**Format**	**Publication**
Canada	2023	SR	Canada: Staff Report for the 2023 Article IV Consultation (see Box 7)
Indonesia	2023	SR	Indonesia: Staff Report for the 2023 Article IV Consultation (see Box 2)
Mexico	2023	SR	Mexico: Staff Report for the 2023 Article IV Consultation (see Annex VI)
Saudi Arabia	2023	SR	Saudi Arabia: Staff Report for the 2023 Article IV Consultation (See Box 2)
USA	2023	SR	United States: Staff Report for the 2023 Article IV Consultation (see Box 8)
Germany	2022	FSAP	Germany: Financial System Stability Assessment
Mexico	2022	FSAP	Mexico: Financial Sector Assessment Program-Financial System Stability Assessment
Japan	2024	FSAP	Japan: Financial Sector Assessment Program-Financial System Stability Assessment
		TN	Japan: Financial Sector Assessment Program-Technical Note on Systemic Risk Analysis and Stress Testing
Kazakhstan	2024	FSAP	Republic of Kazakhstan: Financial Sector Assessment Program-Technical Note on Climate-Related Risks and Financial Stability
India	2025	FSAP	India: Financial Sector Assessment Program-Financial System Stability Assessment
Country analysis			
USA	2021	WP	Modeling the U.S. Climate Agenda: Macro-Climate Trade-offs and Considerations (Barrett et al., 2021)
China	2022	WP	A Comprehensive Package of Macroeconomic Policy Measures for Implementing China's Climate Mitigation Strategy (Chateau et al., 2022a)
Italy	2022	SIP	Securing a Smooth Green Transition (Chateau et al., 2022b)
India	2023	WP	A Framework for Climate Change Mitigation in India (Chateau et al., 2023)
Poland	2023	SIP	Balancing Decarbonization with Energy Security in Poland (Krogulski and Lindquist, 2023)
South Africa	2023	SIP	South Africa Carbon Pricing and Climate Mitigation Policy (Qu et al., 2023)
France	2024	WP	Climate Transition Risk and Financial Stability in France (Lee et al., 2024)
France	2024	SIP	Deep Dive on the Climate Transition for France: Macroeconomic Implications, Fiscal Policies, and Financial Risks (Teodoru et al., 2024)
Australia	2024	SIP	Global and domestic energy transition risks: Australia (Spray and Thube, 2024)
Regional analysis			
G7+	2022	WP	Climate Policy Options: A Comparison of Economic Performance (Chateau et al., 2022c)
Europe	2024	WP	Medium-term Macroeconomic Effects of Russia's War in Ukraine and How it Affects Energy Security and Global Emission Targets (Rojas-Romagosa, 2024)
Europe	2024	DP	The Energy Security Gains from Strengthening Europe's Climate Action (Dolphin et al., 2024)
North America	2024	WP	Cross-border effects of climate policies in North America (Fournier et al., 2024)
Sub-Saharan Africa	2024	SCN	Harnessing Renewables in Sub-Saharan Africa – Barriers, Reforms, and Economic Prospects (Cai et al., 2024)
Global analysis			
Global	2022	SCN	Getting on Track to Net Zero: Accelerating a Global Just Transition in This Decade (Black et al., 2022)
Global	2022	DP	Economic and Environmental Benefits from International Cooperation on Climate Policies (Chateau et al., 2022d)
Global	2024	WP	Energy Security and the Green Transition (Kim et al., 2025)
Forthcoming			
Commodity Special Feature	2025	WEO	Power Hungry: How AI will drive Energy Demand
Canada	2025	FSAP	Financial Sector Assessment Program
Egypt	2025	SIP	A Framework for Climate Change Mitigation in Egypt
Global	2025	WP	The ENV-FIBA Model for Climate Risk Analysis: Framework, Model Details, and Guide

8 Future model developments

To address current and future developments, IMF-ENV is continually updated and improved to incorporate new policies, technologies and modeling features. These developments improve the country support and expand the model's analytical scope. Feedback from bilateral and multilateral work shapes these priorities. The following model extensions aim to enhance our support to countries and prepare IMF-ENV for emerging policy questions and discussions.

8.1 Endogenous technological change (R&D module)

The new R&D module in IMF-ENV will n be used to assess the impact of changes in R&D expenditures on growth and other macroeconomic and sectoral variables. The main modeling mechanism links R&D expenditures to a stock of knowledge (proxied by number of patents) that in turn increases labor productivity and/or TFP growth.

This R&D mechanism is similar to the investment/capital stock dynamics, with the critical difference that we assume a distributed lag structure of the impacts of R&D expenses on the stock of knowledge. Using the Gamma distribution function, we allow for differences across countries and sectors on the shape of the lags. This theoretical specification is based on Smeets Kristkova et al. (2016), who applied it to R&D expenditures in agriculture. We expand the analysis to manufacturing and some service sectors using detailed patent data. The stock of knowledge is proxied by the cumulative number of patent applications received between 1980 and 2019. The analysis leverages data from the INPACT-S project (LaBelle, 2024). To calibrate the parameters of the R&D module and the Gamma distribution, we regress the knowledge stock (proxied by the number of patent applications) on R&D expenditure data (taken from the World Bank's World Development Indicators). Initial results show that increasing the share of R&D expenditure has a positive effect on the stock of knowledge measured by patents with an average lag of around ten years. These results are used to calibrate the parameters of the Gamma distribution

The last step in the parametrization of the R&D module is to link the stock of knowledge to productivity. We consider two measures of productivity: labor productivity, as measured by the World Bank's Global Productivity Sectoral Database for 109 countries (World Bank, 2024), and TFP using EU-KLEMS data for 30 selected advanced economies (European Commission, 2024).

We are planning to include two additional endogenous technological change mechanisms: learning by doing and international technological spillovers. These will be based on existing CGE applications and the relevant literature.

8.2 Labor split between skilled and unskilled workers

The GTAP database provides information for five labor types based on occupations. These are typically grouped into skilled and unskilled workers. The current version of IMF-ENV only distinguishes a single labor type. Thus, this model extension will allow to distinguish different relations between each skill type and capital, following the literature and evidence on skill-biased technological change (Krusell et al., 2000).[62] The split into both skill will generate changes in economy-wide wages for each labor type that

[62] Unskilled labor is found to be a relative substitute and skilled labor a relative complement to capital.

provide information on the functional distribution of income and which will make the model easier to link with a micro-simulation model with household-level data.

8.3 Outdoor Air pollution and associated co-benefits

Ambient air pollutant emissions significantly contribute to premature mortality and morbidity levels and are a significant health risk. While greenhouse gas emissions are already included in IMF-ENV, air pollutant emissions are not yet part of model outputs. The air-pollution module will include detailed accounting of air pollutant emissions. Furthermore, the pollutant concentrations will be used to estimate the health-related and environmental costs (or benefits) of increased (or reduced) air pollution in response to policies.

8.4 Natural resource depletion module

The depletion module is based on work already applied to the ENVISAGE model (Peszko et al., 2020) and it accounts for reserves and country-specific production costs of fossil fuels. In particular, the depletion module calculates and updates the values of the elasticity of the supply function for the fixed natural resource factor for fossil fuel extraction activities: coal, natural gas and oil (see Section 2.3.4). This is done by using detailed data on natural resource reserves and production costs, which has been obtained by integrating the outputs of extractive models for the oil and gas sectors from Rystad UCube, and coal mining from Wood Mackenzie.

8.5 Endogenous current account balance

The default current account balance (CAB) closure rule assumes that it is fixed either as a share of GDP or at a nominal value. However, there are other alternative rules that can be applied.[63] We are planning to include two additional rules that endogenize the CAB:

- GTAP closure: Global investment is allocated across regions depending on region-specific differentials on the expected rates of return to capital and country-specific risk parameters (Corong et al., 2017).
- Wedge closure: The pattern of international investment flows is driven by domestic savings and the accumulation of international reserves (Gouirinchas and Jeanne, 2013). These patterns create a "wedge" between the historical (observed) CAB average values and the expected capital flows from regional differences on the rates of returns to capital.

8.6 Savings and investment modeling

The recursive-dynamic nature of IMF-ENV entails that aggregate investment is determined each year by the overall available savings in each country, which is a function of private savings, public savings (government budget balance) and foreign savings (CAB). We are planning several model extensions that provide more structure and flexibility to this mechanism.

[63] See Bekkers et al. (2020) for a detailed discussion regarding different CAB closures in CGE models.

1. Private savings determinants. This consists in including a new module where private (household) savings are adjusted by demographic factors (aging, dependency ratios), country income levels and other saving determinants. The selection of the determinants will be based on the literature and identified best practices from existing CGE models.

2. Private savings and expected returns to capital. This will complement the previous module with and option where private savings are adjusted to reflect changes in the expected rates of return to capital, which could be determined by policy changes or technological shocks –such as, artificial intelligence, new green technologies. This mechanism will be similar to the increase in foreign net savings (the alternative CAB closure rule) arising from shifts in expected rates of return to capital.

3. Compatibility with new CAB closure rules. The new private savings determinants will be run jointly with the new endogenous CAB closure rules to test if they provide sensible results.

4. Split total investment between public and private investment. The GTAP database only provides information on overall (public plus private) investment. For certain model country aggregations, we will explore the option to split total investment if the required public and private investment data is available.

9 Summary

This working paper provides an extensive documentation of the IMF-ENV model, which has been developed to examine the impacts of policies inducing structural economic changes on both the overall economy and specific sectors. This makes it suitable for examining the medium- and long-term macroeconomic effects as well as structural shifts arising from national and/or global climate mitigation, energy, fiscal and trade policies. The paper starts with the technical description of the core blocks of the model: production, consumption and trade. The paper then defines how the model preserves the macroeconomic balances on demand and supply, household and government income and expenditures, which are linked to the investment-savings account including foreign transactions. Subsequently, the documentation presents the underlying data used in IMF-ENV and discusses the calibration choices made in the model.

Next, the paper presents the extensive range of outputs generated by the model and introduces the IMF-ENV Dashboard and its utilities. Furthermore, the paper provides an extensive compilation of policies and related applications that have been simulated using IMF-ENV. This includes a wide range of energy, climate, and trade policies that can be modeled with significant flexibility. Finally, upcoming model extensions are introduced that outline the subsequent steps in model development aimed at better preparing for future applications on emerging topics like large-scale industrial policies and green technology subsidies, the macroeconomic impacts of artificial intelligence (AI), trade disputes and agreements, and global fragmentation.

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A Annex: Algebraic derivations of CES function

A.1 Optimization problem of a CES production function

Following the cost minimization problem defined in Box 1, the Lagrangian can be set up as:

$$\mathcal{L} = \sum_i P_i V_i + \Lambda \left(X - A \left[\sum_i a_i (\lambda_i V_i)^\rho \right]^{1/\rho} \right)$$

Taking the partial derivative with respect to V_i and the Lagrange multiplier Λ yields the following system of equations:

$$P_i = \Lambda a_i \lambda_i^\rho V_i^{\rho-1} A \left[\sum_i a_i (\lambda_i V_i)^\rho \right]^{(1-\rho)/\rho} = \Lambda a_i A^\rho \lambda_i^\rho V_i^{\rho-1} X^{1-\rho}$$

$$X = A \left[\sum_i a_i (\Lambda_i V_i)^\rho \right]^{1/\rho}$$

Taking the first expression, it can be multiplied by V_i, and then summed. This of course is equal to the value of the bundle, i.e. PX, where P is the aggregate price:

$$PX = \sum_i P_i V_i = \Lambda X^{1-\rho} A^\rho \sum_i a_i \lambda_i^\rho V_i^\rho = \Lambda X^{1-\rho} X^\rho = \Lambda X$$

This shows that Λ, the Lagrange multiplier is the same as the aggregate price, P. We can then re-arrange the expression above to get the optimal input demand, where Λ is replaced by P:

$$V_i = a_i^{1/(1-\rho)} A^{\rho/(1-\rho)} \left(\frac{P}{P_i} \right)^{1/(1-\rho)} \lambda_i^{\rho/(1-\rho)} X$$

We finally end up with equation 70, where the CES primal exponent (ρ) is replaced by the so-called CES elasticity of substitution (σ), and the primal share coefficient (a_i) is substituted with the dual share coefficient (α_i).

$$V_i = \alpha_i^\sigma (A\lambda_i)^{\sigma-1} \left(\frac{P}{P_i} \right)^\sigma X \tag{70}$$

where we made the following substitutions:

$$\sigma = \frac{1}{1-\rho} \Leftrightarrow \rho = \frac{\sigma - 1}{\sigma} \Leftrightarrow \frac{\rho}{1-\rho} = \sigma - 1 \Leftrightarrow \rho.\sigma = \sigma - 1$$

and

$$\alpha_i = a_i^{1/(1-\rho)} = a_i^\sigma \Leftrightarrow a_i = \alpha_i^{1/\sigma}$$

A.2 Calibration of the CES production function

Calibration typically involves inverting functional forms to evaluate the value of a parameter given initial values for variables. Prices and volumes (P_i, P, X and V_i) are normally initialized to a given database or SAM. This may or may not include actual price/volume splits. If not, prices will typically be initialized at unit value—potentially adjusted for a price wedge such as a tax or a margin. The substitution elasticities are also normally inputs—either derived from econometric estimation, other data bases or models, or from a literature review. This leaves the parameters λ_i, α_i and A to calibrate. The technology parameters (λ_i and A) are normally associated with dynamics, so there is little reason not to initialize them to unit value as they can be incorporated in the initial share parameter value without any loss in generality. Thus, the only parameters left to calibrate are the α_i from which it is possible to derive the primal share parameters, s_i, if needed. The calibration formula is derived from the inversion of equation 70:

$$\alpha_i = \left(\frac{V_i}{X}\right)\left(\frac{P_i}{P}\right)^{\sigma}(A\lambda_i)^{1-\sigma} = \left(\frac{V_i}{X}\right)\left(\frac{P_i}{P}\right)^{\sigma} \tag{71}$$

The right-most term is the most used calibration formula where the technology parameters are explicitly set to one. In many introductions to CGE models, the calibration formulas explicitly exclude the price term. This is a dangerous practice that can lead to model bugs that can be hard to detect. It is best to explicitly initialize prices to 1 and use the correct calibration formula. In fact, one way to test model calibration and specification is to initialize prices to an arbitrary value and initialize volumes subject to these prices. Simulating a counter-factual with no shocks should replicate the initial data solution. If not, there is an error in initialization, calibration and/or specification. This option can be activated using the comparative static (COMPSTAT) option in IMF-ENV.

B Annex: Derivation of production equations

This section first introduces the derivations of default production functions that are applicable to all manufacturing and services sectors (Figure 1). Subsequently, it presents additional equations specific to the energy sectors (Figures 4 and 5) and the agriculture sectors (Figures 2 and 3).

B.1 Default Production equations

- Average unit price over capital vintages of total gross production:

$$PX_{r,a}XP_{r,a} = \sum_{v} PXv_{r,a,v}XPv_{r,a,v} \tag{72}$$

- Marginal unit cost of gross production by capital vintage under perfect competition (top-level production function):

$$UC_{r,a,v} = \frac{1}{A^{xpv}_{r,a,v}}\left[\alpha^{xp}_{r,a,v}\left(\frac{PXP_{r,a,v}}{\lambda^{xp}_{r,a,v}}\right)^{1-\sigma^{xp}_{r,a,v}} + \alpha^{ghg}_{r,a,v}\left(\frac{PXGHG_{r,a,v}}{\lambda^{ghg}_{r,a,v}}\right)^{1-\sigma^{xp}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{xp}_{r,a,v}}} \tag{73}$$

- With the zero profit condition being:

$$UC_{r,a,v}.XP_{r,a,v} = PXP_{r,a,v}.XPX_{r,a,v} + PXGHG_{r,a,v}.XGHG_{r,a} \tag{74}$$

- The post-tax unit cost of production with τ^{uc} denoting the tax on the cost of production

$$PXv_{r,a,v} = UC_{r,a,v}\left(1+\tau^{uc}_{r,a,v}\right) \tag{75}$$

- The market or output price equals the unit cost of production adjusted by an output tax denoted by $\tau^{p}_{r,a}$. Optionally, a markup of $\pi^{m}_{r,a}$ could also be added though by default it is set to zero.

$$PP_{r,a} = \left(PX_{r,a} + \pi^{m}_{r,a}\right)\left(1+\tau^{p}_{r,a}\right) \tag{76}$$

- Gross production second level bundles:

$$XPX_{r,a,v} = \alpha^{xp}_{r,a,v}\left(A^{xpv}_{r,a,v}\lambda^{xp}_{r,a,v}\right)^{\sigma^{xp}_{r,a,v}-1}\left(\frac{UC_{r,a,v}}{PXP_{r,a,v}}\right)^{\sigma^{xp}_{r,a,v}} XPv_{r,a,v} \tag{77}$$

$$XGHG_{r,a,v} = \alpha^{ghg}_{r,a,v}\left(A^{xpv}_{r,a,v}\lambda^{ghg}_{r,a,v}\right)^{\sigma^{xp}_{r,a,v}-1}\left(\frac{UC_{r,a,v}}{PXGHG_{r,a,v}}\right)^{\sigma^{xp}_{r,a,v}} XPv_{r,a,v} \tag{78}$$

- Price of second level production bundles:

$$PXP_{r,a,v} = \left[\alpha^{nd1}_{r,a,v}\left(PND^{1}_{r,a}\right)^{1-\sigma^{p}_{r,a,v}} + \alpha^{va}_{r,a,v}\left(PVA_{r,a,v}\right)^{1-\sigma^{p}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{p}_{r,a,v}}} \tag{79}$$

$$PXGHG_{r,a,v} = \sum_{GHG} \left[\alpha^{emi}_{r,a,v} \left[\frac{p\_emi^{PROD}_{r,GHG,v} - ctax^{pi}_{r,GHG,v}}{\lambda^{emi}_{r,GHG,v}} \right]^{\frac{1}{1-\sigma^{emi}_{r,v}}} \right]^{\frac{1}{1-\sigma^{emi}_{r,v}}} \tag{80}$$

- Aggregate bundle of intermediate consumption:

$$ND^{1}_{r,a} = \sum_{v} \alpha^{nd1}_{r,a,v} \left(\frac{PXP_{r,a,v}}{PND^{1}_{r,a}} \right)^{\sigma^{p}_{r,a,v}} XPX_{r,a,v} \tag{81}$$

It should be noted that the equation for ND^1 is summed over all vintages. This is because in the lower nests, the decomposition of the ND^1 bundle is assumed to be independent of the vintage. Differently, the decomposition of the VA is vintage specific as the substitution elasticities further down the nest are allowed to vary by vintage.

- Price of aggregate intermediate bundle:

$$PND^{1}_{r,a} = \left[\sum_{i \in \{ND1\}} \alpha^{io}_{r,i,a} \left(\frac{PA^{a}_{r,i,a}}{\lambda^{io}_{r,i,a}} \right)^{1-\sigma^{n1}_{r,a}} \right]^{\frac{1}{1-\sigma^{n1}_{r,a}}} \tag{82}$$

- Intermediate demand (excluding energy inputs) of commodity i in sector a:

$$XA_{r,i,a} = \alpha^{io}_{r,i,a} \left(\frac{\lambda^{io}_{r,i,a} PND^{1}_{r,a}}{PA^{a}_{r,i,a}} \right)^{\sigma^{nd1}_{r,a}} \frac{ND^{1}_{r,a}}{\lambda^{io}_{r,i,a}} \text{if } i \in \left\{ ND^{1} \right\} \tag{83}$$

- Value added bundle:

$$VA_{r,a,v} = \alpha^{va}_{r,a,v} \left(\frac{PXP_{r,a,v}}{PVA_{r,a,v}} \right)^{\sigma^{p}_{r,a,v}} XPX_{r,a,v} \tag{84}$$

- Price of the value added bundle:

$$PVA_{r,a,v} = \left[\alpha^{l1}_{r,a,v} \left(PLAB^{1}_{r,a} \right)^{1-\sigma^{v}_{r,a,v}} \quad + \ \alpha^{va1}_{r,a,v} \left(PVA^{1}_{r,a,v} \right)^{1-\sigma^{v}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{v}_{r,a,v}}} \tag{85}$$

- Productivity adjusted demand for labor:

$$LAB^{1}_{r,a} = \sum_{v} \alpha^{l1}_{r,a,v} \left(\frac{PVA_{r,a,v}}{PLAB^{1}_{r,a}} \right)^{\sigma^{v}_{r,a,v}} VA_{r,a,v} \tag{86}$$

while the labor demand in number of people is

$$ld^{1}_{r,a} = LAB^{1}_{r,a} \times \lambda^{l}_{r,a} \tag{87}$$

- Demand and price of the KEF bundles:

$$KEF_{r,a,v} = \alpha^{kef}_{r,a,v} \left(\frac{PVA1_{r,a,v}}{PKEF_{r,a,v}} \right)^{\sigma^{v}_{r,a,v}} VA1_{r,a,v} \tag{88}$$

$$PKEF_{r,a,v} = \left[\alpha^{kf}_{r,a,v} \left(PKF_{r,a,v} \right)^{1-\sigma^{kef}_{r,a,v}} + \alpha^{e}_{r,a,v} \left(PNRG_{r,a,v} \right)^{1-\sigma^{kef}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{kef}_{r,a,v}}} \tag{89}$$

- Demand and price of KF bundles:

$$KF_{r,a,v} = \alpha^{kf}_{r,a,v} \left(\frac{PKEF_{r,a,v}}{PKF_{r,a,v}} \right)^{\sigma^{kef}_{r,a,v}} KEF_{r,a,v} \tag{90}$$

$$PKF_{r,a,v} = \left[\alpha^{K}_{r,a,v} \left(PK_{r,a,v} \right)^{1-\sigma^{kf}_{r,a,v}} + \alpha^{nrf}_{r,a,v} \left(\frac{PNRF_{r,a}}{\lambda^{nrf}_{r,a,v}} \right)^{1-\sigma^{kf}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{kf}_{r,a,v}}} \tag{91}$$

- Demand and price of XNRG bundle:

$$XNRG_{r,a,v} = \alpha^{e}_{r,a,v} \left(\frac{PKEF_{r,a,v}}{PNRG_{r,a,v}} \right)^{\sigma^{kef}_{r,a,v}} KEF_{r,a,v} \tag{92}$$

$$PNRG_{r,a,v} = \left[\alpha^{ely}_{r,a,v} \left(PA^{ely}_{r,a,v} \right)^{1-\sigma^{e}_{r,a,v}} + \alpha^{nely}_{r,a,v} \left(PNELY_{r,a,v} \right)^{1-\sigma^{e}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{e}_{r,a,v}}} \tag{93}$$

- Demand for sector-specific natural resource factor (NRF):

$$XNRF^{d}_{r,a} = \sum_{v} \alpha^{nrf}_{r,a,v} \left(\frac{\lambda^{nrf}_{r,a,v} PKF_{r,a,v}}{PNRF^{p}_{r,a}} \right)^{\sigma^{kf}_{r,a,v}} \frac{KF_{r,a,v}}{\lambda^{nrf}_{r,a,v}} \tag{94}$$

- Price of NRF: Natural resources are assumed to be activity-specific, for example crude oil reserves. The supply of natural resources, $XNRF^{s}$, is given by an iso-elastic supply curve, (equation 95), where the supply elasticity is η^{nrf}. The supply specification allows for a horizontal supply curve, i.e. infinite supply. Equation (97) determines the equilibrium price. The latter equation is substituted out of the model.

$$\begin{cases} XNRF^{s}_{r,a} = \chi^{nrf}_{r,a} \left(\frac{\chi^{nrfp}_{r,a} PNRF_{r,a}}{PGDPMP_{r}} \right)^{\eta^{nrf}_{r,a}} & \text{if } \eta^{nrf}_{r,a} \neq \infty \\ \chi^{nrfp}_{r,a} PNRF_{r,a} = PGDPMP_{r} & \text{if } \eta^{nrf}_{r,a} = \infty \end{cases} \tag{95}$$

$$XNRF^{s}_{r,a} = XNRF^{d}_{r,a} \tag{96}$$

$$XNRF^{s}_{r,a} = XNRF^{d}_{r,a} \tag{97}$$

B.2 Energy Sector Equations

Equation (98) determines the demand for the electric bundle, XA^{ely}.[64] Equation (99) determines the demand for the non-electric bundle, $XNELY$. In both equations, the key substitution elasticity is given by σ^{e}. Equation (100) then describes the aggregate price of energy, $PNRG$.

$$XA^{ely}_{r,a,v} = \alpha^{ely}_{r,a,v} \left(\frac{PNRG_{r,a,v}}{PA^{ely}_{r,a,v}}\right)^{\sigma^{e}_{r,a,v}} XNRG_{r,a,v} \tag{98}$$

$$XNELY_{r,a,v} = \alpha^{nely}_{r,a,v} \left(\frac{PNRG_{r,a,v}}{PNELY_{r,a,v}}\right)^{\sigma^{e}_{r,a,v}} XNRG_{r,a,v} \tag{99}$$

$$PNRG_{r,a,v} = \left[\alpha^{ely}_{r,a,v} \left(PA^{ely}_{r,a,v}\right)^{1-\sigma^{e}_{r,a,v}} + \alpha^{nely}_{r,a,v} \left(PNELY_{r,a,v}\right)^{1-\sigma^{e}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{e}_{r,a,v}}} \tag{100}$$

Equation (101) determines the demand for the coal bundle, XA^{coa}. Equation (102) determines the demand for the oil & gas bundle, $XOLG$. In both equations, the key substitution elasticity is given by σ^{nely}. Equation (103) then describes the aggregate price of the non-electric bundle, $PNELY$.

$$XA^{coa}_{r,a,v} = \alpha^{coa}_{r,a,v} \left(\frac{PNELY_{r,a,v}}{PA^{coa}_{r,a,v}}\right)^{\sigma^{nely}_{r,a,v}} XNELY_{r,a,v} \tag{101}$$

$$XOLG_{r,a,v} = \alpha^{olg}_{r,a,v} \left(\frac{PNELY_{r,a,v}}{POLG_{r,a,v}}\right)^{\sigma^{nely}_{r,a,v}} XNELY_{r,a,v} \tag{102}$$

$$PNELY_{r,a,v} = \left[\alpha^{coa}_{r,a,v} \left(PA^{coa}_{r,a,v}\right)^{1-\sigma^{nely}_{r,a,v}} + \alpha^{olg}_{r,a,v} \left(POLG_{r,a,v}\right)^{1-\sigma^{nely}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{nely}_{r,a,v}}} \tag{103}$$

The remaining two energy bundles are oil and gas and emanate from the $XOLG$ bundle. Equation (104) determines the demand for the oil bundle, XA^{oil}. Equation (105) determines the demand for the gas bundle, XA^{gas}. In both equations, the key substitution elasticity is given by σ^{OLG}. Equation (106) then describes the aggregate price of the oil & gas bundle, $POLG$.

$$XA^{oil}_{r,a,v} = \alpha^{oil}_{r,a,v} \left(\frac{POLG_{r,a,v}}{PA^{oil}_{r,a,v}}\right)^{\sigma^{olg}_{r,a,v}} XOLG_{r,a,v} \tag{104}$$

$$XA^{gas}_{r,a,v} = \alpha^{gas}_{r,a,v} \left(\frac{POLG_{r,a,v}}{PA^{gas}_{r,a,v}}\right)^{\sigma^{olg}_{r,a,v}} XOLG_{r,a,v} \tag{105}$$

$$POLG_{r,a,v} = \left[\alpha^{oil}_{r,a,v} \left(PA^{oil}_{r,a,v}\right)^{1-\sigma^{olg}_{r,a,v}} + \alpha^{gas}_{r,a,v} \left(PA^{gas}_{r,a,v}\right)^{1-\sigma^{olg}_{r,a,v}}\right]^{\frac{1}{1-\sigma^{olg}_{r,a,v}}} \tag{106}$$

The final nest in the energy bundle is to decompose the four aggregate energy bundles into their

[64] In the GAMS code, the demand for the four energy bundles ('ely', 'gas', 'oil' and 'coa') are represented by the variable xa_{NRG} that has an additional dimension representing the four main energy carriers. This simplifies the decomposition of these bundles that only requires one set of equations rather than four. In principle, it also makes it somewhat easier to increase the number of energy bundles.

constituent parts that represent the Armington demand for the energy commodities. Equation (107) reflects the Armington demand for energy commodity e, XA, where the cost to producers is given by PA^{a}. The key substitution elasticity for each energy bundle is given by σ^{NRG}. Equation (108) represents the price of the aggregate energy bundles, PA^{NRG}.

$$XA_{r,e,a} = \sum_{v} \alpha^{eio}_{r,e,a,v} \left(\frac{\lambda^{e}_{r,e,a,v} PA^{NRG}_{r,a,v}}{PA^{a}_{r,e,a}} \right)^{\sigma^{NRG}_{r,a,v}} \frac{XA^{NRG}_{r,a,v}}{\lambda^{e}_{r,e,a,v}} \quad \text{if } e \in \{NRG\} \tag{107}$$

$$PA^{NRG}_{r,a,v} = \left[\sum_{e \in \{NRG\}} \alpha^{eio}_{r,e,a,v} \left(\frac{PA^{a}_{r,e,a}}{\lambda^{e}_{r,e,a,v}} \right)^{1-\sigma^{NRG}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{NRG}_{r,a,v}}} \tag{108}$$

B.3 Agriculture Sector equations

Land is a production factor in only agriculture activities. Therefore, the following two equations are only active in the agriculture sectors cro-a and lvs-a when calculating the demand for VA1 bundle:

$$VA^{1}_{r,a,v} = \alpha^{va1}_{r,a,v} \left(\frac{PVA_{r,a,v}}{PVA^{1}_{r,a,v}} \right)^{\sigma^{v}_{r,a,v}} VA_{r,a,v} \tag{109}$$

$$PVA^{1}_{r,a,v} = \left[\alpha^{land}_{r,a,v} \left(\frac{PLand^{p}_{r,a}}{\lambda^{t}_{r,a,v}} \right)^{1-\sigma^{v1}_{r,a,v}} + \alpha^{kef}_{r,a,v} \left(PKEF_{r,a,v} \right)^{1-\sigma^{v1}_{r,a,v}} \right]^{\frac{1}{1-\sigma^{v1}_{r,a,v}}} \tag{110}$$

C Annex: Main elasticity values

Table 2: Key production elasticities

	Parameter	Values	Sources
σ_{xpv}	Substitution between process emissions bundle and net-of-emissions gross output	0 for air pollutants For GHGs: 0.05 for agriculture Old = 0.05; New = 0.25 for manufacturing 0.15 for cement Old = 0.14; New = 28 for chemicals Old = 0.15; New = 0.3 for waste Old = 0.1; New = 0.3 for extraction	van der Mensbrugghe (2024)
σ_p	Substitution between ND1 and VA bundle	0.2 for agriculture [0.4 , 1.0] for manufacturing and services [0.35 , 0.42] for energy sectors Always 0 for old vintage technologies	Okagawa and Ban (2008)
σ_{n1}	Substitution between intermediate goods and services	0 for agriculture [0.1 , 0.4] for manufacturing & services 0.2 for energy sectors	Okagawa and Ban (2008)
σ_v	Substitution between Labor and KTE bundle	Old = 0.06; New = 0.5 for agriculture Old = 0.1; New = 0.8 for manufacturing Old = 0.15; New = [1.2 , 1.3] for services Old = 0.1; New = 0.9 for energy sectors	Okagawa and Ban (2008)
σ_{kef}	Substitution between capital and energy bundle	0.1 for agriculture [0.1 , 0.4] for manufacturing [0.4 , 0.5] for services [0.1 , 0.5] for energy sectors Always 0 for old vintage technologies	Okagawa and Ban (2008)
σ_{kf}	Substitution between capital and natural resource factor	New = 0.2 0 for old vintage technologies	van der Mensbrugghe (2024)
σ_e	Elasticity between electricity and non-electricity energy bundle	Old = 0.125; New = 1 0.025 and 0.2 for oil, coal and gas sectors	van der Mensbrugghe (2024)
σ_{nely}	Elasticity between coal and non-coal bundle	Old = 0.0625; New = 0.51 0.025 and 0.2 for oil, coal and gas sectors	van der Mensbrugghe (2024)
σ_{olg}	Elasticity between energy inputs in liquids bundle	Old = 0.125 ; New = 1 0.025 and 0.2 for oil, coal and gas sectors	van der Mensbrugghe (2024)
σ_{el}	Elasticity between power generation and transmission and distribution	0.05	van der Mensbrugghe (2024)
σ_m	Armington elasticity, domestic versus imports	[0.9, 5] depending on commodity, identical across regions.	Aguiar et al. (2022)
σ_w	Armington elasticity, import origins	[1.8, 10], generally twice higher than σ_m	Aguiar et al. (2022)

Note: Following the putty or semi-putty technology specification, this table shows that the substitution possibilities among factors, inputs and production bundles are assumed to be higher with new vintage capital than with old vintage capital. Values in brackets denote a range of elasticities varying by specific sectors within the overall manufacturing and services sectors.

Table 3: Key Sector specific elasticities

	Parameter	**Values**	Sources
η_{nrf}	Elasticity of Supply of natural resource factor	[1 , 10] for coal depending on region [0 , 0.58] for oil depending on region [0.1 , 1.8] for gas depending on region 0.25 for fishing, 0.5 for forestry, 2 for mining	Calibrated with IEA-WEM
η_t	Elasticity of Land Supply	[0.01, 0.6] depending on the region	Woltjer and Kuiper (2014)
η_{wl}	Elasticity of Labor Supply	[0.05, 0.2] depending on the region	Evers et al. (2008)
η_h	Income elasticities by consumption commodity	[0.25, 1.25] depending on consumption commodity k and region r	Aguiar et al. (2022)
σ_{pow}	Elasticity of substitution between electricity technologies	5	Chateau et al. (2014)
σ_{pb}	Elasticity of substitution between power bundles	2	Chateau et al. (2014)

D Annex: Model dimensions

The G-20 version of IMF-ENV has 25 regions, 36 activities and 28 commodities. Table 4 and Table 5 show the mapping of commodities and economic activities in IMF-ENV from the GTAP database. Table 6 shows the regional mapping. Based on the needs of the project, these aggregations can be changed.

Table 4: Concordance for commodities (i) between IMF-ENV and the GTAP database

1	All Crops (cro)	Paddy Rice (pdr), Wheat (wht), Cereal grains nec (gro), Vegetables, fruits, nuts (v_f), Oil Seeds (osd), Sugar cane, sugar beet (c_b), Plant-based fibers (pfb), Crops nec (ocr)
2	Livestock (lvs)	Bovine cattle, sheep and goats, horses (ctl), Animal products nec (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	Forestry (frs)	Forestry (frs)
4	Fisheries (fsh)	Fishing (fsh)
5	Coal extraction (coa)	Coal (coa)
6	Crude Oil extraction (oil)	Oil (oil)
7	Natural gas (gas)	Gas (gas), Gas manufacture, distribution (gdt)
8	Other extraction activities (OMN)	Other extraction (oxt)
9	Food Products (fdp)	Bovine meat products (cmt), Meat products nec (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products nec (ofd), Beverages and tobacco products (b_t)
10	Textiles (txt)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
11	Paper products & publishing (ppp)	Paper products, publishing (ppp)
12	Petroleum and coal products (p_c)	Petroleum, coal products (p_c)
13	Chemical products (crp)	Chemical products (chm)
14	Non-metallic minerals (nmm)	Mineral products nec (nmm)
15	Iron and Steel (i_s)	Ferrous metalsl (i_s)
16	Non-ferrous metals (nfm)	Metals nec (nfm)
17	Fabricated metal products (fmp)	Metal products (fmp)
18	Electronic equipment (ele)	Computer, electronic and optical products (ele)
19	Transport Equipment (mvh)	Motor vehicles and parts (mvh), Transport equipment nec (otn)
20	Other manufacturing activities (oma)	Wood products (lum), Basic pharmaceutical products (bph), Rubber and plastic products (rpp), Electrical equipment (eeq), Machinery and equipment nec (ome), Manufactures nec (omf)
21	Electricity (ELY)	Coal power baseload (CoalBL), Coal-based CCS (colccs), Oil power baseload (OilBL), Oil power peakload (OilP), Gas power baseload (GasBL), Gas power peakload (GasP), Gas-based CCS (gasccs), Nuclear power (NuclearBL), Advanced nuclear (advnuc), Hydro power baseload (HydroBL), Hydro power peakload (HydroP), Wind power (WindBL), Solar power (SolarP), Other baseload includes biofuels, waste, geothermal, and tidal technologies (OtherBL), Electricity transmission and distribution (TnD)
22	Water services (wts)	Water (wtr)
23	Construction (cns)	Construction (cns)
24	Land transport (otp)	Transport nec (otp)
25	Water Transport (wtp)	Water transport (wtp)
26	Air Transport (atp)	Air transport (atp)
27	Other Business services (osc)	Trade (trd), Accommodation, food and service activities (afs), Warehousing and support activities (whs), Communication (cmn), Financial services nec (ofi), Insurance (ins), Real estate activities (rsa), Business services nec (obs), Recreation and other services (ros), Dwellings (dwe)
28	Other collective services (osg)	Public administration and defense (osg), Education (edu), Human health and social work activities (hht)

Notes: nec = not elsewhere classified. Commodities 1 to 4 correspond to agriculture, 5 to 8 to mining, 9 to 20 to manufacturing, and 21 to 28 to services.

Table 5: Concordance for activities (a) between IMF-ENV and the GTAP database

1	All Crops (cro)	Paddy Rice (pdr), Wheat (wht), Cereal grains nec (gro), Vegetables, fruits, nuts (v_f), Oil Seeds (osd), Sugar cane, sugar beet (c_b), Plant-based fibers (pfb), Crops nec (ocr)
2	Livestock (lvs)	Bovine cattle, sheep and goats, horses (ctl), Animal products nec (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	Forestry (frs)	Forestry (frs)
4	Fisheries (fsh)	Fishing (fsh)
5	Coal extraction (coa)	Coal (coa)
6	Crude Oil extraction (oil)	Oil (oil)
7	Natural gas (gas)	Gas (gas), Gas manufacture, distribution (gdt)
8	Other extraction activities (OMN)	Other extraction (oxt)
9	Food Products (fdp)	Bovine meat products (cmt), Meat products nec (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products nec (ofd), Beverages and tobacco products (b_t)
10	Textiles (txt)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
11	Paper products & publishing (ppp)	Paper products, publishing (ppp)
12	Petroleum and coal products (p_c)	Petroleum, coal products (p_c)
13	Chemical products (crp)	Chemical products (chm)
14	Non-metallic minerals (nmm)	Mineral products nec (nmm)
15	Iron and Steel (i_s)	Ferrous metalsl (i_s)
16	Non-ferrous metals (nfm)	Metals nec (nfm)
17	Fabricated metal products (fmp)	Metal products (fmp)
18	Electronic equipment (ele)	Computer, electronic and optical products (ele)
19	Transport Equipment (mvh)	Motor vehicles and parts (mvh), Transport equipment nec (otn)
20	Other manufacturing activities (oma)	Wood products (lum), Basic pharmaceutical products (bph), Rubber and plastic products (rpp), Electrical equipment (eeq), Machinery and equipment nec (ome), Manufactures nec (omf)
21	Coal powered electricity (clp)	Coal power baseload (CoalBL), Coal-based CCS (colccs)
22	Oil powered electricity (olp)	Oil power baseload (OilBL), Oil power peakload (OilP)
23	Gas Powered electricity (gsp)	Gas power baseload (GasBL), Gas power peakload (GasP), Gas-based CCS (gasccs)
24	Nuclear power (nuc)	Nuclear power (NuclearBL), Advanced nuclear (advnuc)
25	Hydro power (hyd)	Hydro power baseload (HydroBL), Hydro power peakload (HydroP)
26	Wind power (wnd)	Wind power (WindBL)
27	Solar power (sol)	Solar power (SolarP)
28	Other power (xel)	Other baseload includes biofuels, waste, geothermal, and tidal technologies (OtherBL)
29	Electricity transmission and distribution (etd)	Electricity transmission and distribution (TnD)
30	Water services (wts)	Water (wtr)
31	Construction (cns)	Construction (cns)
32	Land transport (otp)	Transport nec (otp)
33	Water Transport (wtp)	Water transport (wtp)
34	Air Transport (atp)	Air transport (atp)
35	Other Business services (osc)	Trade (trd), Accommodation, food and service activities (afs), Warehousing and support activities (whs), Communication (cmn), Financial services nec (ofi), Insurance (ins), Real estate activities (rsa), Business services nec (obs), Recreation and other services (ros), Dwellings (dwe)
36	Other collective services (osg)	Public administration and defense (osg), Education (edu), Human health and social work activities (hht)

Notes: nec = not elsewhere classified. Activities 1 to 4 correspond to agriculture, 5 to 8 to mining, 9 to 20 to manufacturing, and 21 to 36 to services.

Table 6: Regional concordance between IMF-ENV and the GTAP database

1	Argentina (Argentina)	Argentina (ARG)
2	Australia (AUS)	Australia (AUS)
3	Brazil (BRA)	Brazil (BRA)
4	Canada (CAN)	Canada (CAN)
5	China (CHN)	China (CHN)
6	France (FRA)	France (FRA)
7	Germany (DEU)	Germany (DEU)
8	India (IND)	India (IND)
9	Indonesia (IDN)	Indonesia (IDN)
10	Italy (ITA)	Italy (ITA)
11	Japan (JPN)	Japan (JPN)
12	Korea (Korea)	Republic of Korea (KOR)
13	Mexico (MEX)	Mexico (MEX)
14	Russia (RUS)	Russian Federation (RUS)
15	Saudi Arabia (SAU)	Saudi Arabia (SAU)
16	South Africa (ZAF)	South Africa (ZAF)
17	Türkiye (TUR)	Türkiye (TUR)
18	United Kingdom (GBR)	United Kingdom (GBR)
19	United States (USA)	United States of America (USA)
20	Rest of EU & EFTA (REU)	Austria (AUT), Belgium (BEL), Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), Greece (GRC), Hungary (HUN), Ireland (IRL), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Spain (ESP), Sweden (SWE), Switzerland (CHE), Norway (NOR), Rest of EFTA (XEF), Bulgaria (BGR), Croatia (HRV), Romania (ROU)
21	Other Middle East countries (ROP)	Bahrain (BHR), Iraq (IRQ), Islamic Republic of Iran (IRN), Israel (ISR), Jordan (JOR), Kuwait (KWT), Lebanon (LBN), Oman (OMN), Palestineian Territory (PSE), Qatar (QAT), Syrian Arab Republic (SYR), United Arab Emirates (ARE), Rest of Western Asia (XWS)
22	Other Asian countries & New Zealand (ODA)	Hong Kong (HKG), Mongolia (MNG), Chinese Taipei (TWN), Rest of East Asia (XEA), Brunei Darussalam (BRN), Cambodia (KHM), Lao PDR (LAO), Malaysia (MYS), Philippines (PHL), Singapore (SGP), Thailand (THA), Viet Nam (VNM), Rest of Southeast Asia (XSE), Afghanistan (AFG), Bangladesh (BGD), Nepal (NPL), Pakistan (PAK), Sri Lanka (LKA), Rest of South Asia (XSA), New Zealand (NZL), Rest of Oceania (XOC)
23	Other African countries (OAF)	Algeria (DZA), Egypt (EGY), Morocco (MAR), Tunisia (TUN), Rest of North Africa (XNF), Benin (BEN), Burkina Faso (BFA), Cameroon (CMR), Côte d'Ivoire (CIV), Ghana (GHA), Guinea (GIN), Mali (MLI), Niger (NER), Nigeria (NGA), Senegal (SEN), Togo (TGO), Rest of Western Africa (XWF), Central African Republic (CAF), Chad (TCD), Congo (COG), Democratic Republic of the Congo (COD), Equatorial Guinea (GNQ), Gabon (GAB), Rest of South and Central Africa (XAC), Comoros (COM), Ethiopia (ETH), Kenya (KEN), Madagascar (MDG), Malawi (MWI), Mauritius (MUS), Mozambique (MOZ), Rwanda (RWA), Sudan (SDN), United Republic of Tanzania (TZA), Uganda (UGA), Zambia (ZMB), Zimbabwe (ZWE), Rest of Eastern Africa (XEC), Botswana (BWA), Eswatini (SWZ), Namibia (NAM), Rest of South African Customs Union (XSC)
24	Other East European and Eurasian countries (OEA)	Albania (ALB), Belarus (BLR), Serbia (SRB), Ukraine (UKR), Rest of Eastern Europe (XEE), Rest of Europe (XER), Armenia (ARM), Azerbaijan (AZE), Georgia (GEO), Kazakhstan (KAZ), Kyrgyzstan (KGZ), Tajikistan (TJK), Uzbekistan (UZB), Rest of Former Soviet Union (XSU)
25	Other Latin American countries (OLA)	Rest of North America (XNA), Costa Rica (CRI), Guatemala (GTM), Honduras (HND), Nicaragua (NIC), Panama (PAN), El Salvador (SLV), Rest of Central America (XCA), Dominican Republic (DOM), Haiti (HTI), Jamaica (JAM), Puerto Rico (PRI), Trinidad and Tobago (TTO), Rest of Caribbean (XCB), Bolivia (BOL), Chile (CHL), Colombia (COL), Ecuador (ECU), Paraguay (PRY), Peru (PER), Uruguay (URY), Venezuela (VEN), Rest of South America (XSM), Rest of the World (XTW)

Table 7: Concordance for commodities that are consumed by households (k) between IMF-ENV and the GTAP database

1	All Crops (cro)	Paddy Rice (pdr), Wheat (wht), Cereal grains nec (gro), Vegetables, fruits, nuts (v_f), Oil Seeds (osd), Sugar cane, sugar beet (c_b), Plant-based fibers (pfb), Crops nec (ocr)
2	Livestock (lvs) and fish (fsh)	Bovine cattle, sheep and goats, horses (ctl), Animal products nec (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	Forestry (frs)	Forestry (frs)
4	Energy bundle	Electricity (ELY), Coal (coa), Oil (oil), Gas (gas), Gas manufacture, distribution (gdt) and Petroleum, coal products (p_c)
5	Other extraction activities (OMN)	Other extraction (oxt)
6	Food Products (fdp)	Bovine meat products (cmt), Meat products nec (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products nec (ofd), Beverages and tobacco products (b_t)
7	Textiles (txt)	Textiles (tex), Wearing apparel (wap), Leather products (lea)
8	Paper products & publishing (ppp)	Paper products, publishing (ppp)
9	Chemical products (crp)	Chemical products (chm)
10	Non-metallic minerals (nmm)	Mineral products nec (nmm)
11	Iron and Steel (i_s)	Ferrous metalsl (i_s)
12	Non-ferrous metals (nfm)	Metals nec (nfm)
13	Fabricated metal products (fmp)	Metal products (fmp)
14	Electronic equipment (ele)	Computer, electronic and optical products (ele)
15	Transport Equipment (mvh)	Motor vehicles and parts (mvh), Transport equipment nec (otn)
16	Other manufacturing activities (oma)	Wood products (lum), Basic pharmaceutical products (bph), Rubber and plastic products (rpp), Electrical equipment (eeq), Machinery and equipment nec (ome), Manufactures nec (omf)
17	Water services (wts)	Water (wtr)
18	Construction (cns)	Construction (cns)
19	Land transport (otp)	Transport nec (otp)
20	Water Transport (wtp)	Water transport (wtp)
21	Air Transport (atp)	Air transport (atp)
22	Other Business services (osc)	Trade (trd), Accommodation, food and service activities (afs), Warehousing and support activities (whs), Communication (cmn), Financial services nec (ofi), Insurance (ins), Real estate activities (rsa), Business services nec (obs), Recreation and other services (ros), Dwellings (dwe)
23	Other collective services (osg)	Public administration and defense (osg), Education (edu), Human health and social work activities (hht)

Table 8: Emission source matrix (B) in IMF-ENV

	Emission sources:	Land	Capital	coalcomb	coilcomb	roilcomb	gascomb	chemUse	act	fugitive	lulucf	AgrBurn	wastesld
	GHGs:	CH_4 N_2O	CH_4 N_2O	CO_2 CH_4 N_2O	CO_2 CH_4 N_2O	CO_2 CH_4 N_2O	CO_2 CH_4 N_2O	CO_2 N_2O	CO_2 CH_4 N_2O	CO_2 CH_4 N_2O	CO_2	CH_4 N_2O	CO_2 CH_4 N_2O
Agriculture	cro-a	1		1	1	1	1	1			1		
	lvs-a	1	1	1	1	1	1	1			1		
	frs-a			1	1	1	1				1	1	
	fsh-a			1	1	1	1						
Fossil fuel extraction	coa-a			1	1	1	1			1			
	oil-a			1	1	1	1			1			
	p_c-a			1	1	1	1			1			
	gas-a			1	1	1	1			1			
Other extraction	omn-a			1	1	1	1						
Electricity generation	clp-a			1	1	1	1						
	olp-a			1	1	1	1						
	gsp-a			1	1	1	1						
	xel-a			1	1	1	1						
	etd-a			1	1	1	1						
Energy-intensive manufacturing	ppp-a			1	1	1	1						
	nmm-a			1	1	1	1						
	i_s-a			1	1	1	1		1				
	crp-a			1	1	1	1	1					
	nfm-a			1	1	1	1		1				
Other manufacturing	ele-a			1	1	1	1		1				
	fdp-a			1	1	1	1	1					
	txt-a			1	1	1	1						
	mvh-a			1	1	1	1						
	fmp-a			1	1	1	1						
	oma-a			1	1	1	1		1				
Transport services	wtp-a			1	1	1	1						
	atp-a			1	1	1	1						
	otp-a			1	1	1	1						
Other Services	osg-a			1	1	1	1	1					
	osc-a			1	1	1	1	1					
Construction	cns-a			1	1	1	1						
Waste	wts-a			1	1	1	1						1
Households	hhd			1	1	1	1						

Notes: There are no GHG emissions associated with renewable power generation sources sol-a, wnd-a, hyd-a and nuc-a.