



TRANSIENCE

**TRANSITIONING TOWARDS AN EFFICIENT,
CARBON-NEUTRAL CIRCULAR EUROPEAN
INDUSTRY**

Date: 29/05/2025

D4.1 – Socioeconomic module

WP4 – Developing satellite
modules



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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

Deliverables of WP4 (D4.1-D4.7) are intended for the broader stakeholder community of TRANSIENCE with a particular focus on supporting modellers. They provide a structured overview of the individual components/modules that will be integrated into the Model for European Industry Circularity and Climate Change Mitigation (MIC3). This specific deliverable focuses on the socioeconomic model (OPEN_GEM), which sets the boundary framework conditions for MIC3. Modellers can use the socioeconomic model as a standalone tool or alongside other satellite modules of the MIC3 framework to assess diverse scenarios and support policymaking on decarbonisation and circular economy strategies.

3. Short summary of results (<250 words)

This deliverable presents OPEN_GEM, a new open-source Computable General Equilibrium (CGE) model developed in the context of the TRANSIENCE project. It is designed to assess the socioeconomic impacts of climate and circular economy policies across the European Union. The model is multi-regional (28 countries/regions) and multi-sectoral (44 sectors), with a strong focus on energy-intensive industries such as cement, steel, aluminium, and plastics, including primary, secondary, and recycling processes.

OPEN_GEM is calibrated using the Global Trade Analysis Project GTAP v11 Circular Economy Database, with a base year of 2017. It simulates long-term developments from 2020 to 2050 and captures inter-sectoral, macroeconomic, and environmental dynamics, including CO₂ emissions, carbon pricing, and emissions trading.

The model is designed to support policy scenario analysis, providing detailed projections for GDP, consumption, trade, emissions, and sectoral outputs. Its open architecture allows soft-linking with industry-based models, improving representation of technological pathways and mitigation options.

As part of the MIC3 modelling ecosystem, OPEN_GEM contributes to a holistic understanding of industrial circularity and decarbonisation, enabling evidence-based decision-making for a sustainable, climate-neutral European industry.

4. Evidence of accomplishment

This report and the associated [GitHub repository](#).

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL	
CEPS – Centre for European Policy Studies	BE	
E3M – E3-Modelling AE	EL	
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE	
HOL – HOLISTIC IKE	EL	
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE	
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL	
TECNALIA – Fundación Tecnalia Research & Innovation	ES	
UU – Universiteit Utrecht	NL	
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE	
PSI – Paul Scherrer Institut	CH	
UCL – University College London	UK	

Executive Summary

The deliverable presents OPEN-GEM, a newly developed, open-source Computable General Equilibrium (CGE) model, designed to assess the socioeconomic implications of climate and circular economy policies across Europe. Built within the TRANSCIENCE project, it supports the evaluation of ambitious industrial decarbonisation strategies in the EU by capturing the complex interlinkages between economic activities, environmental policies, and global trade.

OPEN-GEM is a multi-sectoral, multi-regional, recursive-dynamic CGE model, representing 44 economic sectors across 28 regions, including all EU member states individually. It is calibrated using the Global Trade Analysis Project GTAP Data Base (v11) for the base year 2017, with updates from the GTAP Circular Economy Data Base. The model simulates projections from 2020 to 2050, providing detailed outputs on GDP, household consumption, investments, trade flows, emissions, and sectoral production.

The model uniquely features a detailed representation of energy-intensive sectors (e.g., cement, steel, aluminium), including primary, secondary, and recycling processes. This allows integration with industry-based models and supports more precise simulation of decarbonisation pathways. It incorporates environmental and climate constraints such as carbon pricing, CO₂ emissions caps, and emission permit trading mechanisms.

OPEN-GEM plays a critical role within the MIC3 open modelling ecosystem, enabling a holistic and integrated analysis of circularity, sustainability, and decarbonisation of European industry. It is designed for transparency, reproducibility, and policy relevance, providing decision-makers with robust evidence on the socioeconomic impacts of the green transition.

The code of the OPEN-GEM can be found in the following repository:
<https://github.com/e3modelling/OPEN-GEM>.

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1 Introduction

Decarbonisation and the transition to a circular economy present several interconnected challenges. One of the key issues is the need for change across industries and households, which often involves high upfront costs, technological innovation, and rethinking entire supply chains. The transition from a production process that relies heavily on fossil fuels to a greener and less resource-intensive process requires a modelling approach that can capture the inter-dependencies of the economic system at sufficient scale and granularity. Computable General Equilibrium (CGE) models offer significant strengths in evaluating the complex and interrelated issues associated with decarbonisation and circularity performance. Their primary advantage lies in their ability to capture economy-wide interactions across sectors, regions, and agents, making them well-suited to assess the broad impacts of environmental and economic policies. CGE models account for market feedbacks, price adjustments, and resource reallocation, allowing analysts to evaluate how changes in one part of the economy ripple through others. This makes them particularly effective for identifying indirect impacts, distributional effects, and policy trade-offs. Moreover, CGE models can be tailored to incorporate environmental constraints, carbon pricing mechanisms, and material flow dynamics, enabling a holistic understanding of how different policy scenarios affect both economic performance and sustainability goals. To this end, an extension of sectoral coverage in macroeconomic models is needed to cover the key characteristics in the demand and supply of the sectors/products that play a key role in the transition to a low-carbon, circular economy.

In this study we present the multi-sector, multi-regional CGE model OPEN_GEM, which is developed within TRANSIENSE. The model is designed to support the socioeconomic assessment of energy and climate policies with a particular focus on the impacts related to GDP and sectoral production. OPEN_GEM, an open-source model, will benefit from using key outputs of the industry-based models in key industrial sectors (i.e., cement, iron & steel, aluminium, etc.) as exogenous inputs—more specifically, the different technologies by sector, the cost structure by different technology, and the adoption of each technology by sector. By soft-linking it with industry-based models, OPEN-GEM will extend its application to cover policies related to the circular economy. A number of different modules will be developed with TRANSIENSE to cover a wide range of technical and structural characteristics of industries related to the decarbonisation and circular economy, altogether comprising the MIC3 model ecosystem to be developed within TRANSIENSE (see Deliverable D3.4 – Framework for industrial transition modelling), providing the framework of the complex communications among them.

This document serves as a methodological and technical guide of OPEN_GEM. Section 2 presents the theoretical foundations on which the model is built and provides the mathematical formulations of all the equations included in the model. Section 3 presents the benefits of this module and Section 4 the integration of this module in the planned interfaces in the MIC3 baseline workflow.

2 Module description

The OPEN_GEM model is an open-source CGE model that is designed within the TRANSCIENCE project. Its aim is to assess the economic implications of energy, climate and circular economy policies on the EU industrial tissue and capture the interactions between the EU member states and the rest of the world.

This version of the model covers the whole world aggregated in 28 countries/regions (see Table 1) where each EU member state is represented individually. The ‘rest of the world’ group of countries is represented as the 28th region of the model.

The model is a multi-sectoral recursive dynamic CGE model driven by accumulation of capital and equipment, which provides details on the macro-economy and its interactions with the environment and the energy system. It covers individually 44 activities including a detailed representation of the industry and energy sectors together with agriculture, transport, and services (see Table 2).

It can be used for the comparative analysis of alternative policy scenarios and the provision of insights on the distributional effects of long-term structural adjustments. In all simulation scenarios, the model ensures that the economic system is always in general equilibrium. Finally, it is a recursive dynamic model¹. Its properties are manifested through stock-flow relationships, technical progress, capital accumulation, agents’ (myopic) expectations, and a 5-year time step.

Table 1: Country-Regional aggregation of the OPEN_GEM model

Country Code	Country/ Region	Country Code	Country/ Region
AUT	Austria	IRL	Ireland
BEL	Belgium	ITA	Italy
BGR	Bulgaria	LTU	Lithuania
CYP	Cyprus	LUX	Luxembourg
CZE	Czechia	LVA	Latvia
DEU	Germany	MLT	Malta
DNK	Denmark	NLD	Netherlands
ESP	Spain	POL	Poland
EST	Estonia	PRT	Portugal
FIN	Finland	ROU	Romania
FRA	France	SVK	Slovakia
GRC	Greece	SVN	Slovenia
HRV	Croatia	SWE	Sweden
HUN	Hungary	ROW	Rest of the World

¹ A recursive dynamic model is a type of economic model that captures changes over time by solving a sequence of static equilibrium problems, one period at a time. In each period, agents (such as households, firms, and the government) make decisions based on current conditions and expectations about the future, but without fully optimising over the entire time horizon (i.e., without perfect foresight). The outcomes from one period—such as capital accumulation, resource use, or emissions—become the inputs for the next. This approach allows the model to track the evolution of the economy over time, making it useful for analysing long-term policy impacts, such as those related to decarbonisation and structural transitions.

Table 2: Sectoral aggregation of the OPEN_GEM model

Code	Description	Code	Description
	Industry	IND25	Copper-secondary
IND01	Non-metallic minerals mining	IND26	Recycling-copper
IND02	Mining of iron ores	IND27	Other metals-primary
IND03	Mining of bauxite ores	IND28	Other metals-secondary
IND04	Mining of copper ores	IND29	Recycling-other metals
IND05	Mining of other ores	IND30	Non-ferrous metals casting
IND06	Potassium fertiliser	IND31	Metal products
IND07	Nitrogen fertiliser	IND32	Paper products, publishing
IND08	Phosphorus fertiliser	IND33	Equipment Goods
IND09	Other chemicals	IND34	Consumer Goods Industries
IND10	Basic pharmaceutical products	IND35	Construction
IND11	Rubber products		Energy
IND12	Plastic products-primary	ENE01	Coal
IND13	Plastic products-secondary	ENE02	Crude Oil
IND14	Recycling-plastics	ENE03	Oil
IND15	Cement	ENE04	Gas
IND16	Other mineral products	ENE05	Power Supply
IND17	Iron and steel-primary		Transport
IND18	Iron and steel-secondary	TRA01	Transport
IND19	Recycling-iron and steel		Agriculture
IND20	Iron and steel casting	AGR01	Agriculture
IND21	Aluminium-primary		Services
IND22	Aluminium-secondary	SRV01	Market Services
IND23	Recycling-aluminium	SRV02	Non-Market Services
IND24	Copper-primary		

2.1 Concept

The OPEN_GEM model is written in GAMS. The implementation of the model is made in two stages:

- 1 **Calibration:** Calculation/Estimation/Population of the model parameters in such a way that the model, when solved, fully replicates the base year data.
- 2 **Dynamic projections and simulations:** This stage regards the development of the reference projection and quantification of counterfactual scenarios.

Based on the Global Trade Analysis Project (GTAP) input-output tables of the base year (2017), the model projects full Input-Output (IO) tables for each EU MS for the period 2020–2050 in a 5-year time step. The main outputs of the model include main macroeconomic accounts (GDP, household consumption, investment, government expenditures, balance of trade, etc.), sectoral production, imports and exports by sector, energy use, and CO₂ energy related emissions.

2.1.1 Mathematical foundations

OPEN_GEM considers all economic agents (classified in groups: firms, households, government and the external sector).

The model formulation takes into consideration the microeconomic theory on agents' behaviour and the macroeconomic relationships and flows among them. The following sections provide the mathematical formulation of the model with detailed presentation of economic agents' behaviour.

2.1.1.1 Firms

Firms adopt an optimising behaviour and operate under a perfect competition regime. A nested multi-factor Constant Elasticity of Substitution (CES) production function is used. Firms' choice regards the optimal level of production inputs (including primary factors of production capital, labour and intermediate inputs energy, and other commodities). The model identifies a number of i firms, j intermediate inputs, labour, and capital.

Firms operating in perfectly competitive sectors decide upon production factor inputs so as to minimise their production costs. Each production factor is paid at its marginal product and firms' unit cost prices² are set to cover the costs of all production factors (capital payment inclusive), not allowing for non-normal profits. It is assumed that each firm³ produces a single good, which is differentiated from any other good produced. Firms' output, factor demands, and associated unit costs are presented below. Each firm uses a constant elasticity of substitution (CES) production technology. The nesting of the CES production function depends on **the substitution possibilities** that characterise the production technology of each firm.

The cost minimisation objective function of the firm is:

$$\min \text{Cost}_{i,r,t} = \sum_f QF_{f,i,r,t} \cdot PQF_{f,i,r,t} \quad [1]$$

subject to the production technology of firms:

$$Q_{i,r,t} = \bar{Q}_{i,r} \cdot \frac{\text{tfp}_{i,r,t}}{\text{tfp}_{i,r}} \cdot \left(\sum_f \theta_{f,i,r,t} \cdot \left(\frac{QF_{f,i,r,t}}{\bar{QF}_{f,i,r}} \right)^\rho \right)^{\frac{1}{\rho}} \quad [2]$$

The respective derived demands for the inputs in the production (capital, labour, materials/intermediate inputs) are given by:

$$PQ_{i,r,t} = \bar{PQ}_{i,r} \cdot \frac{\text{tfp}_{i,r,t}}{\text{tfp}_{i,r}} \cdot \left(\sum_f \theta_{f,i,r,t} \cdot \left(\frac{PQF_{f,i,r,t}}{\bar{PQF}_{f,i,r}} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \quad [3]$$

$$QF_{i,f,r,t} = \bar{QF}_{i,f,r} \cdot \frac{Q_{i,r,t}}{\bar{Q}_{i,r}} \cdot \left(\frac{\bar{PQF}_{f,i,r}}{PQ_{i,r,t}} \cdot \frac{PQ_{i,r,t}}{PQF_{f,i,r,t}} \right)^\sigma \cdot \left(\frac{\text{tfp}_{i,r,t}}{\text{tfp}_{i,r}} \right)^{\sigma-1} \quad [4]$$

where:

i : sector, r : region, t : time, f : inputs in the production function (capital, labour, and intermediate inputs). Note that the (\bar{x}) symbol means that the variable (x) is in its base year value.

² Firms' unit costs depend on the unit cost of factor inputs and on TFP. The representation of TFP is discussed in detail in the next section.

³ A representative firm is used for a branch/economic sector. In the IO table, it is assumed that each column represents a single product produced by a single (representative) firm.

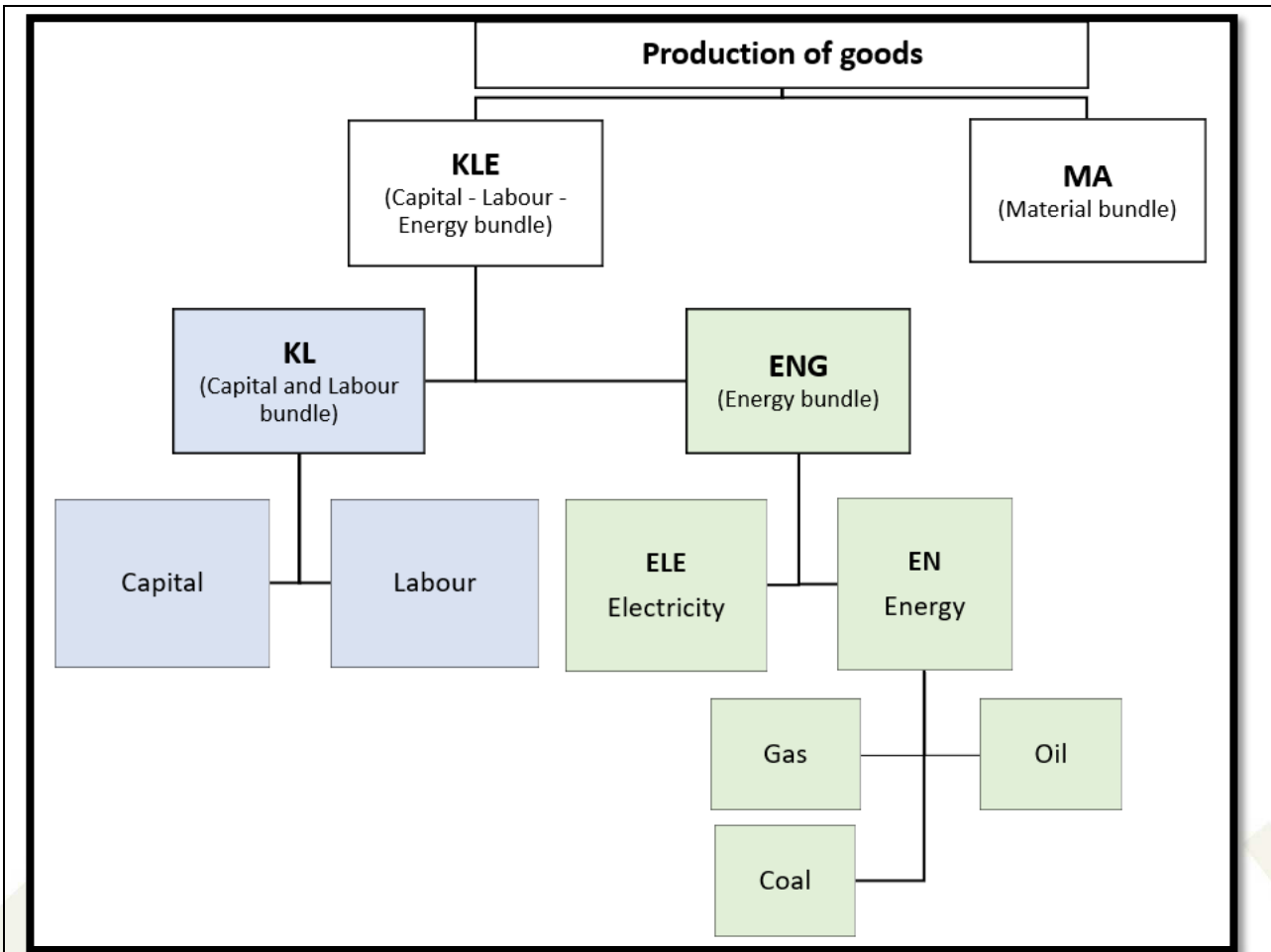
$Q_{i,r,t}$:	production in volume for activity i
$\bar{Q}_{i,r}$:	production in volume for activity i (base year)
$QF_{f,i,r,t}$:	amount of production factor f used in production in year t
$\bar{QF}_{f,i,r}$:	amount of production factor f used in production (base year).
$PQF_{f,i,r,t}$:	unit cost of factor f .
$\bar{PQF}_{f,i,r}$:	unit cost of factor f (base year).
$PQ_{i,r,t}$:	unit cost of production for activity i .
$\bar{PQ}_{i,r}$:	unit cost of production for activity i (base year).
$\theta_{f,i,r,t}$:	share parameter (to calibrate to base year values)
ρ :	elasticity ($\rho = \frac{\sigma-1}{\sigma}$)
σ :	elasticity of substitution between production factors
$tfp_{i,r,t}$:	total factor productivity
$\bar{tfp}_{i,r}$:	total factor productivity at base year (= 1)

The CES production technology applies to all firms. Production functions in OPEN_GEM exhibit a nested separability scheme, involving capital (K), labour (L), energy (E), and materials and transport (M). The nesting scheme differentiates among the sectors so as to take into account the specific features of each activity and to capture the different substitution possibilities that characterise each production sector.

For the remainder of the text, we use the following symbols for variables' subscripts:

- pr, br , (interchangeably) for activity sector
- er, cr, cs (interchangeably) for countries
- t for time gv for government revenues and expenses categories
- $co2$ for CO₂ energy related emissions
- fa for production factor
- se, sr (interchangeably) for institutional sector, i.e., households (h), firms (f), government (g), and world (w)

Figure 1: Nesting scheme in the OPEN_GEM sectors



The nesting scheme develops as follows:

1st level:	Production of Goods (XD) is split into capital, labour, energy bundle (KLE) and materials bundle (MA)
------------------------------	---

$$A_{XD} = a_{xd_0} \cdot \left(d^{kle} \cdot \left(\frac{A_{KLE}}{a_{kle_0}} \right)^\rho + d^{trama} \cdot \left(\frac{A_{MA}}{a_{ma_0}} \right)^\rho \right)^{\frac{1}{\rho}}$$

where: *d*: share parameter and ρ : substitution elasticity parameter

2nd level:	KLE is split into capital and labour bundle (KL) and energy bundle (ENG) MA is split into intermediate inputs materials (IO)
------------------------------	---

$$A_{KLE} = CES(A_{KL}, A_{ENG})$$

$$A_{MA} = CES(A_{IO_{prmane}})$$

3rd level:	KL is split into capital and labour bundle ENG is split into fuels energy bundle (EN) and electricity (ELE)
------------------------------	--

$$A_{KL} = \text{CES}(A_{KAV}, A_{LAV})$$

$$A_{ENG} = \text{CES}(A_{EN}, A_{ELE})$$

4th level:	EN is split into fuels energy intermediate inputs (coal, oil and gas)
----------------------------------	---

$$A_{EN} = \text{CES}(A_{IO_{prfuel}})$$

2.1.1.2 Household

In each region/country in OPEN_GEM, a representative household is modelled that maximises its utility function subject to its budget constraint. Its budget is derived from its income as capital owners from labour supply and the transfers from other institutional sectors.

Its utility function is a Linear Expenditure System (LES⁴) function that considers subsistence minima:

$$U = \left(\sum_i bh_{i,r,t} \cdot \ln(CV_{i,r,t} - CH_{i,r,t}) \right) \quad [5]$$

Where $CV_{i,r,t}$ is total consumption, $CH_{i,r,t}$ is the subsistence minima consumption. Total and disposable income is derived as follows:

$$YDISP = PL \cdot L + W^{oth} \quad [6]$$

where:

$PL \cdot L$: labour income

W^{oth} : non-labour income (e.g. institutional transfers)

The consumer's optimisation problem is defined as:

$$\max_{CV} \int_{t=0}^{\infty} e^{-stp \cdot t} U(CV) \quad [7]$$

$$s. t. \dot{w}(t) = YDISP(t) - PCI(t) \cdot CV(t) - PCI(t) \cdot CH(t) \quad [8]$$

where stp is the social time preference / subjective rate of discount. Solving the above problem, the optimal demand for total consumption is derived:

$$CV = CH + \mu \cdot \frac{bh}{PCI} \cdot (YDISP - PCI \cdot CH) \quad [9]$$

μ is a proxy to the marginal propensity to consume $\mu = \frac{stp}{ir}$, and ir is the interest rate. bh is the LES private consumption share parameter. Once the household decides total household consumption it needs to decide over the different consumption by product (PR).

2.1.1.3 Investment

OPEN_GEM is a recursive dynamic model solved sequentially over time. It is assumed that investment taking place in time t increases the production capacity in the following period at time $t+1$. The law of motion of

⁴ See Stone (1954)

capital stock is given by:

$$A_KAVC_{pr,er,t} = (1 - d_{pr,er,t})^{\Delta t} \cdot A_KAVC_{pr,er,t-1} + \frac{1 - (1 - d_{pr,er,t})^{\Delta t}}{d_{pr,er,t}} A_INVP_{pr,er,t} \quad [10]$$

OPEN_GEM is a savings-driven model. Firm's investment is translated into demand for investment goods, which are produced from the rest of the sectors of the economy through the constant coefficient $tinvpv_{pr}$:

$$A_INVP_{pr,er,t} = tinvpv_{pr,er,t} \cdot \frac{exo_investments_{er,t}}{P_INVP_{pr,er,t}} \quad [11]$$

where:

$exo_investments_{er,t}$: exogenous investments $tinvpv_{pr,er,t}$: share of each firm in delivery of investment

$V_INV_{se,er,t}$: investment value by agent

$P_INVP_{pr,er,t}$: price of investment product

2.1.1.4 Government

Government's behaviour (spending) is exogenous to the OPEN_GEM model. Government's final demand by product ($A_GC_{pr,er,t}$) is obtained by applying fixed coefficients ($tgcv_{pr,er,t}$) to the exogenous volume of government consumption ($gctv_{er,t}$):

$$A_GC_{pr,er,t} = gctv_{er,t} \cdot tgcv_{pr,er,t} \quad [12]$$

Exogenous calculation of government consumption is assumed in line with the exogenous targets of the other components of GDP. A set of exogenous assumptions should be included in the Baseline scenario (i.e., technical progress, investments, government consumption, etc.) in line with selected exogenous targets (i.e., investment to GDP, GDP growth, etc.).

The following equation describes all tax revenues and subsidy expenditure of the government disaggregated by government tax/revenue categories:

1. Government revenue from **duties** is the sum of bilateral duty rates for all the imported products adjusted by the price index.

$$V_FGRB_{gv,pr,er,t} = \sum_{cr} txduto_{pr,er,cr,t} \cdot A_IMPO_{pr,er,cr,t} \cdot \frac{WPI_t}{WPI_0} \quad GV=DUT \quad [13]$$

where:

$txduto_{pr,er,cr,t}$: bilateral duty rate

$A_IMPO_{pr,er,cr,t}$: imports in volume

WPI_t : the world price index

WPI_0 : the world price index in the base year

2. Government revenues or expenditures on **taxes less subsidies of production**:

$$V_FGRB_{gv,pr,er,t} = txproduction_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} \cdot A_XD_{pr,er,t} \quad GV=SUB \quad [14]$$

where:

$txproduction_{pr,er,t}$: the taxes less subsidies rate

$A_XD_{pr,er,t}$: production in volume

3. Government revenue **on indirect taxes** is the sum of the respective tax rates multiplied by production, products, households' energy consumption and on firms' energy

$$V_FGRB_{gv,pr,er,t} = txproducts_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} \cdot \left[\sum_{br} (A_IO_{pr,br,er,t}) + A_GC_{pr,er,t} + A_HC_{pr,er,t} + A_INVP_{pr,er,t} \right] \quad GV=IT \quad [15]$$

where:

$txproducts_{pr,er,t}$: the taxes less subsidies on products

$A_IO_{pr,br,er,t}$: IO deliveries between sectors of activities

$A_HC_{pr,er,t}$: the deliveries to private consumption

$A_GC_{pr,er,t}$: deliveries to public consumption by branches

$A_INVP_{pr,er,t}$: the products used in investment deliveries by sector

4. Government revenue on **environmental taxes** includes taxes on firms proportional to their emissions less the endowments from unauctioned permits plus tax revenues from households' environmental tax

$$V_FGRB_{gvb,pr,er,t} = TXENV_{pr,er,t} \cdot EMMBR_{pr,er,t} + TXENVH_{pr,er,t} \cdot A_EMMH_{pr,er,t} \quad GVB= ENV \quad [16]$$

where:

$TXENV_{pr,er,t}$: the environmental tax for firms

$A_EMMBR_{pr,er,t}$: the energy related emissions by branches

$TXENVH_{pr,er,t}$: the environmental tax for household

$A_EMMH_{pr,er,t}$: the energy related emissions for household

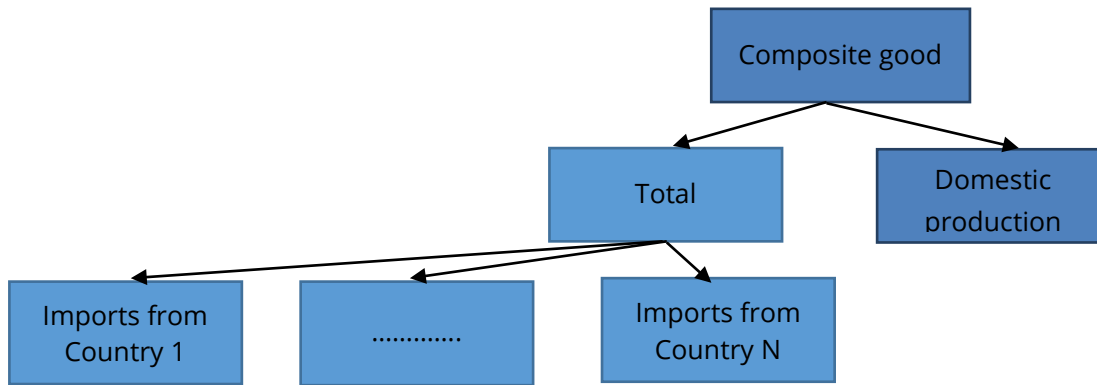
2.1.1.5 External Sector

Firms and households consume a composite good that is composed of an imported part and a domestically produced part. Imported and domestically produced goods are considered as imperfect substitutes (Armington, 1979). The supply decision of a good in the domestic economy is split in two stages:

1. At the first stage, firms decide on the overall imports that they require.
2. At the second stage, firms decide from which countries they will import. They split total import demand decided at stage 1 to regional/country demand.

The import price of each country (destination) is based on the unit cost of production of the supplying country (origin).

Figure 2: Trade decision tree



Firms' cost minimisation problem (for the Imports 1st level) is:

$$\min C_{pr,er,t} = P_{XD_{pr,er,t}} \cdot A_{XXD_{pr,er,t}} + P_{IMP_{pr,er,t}} \cdot A_{IMP_{pr,er,t}} \quad [17]$$

where:

$P_{XD_{pr,er,t}}$: price of domestically produced good

$A_{XXD_{pr,er,t}}$: production for domestic use

$P_{IMP_{pr,er,t}}$: import price

$A_{IMP_{pr,er,t}}$: imports

such that:

$$A_{Y_{pr,er,t}} = AC_{pr,er,t} \cdot \left[\delta_{pr,er,t} \cdot \frac{\frac{\sigma_{x_{pr,er,t}}^{-1}}{A_{XXD_{pr,er,t}}}}{\sigma_{x_{pr,er,t}}^{-1}} + (1 - \delta_{pr,er,t}) \cdot \frac{\frac{\sigma_{x_{pr,er,t}}^{-1}}{A_{IMP_{pr,er,t}}}}{\sigma_{x_{pr,er,t}}^{-1}} \right] \quad [18]$$

where:

$A_{Y_{pr,er,t}}$: composite good

$AC_{pr,er,t}$: scale parameter in the Armington function

$\delta_{pr,er,t}$: share parameter estimated from the base year data related to the value shares of $A_{XXD_{pr,er,t}}$ and $A_{IMP_{pr,er,t}}$ in the demand for composite good $Y_{pr,er,t}$

σ_x : the Armington elasticity between imported and domestically produced goods

The optimal demand for domestic and imported goods is obtained by employing the Shephard's lemma⁵.

$$A_{XXD_{pr,er,t}} = A_{Y_{pr,er,t}} \cdot AC_{pr,er,t}^{\sigma_{x_{pr,er,t}}^{-1}} \cdot (1 - \delta_{pr,er,t})^{\sigma_{x_{pr,er,t}}} \cdot \left(\frac{P_{Y_{pr,er,t}}}{P_{XD_{pr,er,t}}} \right)^{\sigma_{x_{pr,er,t}}} \quad [19]$$

$$A_{IMP_{pr,er,t}} = A_{Y_{pr,er,t}} \cdot AC_{pr,er,t}^{\sigma_{x_{pr,er,t}}^{-1}} \cdot \delta_{pr,er,t}^{\sigma_{x_{pr,er,t}}} \cdot \left(\frac{P_{Y_{pr,er,t}}}{P_{IMP_{pr,er,t}}} \right)^{\sigma_{x_{pr,er,t}}} \quad [20]$$

where:

$A_{IMP_{pr,er,t}}$: the imports by branch

$P_{Y_{pr,er,t}}$: the unit cost for the composite good

⁵ The partial derivative of the cost function with respect to the price of an input gives the conditional demand for that input, holding output constant.

$$P_{Y_{pr,er,t}} = \frac{1}{AC_{pr,er,t}} \cdot \left[\delta_{pr,er,t}^{\sigma_{x,pr,er,t}} \cdot P_{IMP_{pr,er,t}}^{1-\sigma_{x,pr,er,t}} \cdot + (1 - \delta_{pr,er,t})^{\sigma_{x,pr,er,t}} \cdot P_{XD_{pr,er,t}}^{1-\sigma_{x,pr,er,t}} \right]^{\frac{1}{1-\sigma_{x,pr,er,t}}} \quad [21]$$

$$P_{IMP_{pr,er,t}} = \left[\sum_{cr} betashare_{pr,er,cr,t}^{\sigma_{pr,er,t}} \cdot P_{IMPO_{pr,er,cr,t}}^{(1-\sigma_{pr,er,t})} \right]^{\left(\frac{1}{1-\sigma_{pr,er,t}} \right)} \quad [22]$$

where:

$P_{IMP_{pr,er,t}}$: price of total imports

$betashare_{pr,er,cr,t}$: share parameter

$\sigma_{pr,er,t}$: the elasticity of substitution

$P_{IMPO_{pr,er,cr,t}}$: import price of good pr for country er originating from country cr

$$P_{IMPO_{pr,cs,cr,t}} = P_{PWE_{pr,cr,t}} + txduto_{pr,cs,cr,t} \cdot \frac{WPI_t}{WPI_0} + \sum_{itrn} (cif_vtwr_{itrn,pr,cs,t} \cdot P_{TR_{itrn,t}}) \quad [23]$$

where:

$P_{PWE_{pr,cr,t}}$: the export price in international currency

$cif_vtwr_{itrn,pr,cs,t}$: the demand share for transport margins

$P_{TR_{itrn,t}}$: the international transport margin price

2.1.1.6 International transport services

The GTAP Data Base identifies two sets of data as regards to trade:

1. **bilateral trade flows of goods and services** (the representation of which in the OPEN_GEM model is described in the previous section)
2. **supply of international trade margins** (i.e., freight transport services)

The GTAP parameters related to trade are:

Name	Description
VST (mg*,er)	Margin exports
VTWR (mg,pr,er,cr)	Margin usage in facilitation of flow of commodity pr from country er (origin) to country cr (destination)

* mg: air, land, water, Source: McDougal (2006)

The sector that supplies the international transport services (i.e., water, air, and land transport) earns the difference between Cost, Insurance, and Freight (C.I.F.) and Free on Board (F.o.B.) ($\sum_r VST_{j,r}$, the supply of margins). The market clearance conditions for the international market services imply that **the sum across all regions of service exports** equals **the sum of all bilateral trade flows of service inputs** (usage).

$$\sum_r vst_{j,r} = \sum_{i,r,s} vtwr_{j,i,r,s} \quad [24]$$

In the OPEN_GEM model, **the international transport margin price** is determined by the following equation:

$$P_{TR_t} \leq \sum_{er} \left(\theta_{tavst_{er,t}} \cdot \frac{P_{PWE_{pr,er,t}}}{P_{PWE_{pr,er,0}}} \right) \quad [25]$$

where:

$\theta_{tavst_{er,t}}$: measures **the share of each country in total international transport margins** in the base year. The activity level of each type of transport is defined as:

$$A_{YVST_t} \cdot vtag_t \geq \sum_{br,er,cr} (A_{EXPO_{pr,er,cr,t}} \cdot cif_vtwr_{pr,er,cs,t}) \quad [26]$$

where:

$vtag_t$: the output of transport in the international pool in the base year

Exports of transport services are given by:

$$A_{YVTWR_{er,t}} = A_{YVST_t} \cdot vtag_t \cdot \theta_{tavst_{er,t}} \quad [27]$$

The bilateral import price equals the export price of the exporter in case of **tradable services**, while in the case of **merchandise sectors** the bilateral import price is given by the export price plus the **bilateral cif/fob margins**.

$A_{IMPO_{br,cr,cs,t}}$: denotes imports of good pr demanded by country cr from country cs .

$$A_{IMPO_{br,cr,cs,t}} = A_{IMP_{nr,cr,t}} \cdot \left(\text{betashare}_{br,cr,cs,t} \cdot \frac{P_{IMP_{br,cr,t}}}{P_{IMPO_{br,cr,cs,t}}} \right)^{\text{sigma}_{br,cr,t}} \quad [28]$$

and

$$A_{EXPO_{br,cr,cs,t}} = A_{IMPO_{br,cs,cr,t}} \quad [29]$$

2.1.1.7 Prices

Intermediate and final consumers buy the composite good A_Y at the price P_Y plus taxes. Below, we report the different price formulations included in the OPEN_GEM model:

$$P_{IO_{pr,er,t}} = txproducts_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} + P_{Y_{pr,er,t}} \quad [30]$$

$$P_{HC_{pr,er,t}} = txproducts_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} + P_{Y_{pr,er,t}} \quad [31]$$

$$P_{GC_{pr,er,t}} = txproducts_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} + P_{Y_{pr,er,t}} \quad [32]$$

$$P_{INVP_{pr,er,t}} = txproducts_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} + P_{Y_{pr,er,t}} \quad [33]$$

where:

$P_{IO_{pr,er,t}}$: price of intermediate inputs to production

$P_{HC_{pr,er,t}}$: price of deliveries to private consumption by branch

$P_{GC_{pr,er,t}}$: price of delivery to public consumption by branch

$P_{INVP_{pr,er,t}}$: price of delivery to investments by branch

The producer price is given by:

$$P_{XD_{brt,er,t}} = P_{PD_{brt,er,t}} + txproduction_{brt,er,t} \cdot \frac{WPI_t}{WPI_0} \quad [34]$$

$$P_{PWE_{pr,er,t}} = P_{PD_{pr,er,t}} + txproduction_{pr,er,t} \cdot \frac{WPI_t}{WPI_0} \quad [35]$$

where:

$P_{XD_{brt,er,t}}$: the (domestic) supply price addressed to domestic demand

$P_{PWE_{pr,er,t}}$: the (domestic) supply price addressed to exports

$txproduction_{pr,er,t}$: the rate of taxes less subsidies on production

2.1.1.8 Equilibrium

The market clearance equation is:

$$A_{XD}_{pr,er,t} = A_{XXD}_{pr,er,t} + \sum_{cr} A_{EXPO}_{pr,er,cr,t} + A_{YVTWR}_{pr,er,t} \quad [36]$$

Total supply of goods (domestically produced and imported) expended to intermediate consumption, private and public consumption, and investments.

$$A_{Y}_{pr,er,t} = \sum_{br} (A_{IO}_{pr,br,er,t}) + A_{HC}_{pr,er,t} + A_{GC}_{pr,er,t} + A_{INVP}_{pr,er,t} \quad [37]$$

The market clearance equations for capital, which is mobile across sectors but not across regions, are:

$$\sum_{pr} A_{KAV}_{pr,er,t} = \sum_{pr} A_{KAVC}_{pr,er,t-1} \quad [38]$$

where:

$A_{KAVC}_{pr,er,t}$: the total amount of capital stock available, fixed within the time period.

The market clearance equations for labour, which is mobile across sectors but not across regions, are:

$$\sum_{pr} A_{LAV}_{pr,er,t} = TotPopulation_{er,t} \quad [39]$$

where:

$TotPopulation_{er,t}$: the exogenous total population by region

$A_{LAV}_{pr,er,t}$: the labour demand by sector and by region.

2.1.1.9 Environment

The OPEN_GEM environment module includes the CO₂ energy related emissions. A CO₂ reduction policy can be implemented either through the imposition of an exogenous tax or through the introduction of an emission reduction constraint.

From a technical point of view the introduction of an exogenous carbon tax requires:

- i) the activation of the appropriate switches - $swtxexobr(br,er,an)$ for firms or/and $swtxexoh(br,er,an)$ for households
- ii) the assignment of the desired level of carbon tax to the $txem(br,er,an)$ parameter for firms and to $txemh(pr,er,an)$ for households.

In the case where an emission reduction target needs to be introduced the following are required:

- i) switch activation: $swclubbr(br,er,cc,an)$ for firms or/and $swclubh(pr,er,cc,an)$ for households.
- ii) set of the desired target (i.e. imposing an GHG emission cap) in the $supperfeu(cc,an)$ parameter.

The imposition of an exogenous carbon tax or of an emission reduction target (where a carbon price that clears the emission permit market is calculated endogenously) increases the user cost of CO₂ energy related emitting activities. CO₂ energy related emissions of each sector (see [40] for firms and [41] for households) are calculated based on energy consumption (energy related emissions).

$$A_{EMMBR}_{br,er,t} = \sum_{prfuel} bec_{prfuel,br,er,t} \cdot aer_{prfuel,br,er,t} \cdot eaf_{prfuel,br,er,t} \cdot A_{IO}_{prfuel,br,er,t} \quad [40]$$

where:

$A_{EMMBR}_{pr,er,t}$: the GHG emissions by branches

$bec_{prfuel,br,er,t}$: emission factor for energy related CO₂ in the branch level

$aer_{prfuel,br,er,t}$: share of energy consumption with emissions in the branch level

$eaf_{prfuel,br,er,t}$: emission adjustment factor in the branch level

$A_{IO}_{prfuel,br,er,t}$: intermediate demand of fuels in the branch level

$$A_{EMMH}_{prfuel,er,t} = bech_{prfuel,er,t} \cdot aerh_{prfuel,er,t} \cdot A_{HC}_{prfuel,er,t} \quad [41]$$

where:

$A_{EMMH}_{prfuel,er,t}$: the CO₂ energy related emissions of households by product

$bech_{prfuel,er,t}$: emission factor for energy related GHG in households

$aerh_{prfuel,er,t}$: share of energy consumption with emissions in households

$A_{HC}_{prfuel,er,t}$: household energy demand

The respective equation for the total demand of emission permits (firms and household) is given below:

$$DEMPEREU_{cc,t} = \sum_{er,br} (A_{EMMBR}_{br,er,t} \cdot swclubbr_{br,er,cc,t}) + \sum_{er,br} (A_{EMMH}_{br,er,t} \cdot swclubh_{br,er,cc,t}) \quad [42]$$

where:

$swclubbr_{br,er,cc,t}$: switch for permit market participation for sectors

$swclubh_{br,er,cc,t}$: switch for permit market participation for households

The market clearance of the emission permit market results in $P_{PCLUBAG}_{cc,t}$ or else in the price of emission permits. The equations below describe the market clearance.

$$superfeuc_{cc,t} \geq DEMPEREU_{cc,t} \quad \begin{array}{l} \text{dual variable} \\ P_{PCLUBAG}_{cc,t} \end{array} \quad [43]$$

where:

$superfeuc_{cc,t}$: supply of permits (user defined)

In OPEN_GEM, the exogenous carbon tax (see [45], [47]) or the endogenous carbon price (see [44], [46]) have been assigned in the $TXENV(br,er,an)$ variable for firms and in the $TXENVH(br,er,an)$ for households.

$$TXENV_{br,er,t} = \sum_{cc} P_{PCLUBAG}_{cc,t} \cdot swclubbr_{br,er,cc,t} \quad [44]$$

$$TXENV_{br,er,t} = txem_{br,er,t} \cdot swtxexobr_{br,er,t} \quad [45]$$

$$TXENVH_{br,er,t} = \sum_{cc} P_{PCLUBAG}_{cc,t} \cdot swclubh_{br,er,cc,t} \quad [46]$$

$$TXENVH_{br,er,t} = txemh_{br,er,t} \cdot swtxexoh_{br,er,t} \quad [47]$$

The price signal in firms and households to abate emissions has been modelled to cover the energy related (CO₂) emissions by the combustion of fossil fuels. The carbon tax or the carbon price is added in the unit cost of energy which are used in firm's production [48] or in household's consumption [49].

$$P_{ENPR}_{prfuel,br,er,t} = P_{IO}_{prfuel,br,er,t} + TXENV_{br,er,t} \cdot bec_{prfuel,br,er,t} \cdot aer_{prfuel,br,er,t} \cdot eaf_{prfuel,br,er,t} \quad [48]$$

$$P_{HC}_{br,er,t} = txproducts_{br,er,t} \cdot \frac{WPI_t}{WPI_0} + P_{Y}_{br,er,t} + TXENVH_{br,er,t} \cdot bech_{br,er,t} \cdot aerh_{br,er,t} \quad [49]$$

where:

$P_{ENPR}_{prfuel,br,er,t}$: the unit cost of energy including abatement cost in the branch level

$P_{IO_{prfuel,br,er,t}}$: the unit cost of energy excluding abatement cost in the branch level

$P_{HC_{br,er,t}}$: the unit cost of consumption by product including abatement cost in households

2.1.1.10 Macroeconomic Closure

Each economic agent (firms, households, government, world) has savings that are used to finance investments. At the global level, total savings should be equal to total investments.

$$\sum_{se,r} V_{SAVE_{se,r,t}} = \sum_{se,r} V_{INV_{se,r,t}} \perp r_{tlrworld}_t$$

This equation determines a global interest rate, set so as to equalise global investment with global surpluses. In particular, the dual variable of this equation, the $r_{tlrworld}_t$, is used to increase/decrease the household consumption and thus decrease/increase the household savings for the equation to be met.

2.2 Data (inputs and outputs)

2.2.1 Inputs

For the calibration of OPEN_GEM, the Global Trade Analysis Project (GTAP) Data Base is used. The latest version of the GTAP Data Base v11 covers the whole world, aggregated into 65 activities and 160 countries, in the years 2004, 2007, 2011, 2014, and 2017. OPEN_GEM focuses on key energy intensive industrial sectors and uses the latest GTAP Circular Economy Data Base v11 that contains detailed representation of primary, secondary, and recycling activities for metals (steel, aluminium, copper, etc.) plastics, and non-metallic minerals. It provides full coverage of economic, bilateral trade, energy, and environmental accounts in a consistent multi-sectorial framework. The calibration of the model is based on the most recent year, for which a fully detailed dataset is available—the year 2017.

Finally, the elasticities used in the OPEN_GEM model are extracted from the GTAP Data Base: the Armington (trade) elasticities and the elasticities of substitution in production. The GTAP Data Base is a source of trade elasticities at two levels: i) domestic/Imported and ii) between different countries. These elasticities are provided for each commodity included in the GTAP Data Base. Elasticities differ among sectors, but values for each sector are identical for all countries/regions. Econometric estimates by sector and by country are not common in the literature as there are data limitations and resulting estimates might be highly volatile. Elasticities of substitution in production are based on GTAP and the CES nesting scheme.

2.2.2 Outputs

The main outputs of the model are quantities in monetary value measured in billion \$ base year values 2017:

- **Macroeconomic Aggregates:** GDP, Household consumption, Investments, Government expenditures, Imports, Exports by country / region
- **Sectorial results:** Production, Exports, Imports

3 Novelty or benefits of the module

OPEN_GEM is an open-source model that has a detailed representation on circular economy in key energy-intensive sectors. It is based on the most recent data from the GTAP Data Base and can be used to simulate and analyse policies related to the circular economy. The model features resource extraction sectors, primary and secondary supply of materials, and associated recycling activities. It can simulate policies that can facilitate the use of materials from secondary markets, material taxation, production structure rationalisation (material efficiency through better designs), and product lifetime extension through adjustment of the recycling rate⁶.

The detailed sectoral coverage on the circular economy allows a soft-link with industry-based models that have a more detailed representation of different technologies and the emissions mitigation options that can be applied in climate mitigation scenarios. OPEN_GEM can retrieve such information via a soft-link with the industry-based models within TRANSIENCE to re-calibrate the production process of the sectors, to align with the substitution possibilities that are represented in the industry-based modes.

OPEN_GEM provides projections on sectoral production within a model framework that considers the interlinkages among sectors and countries via the structure of the input-output tables and the bilateral trade. This model can be used to show how climate and energy policies can drive material efficiency/recycling and what the associated economic and employment impacts are. In particular, through its explicit representation of primary and secondary markets, the model adds additional flexibility regarding the options that industries have to improve their energy and carbon intensities. The model can simulate different enabling conditions including material taxes and other taxes and examine the economic efficiency of alternative fiscal policies.

⁶ The current version does not feature stock of durable goods. This extension can take place according to data availability.

4 Integration in MIC3/ Module linkages

4.1 Placement within MIC3

OPEN_GEM will be integrated with the product and service (P&S) database (see D4.2) to receive inputs regarding the production structure, the unit cost of production, and the different technologies on the key energy-intensive sectors from the industry-based models. OPEN_GEM will feed the P&S database with projections regarding GDP, population, and sectoral production. Figure 3 shows the planned interfaces in the MIC3 baseline workflow as presented in D3.4.

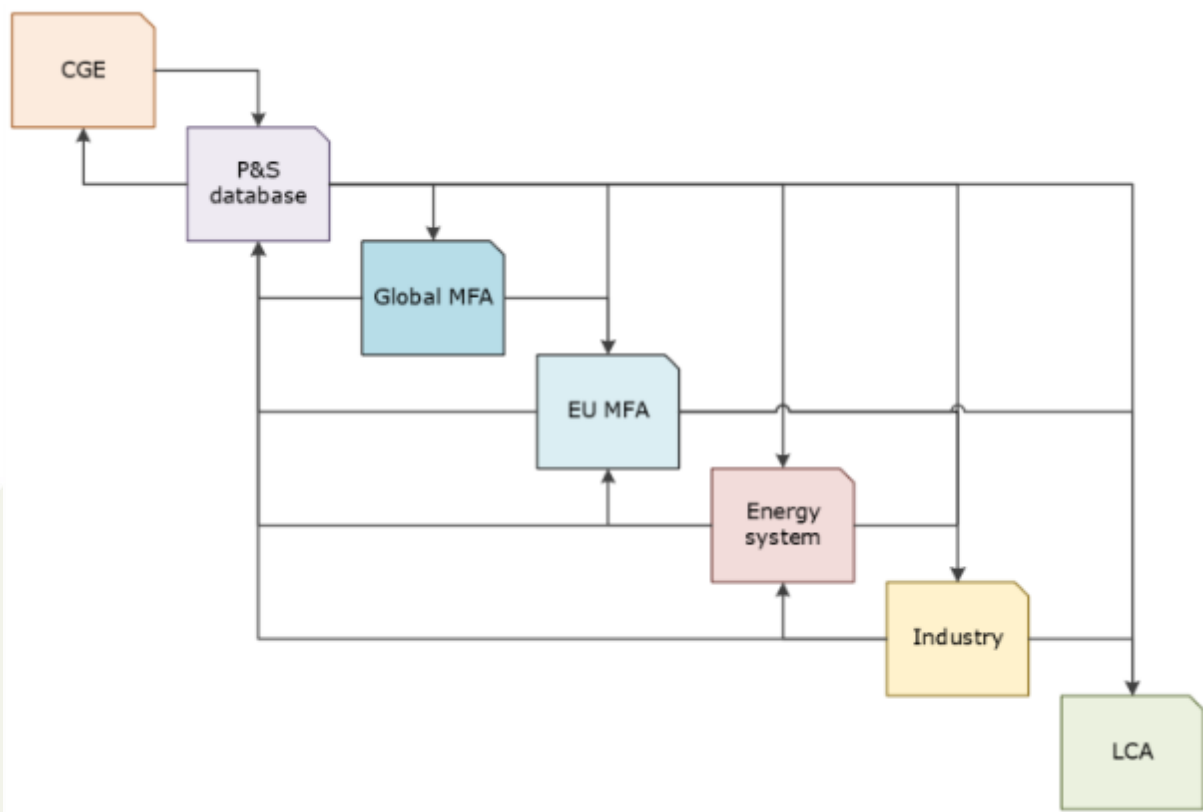


Figure 3: Planned interfaces in the MIC3 baseline workflow from D3.4

4.2 Further developments

In the next phase, the soft links and the integration with the industry-based models will be explicitly determined and finalised. OPEN_GEM will benefit from using as exogenous inputs key outputs of the industry-based models in key industrial sectors (i.e., cement, iron & steel, aluminium, etc.). More specifically, these include the different technologies by sector, the cost structure by different technology, and the adoption of each technology by sector.

ANNEX

- Link to repository: <https://github.com/e3modelling/OPEN-GEM>.
- Link to dataset: [GTAP Data Bases: GTAP 11 Data Base](#) (*GTAP Circular Economy Data Base*)