ENhancing our understanding of Trade Impacts on Climate, industries, and the Environment

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D3.2 – Progress in model improvements

WP3 – Extend and improve the modelling of trade and its environmental impacts

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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

Internal use for management and work organisation.

3. Short summary of results (<250 words)

This deliverable reports the mid-term progress under the ENTICE project's WP3 tasks on extending and improving the modelling of trade and its environmental impacts, following the roadmap established in deliverable D3.1. Work has advanced along five lines. Task 3.2 formalised a generic, accounting-consistent methodology to split input–output data and structures and integrate new sectors (e.g., emissions-intensive industries, clean-tech manufacturing, and critical materials), with implementation to scale up once datasets developed in WP2 are finalised. Task 3.3 completed Step 1 on integrating New Trade Theory by delivering a unified Armington–Krugman–Melitz framework and a GTAP-based GAMS calibration toolkit with closed-form solutions for key fixed costs; next steps focus on proof-of-concept implementation in selected large-scale models and partner guidance. Task 3.4 has extended R&D data series, and is currently constructing knowledge-spillover matrices using different proxies (GMRIO-, patent- and FDI-based), alongside two modelling templates: a transferable R&D/knowledge-stock framework and a directed technological change proof of concept with endogenous market structure and vertical energy linkages; next steps target an internal dataset release by early autumn 2026 and multi-regional extensions. Task 3.5 translated this ambition into an operational roadmap, clarifying alignment requirements, exchange variables, and coupling options, with initial one-way soft-link tests planned. Task 3.6 defined lookup-table and CGE-prototype integration routes for AFOLU emissions and initiated an updated land-cover baseline and transition matrix to support LULUCF and biodiversity indicators.

4. Evidence of accomplishment

This report.

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Preface

In today's interconnected global economy, understanding the trade-climate nexus is more critical than ever. Trade policies significantly influence environmental outcomes, while climate change affects trade flows. However, the complex relationship between these areas remains insufficiently explored, often due to data limitations, gaps in economic modeling and the evolving nature of global supply chains. The ENTICE project aims to bridge these knowledge gaps by advancing our understanding of the trade-climate-industry (TCI) nexus. It examines how trade policies impact environmental sustainability and how climate policies shape global trade dynamics. By developing fact-based insights and innovative modeling tools, ENTICE supports informed decision-making at this crucial intersection of trade, climate, and sustainability.

E3M – E3-MODELLING AE	EL	
CMCC – FONDAZIONE CENTRO EURO-MEDITERRANEOSUI CAMBIAMENTI CLIMATICI	IT	
WI – WUPPERTAL INSTITUT FUR KLIMA, UMWELT, ENERGIE GGMBH	DE	
REFORM – FUNDACJA INSTYTUT REFORM	PL	
VUA – STICHTING VU	NL	
HOL – HOLISTIC IKE	EL	
ENEXTGEN – ENEXTGEN S.R.L.	IT	
UoS – UNIVERSITY OF SOUTHAMPTON	UK	
UNIVR – UNIVERSITA DEGLI STUDI DI VERONA	IT	
SEURECO – SEURECO SOCIETE EUROPEENNE D'ECONOMIE SARL	FR	
ICCS – EREVNITIKO PANEPISTIMIAKO INSTITOUTO SYSTIMATON EPIKOINONION KAI YPOLOGISTON	EL	
POLIMI – POLITECNICO DI MILANO	IT	
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ZEW – LEIBNIZ-ZENTRUM FUR EUROPAISCHE WIRTSCHAFTSFORSCHUNG GMBH MANNHEIM	DE	
UU – UNIVERSITEIT UTRECHT	NL	
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Executive Summary

This deliverable (D3.2) provides a mid-term progress update on WP3 ("Extend and improve the modelling of trade and its environmental impacts") of the ENTICE project. Building on the timeline set out in D3.1, it reports methodological and modelling advances achieved since October 2025 and describes the next implementation steps across the five WP3 improvement axes: enhanced sectoral disaggregation (Task 3.2), new trade-theory integration (Task 3.3), technological change modelling (Task 3.4), linking with physical material-flow modelling (Task 3.5), and land-use/environmental indicator extensions (Task 3.6).

- Task 3.2: a generic methodology for consistent sector splitting of macroeconomic/computable general equilibrium (CGE) input–output structures was formalised (illustrated with GEM-E3), including guidance on how new sectors connect to investment, intermediate demand, household consumption, and trade. The next phase shifts to cross-model coordination and first implementations once datasets currently being developed in WP2 are available.
- Task 3.3: Step 1 was completed, delivering a unified analytical framework comparing Armington, Krugman, and Melitz trade modelling structures and an operational GTAP-based calibration toolkit (GAMS), including closed-form solutions for key fixed costs; the next step is proof-of-concept implementation in selected consortium models and partner guidance (Steps 2–3).
- Task 3.4: progress combined a consolidated review of technological-change representations with substantial advances on data and modelling: research and development (R&D) data series were extended and alternative proxies for knowledge spillovers were initiated (based on Global Multi-Regional Input-Output (GMRIO), patents, foreign direct investment (FDI)), alongside a transferable R&D/knowledge-stock framework and a directed technological change (DTC) proof of concept. Upcoming work focuses on finalising spillover proxies, sharing a first dataset by early autumn 2026, and extending the DTC model to a multi-regional setting.
- Task 3.5: the model-linking problem with DYNERIO was translated into an operational roadmap, clarifying alignment requirements, exchange-variable candidates, and coupling options. Near-term priorities are concordance matrices aligned with WP2 developments and first one-way soft-link tests.
- Task 3.6: two implementation pathways were structured (lookup-table/response curves based on the GLOBIOM model vs. a CGE prototype route), and empirical work started to update the land-cover baseline and to define a land-transition matrix to support the integration of LULUCF and biodiversity indicators in the ENTICE models. Next steps include integrating the updated baseline into GLOBIOM and running initial response-curve simulations.

Overall, implementation remains aligned with the work plan and timeline set out in D3.1 ("Mapping of model improvements: what, why, how"), with progress differing across tasks depending on their dependence on WP2 data developments. Consortium coordination is ensured through regular WP3 meetings and targeted technical workshops to support the transition from conceptual design to model-specific implementation. Particular attention will be paid to ensuring that the work carried out in WP3 is shared across the consortium and remains usable for WP4 and WP5 through shared data, documentation, and consortium-wide meetings, and, once the research activities are finalised, beyond the consortium through open-access dissemination and public repositories (e.g. Zenodo, GitHub, and the I^{2}AM Paris platform).

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1 Introduction

Structural macroeconomic models[1] have long been used to assess the impacts of trade, particularly trade liberalisation, and especially for agricultural products (Hertel, 1996). However, the current state of the art in macroeconomic and computable general equilibrium (CGE) modelling—especially the large-scale models commonly used for policy impact assessment—still face important limitations when analysing policies in the context of the trade–climate–industry (TCI) nexus. Deliverable D1.4 “Modelling Research Needs” highlights several persistent gaps in TCI modelling, despite recent theoretical advances:

- Trade modelling still relies almost exclusively on the Armington assumption, which restricts the representation of firm heterogeneity, productivity effects, and trade dynamics. While modern trade theories and frameworks (e.g., Melitz-type models) provide more realistic mechanisms, they remain difficult to implement in large-scale models because of computational and data constraints.
- Endogenous technical change mechanisms (e.g. learning-by-doing, R&D, spillovers) are increasingly incorporated, particularly in energy sectors, but application remains partial and raise challenges related to consistency with CGE structures, parameter uncertainty, and non-linear dynamics.
- Additional structural gaps persist: international transport is still poorly integrated with trade dynamics; material flows are insufficiently detailed in input-output-based models; and assessment capacity is often limited by insufficient sectoral modelling details.

To address these limitations, WP3 seeks to strengthen modelling capabilities along five complementary lines. First, it widens sectoral coverage of the macroeconomic models, notably by refining the representation of emissions-intensive activities and of manufacturing sectors producing clean-energy technologies (Task 3.2). Second, it upgrades the trade module itself (Task 3.3). Building on advances in New Trade Theory and subsequent intra-industry trade approaches, ENTICE will develop a general methodology to embed these mechanisms in large-scale models, ranging from simple, broadly transferable implementations to more detailed and advanced options. Third, WP3 improves the treatment of technological progress in large-scale models, an essential element of the TCI nexus to capture the “technique effect”, alongside the “scale” and “composition” channels commonly used to analyse the trade–environment relationship (Task 3.4). Fourth, it will produce a proof of concept that links large-scale macroeconomic models to a physical input–output modelling tool (Task 3.5). Finally, it will enhance the ability of models to represent agricultural and land-use greenhouse gas emissions and to assess the environmental and biodiversity consequences of trade, climate, and industrial policies by developing and integrating additional environmental indicators beyond GHG emissions and energy use (Task 3.6).

These tasks started in October 2025, and a detailed work plan has been established (see Deliverable D3.1, “Mapping of model improvements: what, why, how”). This work plan builds on (*i*) a model survey conducted in June 2025, which compiled information on the current state of the ENTICE model ensemble (geographical and sectoral coverage, mitigation options, policy-assessment capacity, etc.) and on teams’ expectations

[1] In this document, “structural”, “large-scale”, or simply “macroeconomic” models refer to multi-regional, multi-sector economic models, including computable general equilibrium models as well as other macroeconomic models such as macroeconometric ones.

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regarding model improvements, and (*ii*) a series of internal workshops held in September and October 2025, which enabled task leaders to propose and discuss an initial work plan with the modelling teams. In this context, the present document provides a task-by-task overview of progress since December 2025, serving as a progress report eight months after the start of the model-improvement activities and one year ahead of their finalisation.

2 Sector disaggregation (Task 3.2)

2.1 Objectives

Task 3.2 aims to enhance the sectoral representation of macroeconomic models by means of more detailed representation of key industries and integrating new datasets developed in WP2. The main objectives are:

- To define and implement new sectoral disaggregation in macroeconomic models, focusing on energy-intensive industries (e.g., steel, cement, chemicals), clean technology manufacturing (e.g., solar photovoltaic (PV), wind, batteries, electric vehicles (EVs), electrolysers), and critical materials (e.g., lithium, copper).
- To integrate the related disaggregated datasets from WP2 (e.g., an extended GTAP database and input–output splits) into macroeconomic modelling frameworks.
- To support the inclusion of additional modelling dimensions, such as land use and international transport based on WP2 data developments.
- To develop generic methodological guidelines to support consistent sectoral disaggregation across models.

2.2 Progress

Since the official start of Task 3.2 in October 2025 work has focused on developing the methodological and conceptual framework required for sectoral disaggregation, taking into account the anticipated outputs of WP2. At this stage, activities have been primarily exploratory and preparatory, using the GEM-E3 model as a reference framework, and aimed at defining how disaggregation will be implemented in macroeconomic models once the relevant data becomes available. GEM-E3 was selected as a reference framework due to its prior experience in incorporating explicitly represented non-standard sectors beyond the standard GTAP structure, including batteries, EV transport equipment, renewable energy equipment, hydrogen, electrolysers, CCS-related technologies, and advanced energy appliances. This experience provides a useful basis for developing broader implementation guidance across models.

A general approach for representing disaggregated sectors within macroeconomic models has been developed, drawing on existing practices in computable general equilibrium (CGE) and macroeconomic modelling. The work in Task 3.2 focuses on how newly defined sectors can be consistently represented within macroeconomic models once the disaggregated datasets from WP2 become available. In this context, the work has concentrated on identifying how new sectors can be linked to existing production, demand, investment, and trade structures while maintaining accounting consistency and preserving macroeconomic interactions within the models. At this stage, the work focuses on formalising the methodological approach in preparation for the future integration of WP2 datasets.

A key component of the work has been to define how newly introduced sectors will be represented within macroeconomic models from an economic perspective. This includes specifying production structures in terms of input intensities (capital, labour, energy, and materials) and ensuring consistency with existing model equations and accounting identities. Different possible modelling approaches are currently being explored, depending on sector characteristics, model structure, and data availability. These range from relatively simple Leontief-type representations to more flexible CES-based structures and, where relevant,

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more bottom-up or technology-detailed approaches. Particular attention is being given to sectors where technological differentiation and substitution possibilities may play an important role, such as batteries, hydrogen technologies, and differentiated steel production routes. In line with the structure of macroeconomic models, newly introduced sectors are expected to follow existing model equations, ensuring that prices, output, trade, and employment remain endogenously determined and that macroeconomic feedbacks (i.e. via capital, labour and product markets) are preserved.

An important outcome of the preparatory work has been the identification of different channels through which new sectors enter the economy, depending on their characteristics. Four main channels have been defined:

- Investment demand, which is particularly relevant for clean technology manufacturing sectors (e.g., solar PV, wind turbines, hydrogen equipment), where demand is driven by capital formation and deployment of new technologies.
- Intermediate demand, where sectors provide inputs to other industries (e.g., steel, cement, critical materials).
- Household consumption, where relevant, through the consumption matrix[2] and demand by purpose.
- Trade, reflecting the role of sectors in international supply chains and bilateral trade flows.

The integration of new sectors is expected to differ across sectors and models according to their economic role, data availability, and analytical focus. The proposed approach therefore provides guidance on how new sectors can be linked to different demand channels, production structures, and trade linkages. Further implementation guidance will be developed and consolidated as part of Deliverable D3.3 ("Extending sectoral coverage"), due in June 2027.

Illustrative examples have been developed, based on the GEM-E3 model (Capros et al., 2017), to demonstrate how enhanced sectoral disaggregation can be implemented in practice. These examples outline how new sectors can be integrated within modelling frameworks, how their production structures can be specified based on input intensities, and how their interaction with the rest of the economy can be represented through different demand channels. In particular, the examples demonstrate how demand for specific technologies can be linked to sectoral activity (e.g., equipment demand driven by energy system investments), as well as how disaggregation improves the representation of international trade flows for specific products. These examples are intended to serve as templates for future implementation across models.

Interaction with project partners has so far taken place through presentations in project meetings and WP-specific online meetings, where the proposed methodological framework and illustrative examples have been shared. These exchanges have been used to gather initial feedback and prepare for the next phase of the task, which will involve more structured collaboration with modelling teams.

[2] Where consumption data are available, Task 3.2 will provide guidance on how such matrices can be linked to newly defined sectors within macroeconomic models, building on existing data sources (e.g. Eurostat).

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2.3 Next steps

The next phase of Task 3.2 will focus on implementation in the participating macroeconomic modelling frameworks (NEMESIS EU, NEMESIS World, ICES, ZEW Model, DYNERIO, LBAM, GEM-E3, GTAP, FIDELIO, GLOBIOM, OPEN-PROM, IMAGE, GEMINI-E3, SORMAC-25, and ENVISAGE), coordination across modelling teams, and further development of methodological guidance. In the short term (mid-2026), an Excel-based survey will be circulated to modelling teams to identify sectoral priorities and planned integration in each model. Based on this, a cross-model integration matrix will be developed, mapping which sectors will be implemented and at what level of detail. Coordination meetings will also be organised to align modelling approaches and discuss key methodological choices.

Between July and December 2026, modelling teams will begin working on the integration of selected new sectors within their respective modelling frameworks, according to model capabilities, sectoral priorities, and analytical focus. This work will be carried out in coordination with the GEM-E3 team, which will support the process through the development of methodological guidance, illustrative examples, and discussions on possible implementation approaches, including production structures, demand linkages, and sector-specific modelling assumptions. Different modelling teams are expected to focus on different groups of sectors, allowing teams with relevant expertise and modelling focus to lead the development and testing of sector-specific implementation approaches within the consortium.

At the same time, methodological guidance will be further elaborated, including approaches for representing new sectors within macroeconomic models, linking them to different demand components, and incorporating WP2 bottom-up data. Work will also continue on sector-specific modelling assumptions and parameters, where relevant. A first set of methodological guidelines and implementation examples will be finalised by the end of 2026, in line with the timeline defined in D3.1.

In the final phase (up to April 2027), the focus will be on completing, refining, and consolidating the integration of new sectors across participating models, taking into account model-specific capabilities and implementation approaches. The resulting methodological guidelines and implementation approaches will subsequently feed into and be documented in Deliverable D3.3 (“Extending sectoral coverage”), due in June 2027, which will report on the extended sectoral coverage and its application across the participating modelling frameworks.

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3 Integrating new trade theories into large-scale macroeconomic models (Task 3.3)

3.1 Objectives

Task 3.3 contributes to the overall ambition of WP3 by improving the representation of international trade within large-scale macroeconomic models used for policy analysis in the Trade–Climate–Industry (TCI) nexus (see Deliverable D1.2 "TCI framework and synthesis of cocreation results"). The task specifically aims to:

- Move beyond the standard Armington specification of bilateral trade by incorporating modern trade theory mechanisms, namely monopolistic competition, firm entry/exit and firm heterogeneity;
- Enable models to capture productivity selection effects, scale economies, and gains from variety, which are critical for assessing trade, industrial, and climate policies;
- Provide a robust, transparent, and implementable calibration strategy for Melitz-type models compatible with widely used datasets (e.g., GTAP);
- Ensure that these enhancements remain computationally tractable and scalable, facilitating their adoption across the diverse ENTICE modelling teams (and beyond).

By doing so, Task 3.3 strengthens the capacity of models to assess the economic impact of policies such as carbon border adjustment mechanisms and other industrial and trade-related climate policies.

3.2 Progress

By April 2026, the team has successfully delivered the first milestone (Step 1) that lays out an analytical and computational framework comparing alternative trade modelling specifications and develops a practical and complete calibration strategy. Specifically, we delivered internally[3]:

- A paper containing full model derivations and the description of a novel calibration approach for models à la Melitz. The paper includes the derivations for the three trade-theory models (Armington, Krugman and Melitz) with a comparison in terms of equations and variables as well as, for the Melitz version, a calibration protocol for the model in levels. Finally, it also shows how to transform the model from levels to hat-algebra[4].
- Files including: (*i*) the GAMS code used to calibrate Melitz using GTAP-based data, (*ii*) the GDX file containing the GTAP data, (*iii*) the GAMS code in PDF, and (*iv*) a readme file explaining what we do with the code.

In the paper, we construct a unified multi-country, multi-sector, albeit stylised, CGE model to provide a systematic comparison between three trade modelling paradigms:

- Armington (perfect competition with homogeneous firms), the current workhorse trade structure in

[3] The documents have been shared internally with the consortium through the SharePoint repository.

[4] *Hat algebra* means that the model is expressed in deviations from an equilibrium rather than in absolute levels; it usually reduces parameter calibration and estimation requirements (see Arkolakis et al., 2012).

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large-scale CGE models;

- Krugman (monopolistic competition with endogenous firm entry/exit and *homogeneous* firms);
- Melitz (monopolistic competition with endogenous firm entry/exit and *heterogeneous* firms).

This comparison explicitly identifies the additional equations and variables required when moving from Armington to richer trade structures as well as the implications for model dimensionality and data and calibration requirements. This step is essential to ensure consistency and comparability across modelling approaches, facilitating adoption by different modelling teams within and beyond ENTICE. All three model versions have been fully derived from first principles. Importantly, the version with firm heterogeneity has been derived following the full Melitz specification where firm heterogeneity is introduced through productivity draws, endogenous selection mechanisms determine market participation, and equilibrium conditions are expressed solely in terms of aggregate variables.

A major advancement of Step 1 is the development of a novel calibration strategy, addressing a central limitation in the literature. While Melitz (2003) leaves the distribution of firm productivity unspecified, it has become standard, following Chaney (2008), in quantitative trade models to assume that productivity is Pareto distributed[5]. This assumption is also adopted in Balistreri et al. (2011), a key reference for integrating Melitz-type features into CGE models. When combined with a formulation in terms of gross changes, the Pareto assumption greatly simplifies the calibration procedure, as shown for example in Breinlich & Cuñat (2016), and as we also demonstrate in the final section of the paper. However, this simplification does not carry over when the model is expressed in levels, as is standard in large-scale CGE models. A key challenge concerns the calibration of fixed entry, production and export costs, which are not directly observable. The approach in Balistreri et al. (2011) involves solving the full CGE model iteratively to recover these costs so as to match observed trade flows. This procedure is computationally demanding and difficult to scale to large applied models commonly used for policy analysis, including those in ENTICE. Our main contribution is to build on Campolmi et al. (2025) by showing how to rewrite the model in terms of observable sales shares. This reformulation allows us to derive closed-form solutions for the calibration of the fixed production, export and entry costs. By eliminating the need for iterative numerical procedures that require repeatedly solving the full large-scale model, our approach significantly improves computational efficiency and makes the framework readily applicable to large-scale CGE models, thereby overcoming a major practical limitation. Finally, the trade model has also been reformulated using hat algebra, allowing it to be expressed in terms of gross changes and to reduce the calibration requirements even more. This is important, since a few ENTICE models are formulated in hat algebra, while most are in levels. As clarified at the beginning, calibration is implemented using GTAP-based data in GAMS, and the corresponding code has been shared with all teams.

Overall, the work done so far has placed strong emphasis on calibration feasibility and implementation, addressing known modelling constraints: closed-form solutions allow a direct calibration of the key parameters (most importantly fixed entry, production and export costs). It has also focused on advancing the development of a GAMS-based calibration toolkit earlier than initially planned. These achievements

[5] The Pareto distribution is a probability distribution in the form of a power law. It is widely known for modelling phenomena where a small proportion of occurrences account for the majority of the effect.

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directly address the key barriers identified in Deliverable D3.1 regarding the integration of New Trade Theories into large-scale macroeconomic models.

3.3 Next steps

The next phase of Task 3.3 will focus on implementation and integration into the consortium models, i.e., Step 2 and 3 as indicated in Deliverable D3.1. Specifically, the main planned activities are:

- Step 1 - Development of an enriched model incorporating Melitz-type mechanisms
- Step 2 - Implementation of a proof-of-concept model within a selected CGE framework
- Step 3 - Provision of model-specific guidance to partners
- Preparation of Deliverable D3.4 ("Integrating new trade theories", M30)

These steps will ensure that the theoretical and methodological advances achieved so far are translated into operational modelling improvements. We plan on completing Step 2 by end of September 2026. The resulting method, including its code and documentation, will be made available beyond the consortium as open source, following the completion of the research activities and the open-access scientific publications.

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4 Technological change modelling (Task 3.4)

4.1 Objectives

Task 3.4 aims to strengthen the modelling of technological change in macroeconomic models and to deliver a robust assessment of the technique effect in policy analysis within the TCI nexus (together with the scenario analysis of WP4 and WP5). To this end, the task reviews how technological change is represented in macroeconomic models and integrated assessment models (IAMs), identifies existing approaches to modelling endogenous technological change, proposes a general approach that can be implemented across a wide range of macroeconomic models, and develops alternative approaches. To meet these objectives, the work is organised around three main pillars. The first pillar focuses on collecting, completing, and analysing the data needed to quantify R&D investment, R&D and knowledge stocks, and spillover effects. The other two pillars develop complementary modelling approaches to represent technological change in large-scale models, reflecting the diversity of possible endogenization mechanisms: one based on R&D-driven processes augmented by knowledge spillovers, and the other grounded in the DTC framework.

4.2 Progress

4.2.1 Technological change in macroeconomic and climate-economy models

As a first step, a review of model improvement requirements and existing modelling approaches was carried out, building on the work completed in Deliverable D1.4 "Modelling Research Needs" that summarises how macroeconomic, integrated assessment models, and other types of models treat the technological change.

Table 1: Technological change in a large range of macroeconomic and climate-economy models

Model types	Total number of models inventoried	Number of models with exogeneous technological change	Number of models with endogenous technological change[1]				
			LbD	LbR	Knowledge spillovers	DTC	Other
Computable General Equilibrium	23	20	2	1	2	1	--
Macro-econometric models	3	0	1	1	1		1
Integrated Assessment model	25	20	4	2	2	1	1
Land use-oriented models	5	4		1			
Dynamic Input-Output	2	2					
Energy system models	27	23	4	2			
Other models	11	8	1	1			1

[1]: Models can implement several endogenous technological change mechanisms; LbD: Learning-by-Doing; LbR:-Learning-by-Researching; DTC: Directed Technological Change.

Source: ENTICE D1.4 – Modelling Research Needs (Trachanas et al., 2026).

A large majority of the models reviewed keep technology change as exogenous. However modern approaches typically link productivity improvements to mechanisms such as R&D investment, learning effects from cumulative production, and economies of scale. Deliverable D1.4 identifies two dominant approaches for modelling endogenous technological change. First, learning-based mechanisms link technology performance or costs to accumulated experience (for example, through greater deployment and use of a technology)—this is called learning-by-doing (LbD). Second, R&D-based mechanisms treat knowledge as a capital-like stock built through deliberate research investments, which then raises productivity—this is called learning-by-researching (LbR). These approaches are widely used because they are conceptually straightforward and can be calibrated with empirical evidence. Other, less common approaches include mechanisms, where relative prices influence the direction of efficiency improvements, and "backstop" technologies, whose adoption responds to prices while their underlying characteristics remain largely fixed. The literature also stresses the importance of spillovers and technology diffusion, where innovation in one sector or region can raise productivity (or reduce technology costs) elsewhere through channels like trade and investment, and of DTC, where policy and incentives steer innovation toward particular technologies or inputs. In practice, large-scale models may combine several of these mechanisms to capture multiple drivers of technological progress.

Among the 14 models involved in ENTICE, six incorporate endogenous technological change mechanisms: ENVISAGE, GEM-E3, IMAGE, NEMESIS-EU, OPEN-PROM, and the ZEW model. In ENVISAGE, GEM-E3 and NEMESIS-EU, technological change is primarily modelled through LbR. The specific implementations, however, differ markedly. In GEM-E3[6], innovation is additionally driven by human capital and can be combined with LbD (Fragkiadakis et al., 2019). In NEMESIS-EU[7], private and public R&D investments complement other innovative assets, including ICT and other intangibles, notably learning and software (Boitier et al., 2022). In ENVISAGE, knowledge stocks originate from past R&D investment and depreciate over time (van der Mensbrugghe, 2024); a similar logic applies in GEM-E3 and NEMESIS-EU, but with the addition of inter-region and inter-sector knowledge spillovers. Moreover, R&D investment decisions can be endogenous in GEM-E3 and NEMESIS-EU, reflecting expected private returns to research, whereas they are typically set as a fixed share of GDP in ENVISAGE. Finally, knowledge accumulation improves labour productivity in ENVISAGE, while it raises total factor productivity in GEM-E3 and NEMESIS-EU. The ZEW model, by contrast, is built around a fully specified DTC framework with endogenous market structure and vertical linkages (see below for details). In IMAGE, OPEN-PROM, and GEM-E3, LbD is implemented such that technology deployment reduces costs through experience and economies of scale, typically via learning curves linking cumulative installed capacity to an efficiency parameter calibrated from the literature or using empirical data. In addition, IMAGE includes spillovers across regions and sectors through technology trade.

4.2.2 Data collection and processing

The first pillar of the task is the collection and processing of a dataset measuring the knowledge spillovers. This work starts with the collection and completion of data on R&D investments. Le Mouël et al. (2025)[8] provide a first set of data on R&D investment by region (45 countries), economic activity (25 manufacturing industries and the computer programming service sector), and technology (37 digital and green technologies) from 2000 and 2021 (see Figure 1 for illustration). In 2026, this dataset has been consolidated

[6] Uses of the model with endogeneous technological change: (Fragkiadakis et al., 2025; Aleluia Reis et al., 2023; Fragkiadakis et al., 2020; Nogueira et al., 2023)

[7] Uses of the model with endogenous technological change: (Boitier et al., 2022; Ravet et al., 2019; Brécard et al., 2006)

[8] A first open-access version is available on Zenodo: https://zenodo.org/records/15776918. A new release should be done in Summer 2026.

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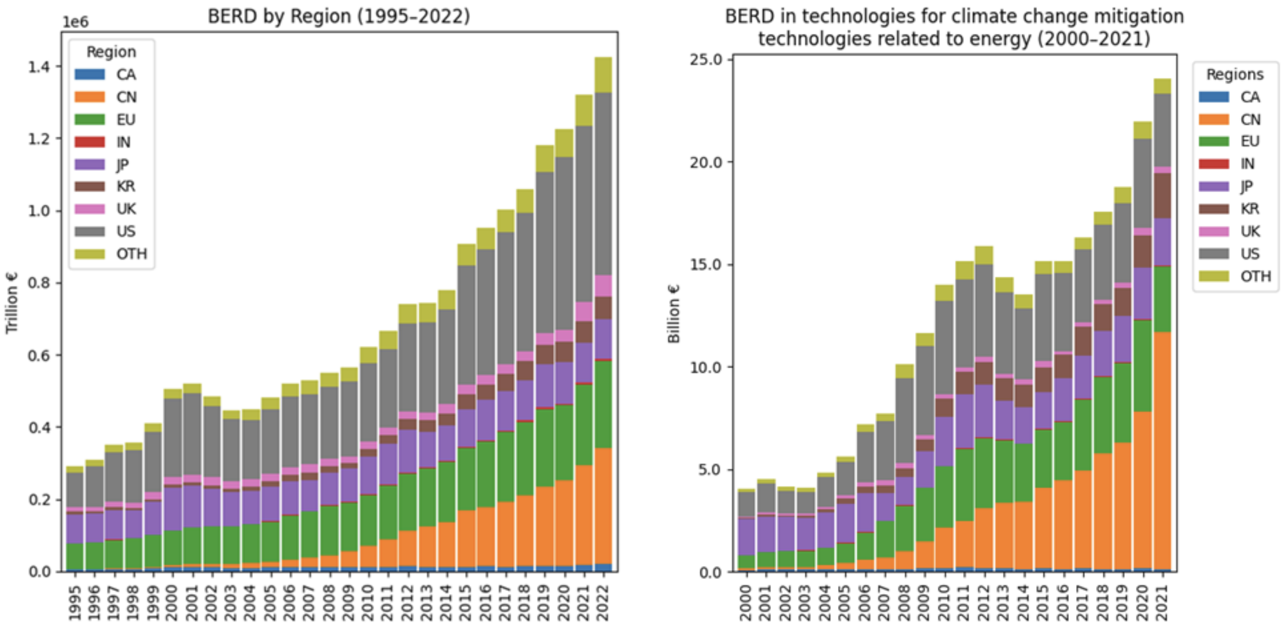
by implementing intra-, inter-, and extrapolation methods, ensuring continuous series over the period 2000–2021 and extended to 66 green technologies.

Figure 1: Business expenditures on R&D (BERD) by major economies

a) Total BERD **b) BERD in climate mitigation technologies**



Source: Le Mouël et al., (2025)

These detailed R&D expenditure data provide the core inputs for constructing knowledge stocks by region, sector and technology group, and for representing knowledge and technology transfers between countries and sectors. To quantify knowledge spillovers, we investigate three alternative methods.

The first relies on global multi-regional input–output (GMRIO) databases and uses, in particular, inter-industry transaction matrices as proxies for knowledge flows, approximating them with intermediate input exchanges. This approach can be implemented using several GMRIO datasets, including open-source databases such as EXIOBASE[9] (Stadler et al., 2026, 2021), FIGARO[10] (Eurostat, 2021) or GLORIA[11] (Lenzen et al., 2017) as well as proprietary databases such as GTAP[12] (Aguiar et al., 2025). However, using intermediate consumption as a proxy for knowledge spillovers is not fully satisfactory, since embodied knowledge in goods and services may be transmitted more strongly through capital goods (investment) than through intermediate inputs. We, therefore, also investigate the construction of knowledge-flow proxies based on investment (capital) flow matrices. A key limitation is that such matrices are rarely available in the literature. Södersten et al. (2018) proposed a methodology to build investment flow matrices, which are applied to EXIOBASE (Wood & Södersten, 2021). Related work was carried out by Norman-López, et al. (2023), albeit limited to the EU and some sectors of which eight power-generation technologies were detailed. This capital-

[9] https://doi.org/10.5281/zenodo.15776918

[10] https://ec.europa.eu/eurostat/web/esa-supply-use-input-tables/database#figarotables

[11] https://ielab.info/labs/ielab-gloria

[12] https://www.gtap.agecon.purdue.edu/databases/v12/

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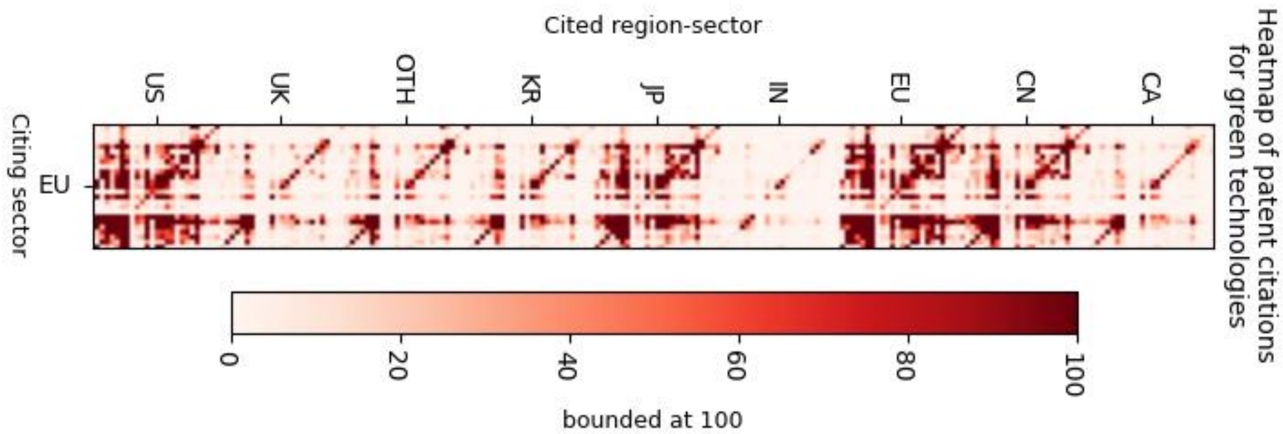
flow-based approach is thus an alternative promising route for quantifying cross-country and cross-sectoral knowledge flows.

The second approach to quantify knowledge flows is based on patent statistics and uses patent citations to construct citation matrices. Newly registered patents identify prior patents that contributed to their development, thereby providing information on knowledge linkages within innovation processes. After substantial data processing, these citation links can be aggregated to build patent citation matrices by region, economic activity and technology cluster. Nomaler & Verspagen (2025) constructed such matrices for four technology groups (old digital—JTAG; new digital—WIPO; green technologies; and other technologies; see Figure 2).

Figure 2: Heatmap of patent citations for green technologies for EU



Source: Authors calculation based on Nomaler & Verspagen (2025)

Finally, the third approach uses foreign direct investment (FDI) flows as proxies for knowledge flows. Its implementation is, however, constrained by the limited availability of detailed bilateral FDI data combining inward and outward positions/flows by both country and sector. Most existing datasets are incomplete along one or more dimensions; for example, IMF (2026) or Pagano et al. (2020) provide limited sectoral detail, UNCTAD (2025) has limited bilateral and sectoral coverage, and the wiiw (2022) database has more restricted geographical coverage. Implementing this approach, therefore, requires substantial upstream data processing before knowledge-flow matrices can be constructed. This processing could be conducted in close coordination with the work on capital flow matrices, which may help downscale country-level FDI information to the sectoral level.

4.2.3 Modelling technological change

General innovation framework

A first general innovation framework is currently under development to enable modelling teams to implement endogenous innovation in their respective models. The initial version is intentionally parsimonious and designed to make direct use of the data produced on R&D expenditures and knowledge flows. The framework starts from private and public R&D expenditures, disaggregated by region, sector and technology, to construct R&D stocks at this level using the perpetual inventory method. Knowledge stocks are then computed by combining these R&D stocks with measures of knowledge flows, with the specific proxy retained depending on the outcomes of the ongoing data collection and processing. Finally, innovation flows are modelled as a function of knowledge-stock growth, weighted by each sector's capacity to absorb incoming knowledge. This absorptive capacity is proxied by the sector's own R&D intensity. Accordingly, for a given increase in external knowledge received by a sector, higher R&D investment strengthens its ability to translate that knowledge into a greater number of innovations, ultimately increasing productivity (Cohen & Levinthal, 1989; Le Mouël, 2019). This provides a first, general approach that will be shared with the modelling teams as a transferable template for implementation. More sophisticated extensions, as well as parameter estimation, particularly regarding the relationship between changes in knowledge stocks and productivity, will be explored at later stages of the task.

Directed technological change

Model development has advanced significantly since the initiation of the task in October 2025. Building on the conceptual framework from Acemoglu et al. (2012), a fully specified DTC model with endogenous market structure and vertical linkages has been developed and calibrated. The core innovation lies in the integration of Cournot competition with free entry and exit into a multi-sector DTC framework, departing from standard monopolistic competition assumptions. This allows for endogenous markup formation based on firm-level profitability and sector-specific concentration, with markups derived from Eurostat (Eurostat, 2024a, 2024b). In addition, the upgraded model also explicitly represents upstream-downstream linkages in the energy system, distinguishing between energy generation (upstream) and energy-consuming sectors (downstream). Innovation in one segment affects the other through price-mediated supply and demand effects; for instance, improvements in renewable electricity generation reduce input costs for electric end-use technologies, increasing their profitability and attracting more R&D effort.

In the model, innovation stems from scientists allocated to do research in a specific sector and fuel type driven by relative profit opportunities. Novel to this model extension is the competition effect that pushes scientists to whichever sector and fuel type that has higher markups due to weaker competition intensity. Depending on the sector, this can reinforce or overcome technological lock-in. Most recent work has focused on calibrating the model to match sectoral and fuel type-specific (a) energy consumption; (b) price markups; and (c) innovation efforts to observed data from the International Energy Agency (IEA, 2025), Eurostat's Structural Business Statistics (Eurostat, 2024a, 2024b) and the European Patent Office's (EPO) PATSTAT (EPO, 2025).

This first draft of the model forms a generalised, empirically grounded approach to endogenising technological change through R&D in up- and downstream markets, characterised by Cournot competition. This draft of the proof-of-concept model has been developed as a single-region framework to isolate and analyse the core implications of two key innovations: (*i*) the introduction of Cournot competition with endogenous markups and free entry of firms, and (*ii*) the vertical integration between upstream energy generation and downstream energy-using sectors. This simplified structure allows for a clear identification of how market structure and sectoral linkages shape innovation incentives and the dynamics of electrification under different policy regimes. The mechanism is readily amenable to integration into large-scale models, requiring no additional assumptions beyond an extension of the calibration outlined above.

Compared with the timeline set out in Deliverable D3.1, all four main steps have progressed substantially. Some adjustments have nevertheless been introduced: the review of existing modelling approaches will be extended to include parameter estimates and/or calibration evidence, while the work on designing a general approach to endogenising technological change either through R&D investment and knowledge spillovers or through directed technological change has advanced faster than initially planned.

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4.3 Next steps

For Task 3.4, the next steps are to prepare and process the raw datasets that will be used as proxies for knowledge spillovers. This will be followed by the computation of knowledge-flows and a comparison of results across the alternative approaches. This work will run from late spring 2026 to early autumn 2026, with the objective of sharing the dataset, at least internally, by September/October 2026. The dataset will then be made openly available through a public repository (e.g., Zenodo and/or the I^{2}AM PARIS platform) by spring 2027, together with the finalisation of Deliverable D3.5 ("Technological change modelling", M30).

In addition, we will continue the development of the modelling approach based on LbR. The first objective is to facilitate broad implementation across models by sharing open code (e.g., in Python and/or GAMS) that can be populated with the task datasets on R&D and knowledge. This step will be discussed among modelling teams until summer 2026, with the aim of operationalising the general framework by November/December 2026. From autumn 2026 onwards, the framework will be refined to incorporate additional features, such as endogenous private-sector R&D decisions, a more detailed treatment of sectoral productivity impacts, and distinctions between quality and process innovation. The specific extensions to be developed will be defined in October 2026.

For the DTC approach, the next phase of model development will extend the current framework to a multi-regional setting, incorporating strategic trade interactions and cross-border spillovers. This extension will be closely aligned with the methodological advances developed in Task 3.3. The multi-regional model will feature region-specific Cournot oligopolies and vertically linked markets, enabling the analysis of asymmetric policy adoption, carbon leakage, and competitiveness effects. In parallel, we will incorporate cross-regional and cross-sectoral innovation spillovers, leveraging the enhanced data infrastructure developed in WP2—in particular, the disaggregated GTAP database and improved allocations of R&D expenditures across technologies and sectors. The spillovers will be parameterised using the data work conducted within this task, either by directly using the knowledge spillover/stock measures produced, or by relying on comparable proxies such as patent-citation matrices adapted to model-specific needs, together with sector-level R&D intensity metrics, to ensure the empirical grounding of knowledge diffusion processes.

Overall, this development path ensures coherence with the broader ENTICE modelling framework and strengthens the models' capacity to assess the TCI nexus, notably when evaluating policies such as carbon border adjustment mechanisms, green industrial strategies, and international technology cooperation.

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5 Linking macroeconomic models with material flows and mineral resources (Task 3.5)

5.1 Objectives

Task 3.5 addresses one of the main limitations of large-scale macroeconomic modelling in the context of assessing the TCI nexus. While macroeconomic models are well suited to represent production, trade, investment and demand in monetary terms, they generally do not track in a sufficiently explicit way the physical dynamics of material extraction, transformation, use, scrapping and recycling. This is particularly relevant for the green transition, since many low-carbon technologies depend on complex and geographically concentrated supply chains of critical raw materials. In line with the rationale already set out in Deliverable D3.1 the task therefore aims to establish a structured connection between macroeconomic models and a physical representation of material flows and mineral resources, so that future scenario analysis can better account for material requirements, resource constraints and the timing of technology stock turnover.

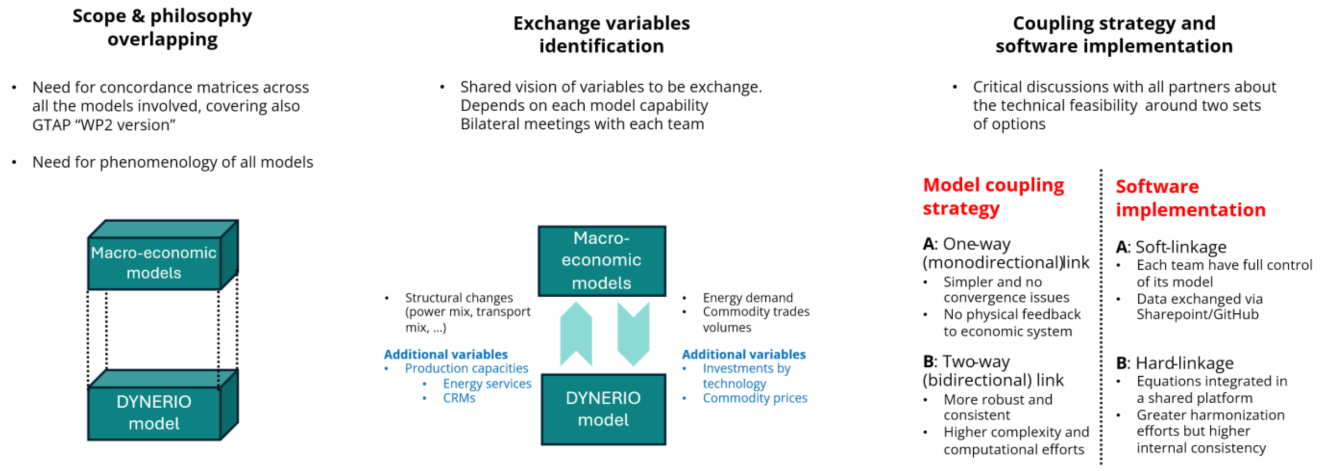
The first operational goal is to define a methodological framework that is robust enough to deal with the heterogeneity of the models involved, while remaining concrete enough to guide implementation choices in the following phases of the task. This implies clarifying what kind of information can be exchanged between the macroeconomic models and a physical stock-flow model (DYNERIO), identifying different levels of integration complexity, and preparing the conditions for proof-of-concept exercises. The longer-term objective remains the formalisation of the model links that will be reported in Deliverable D3.6 (“Links w/ minerals and materials”, M30) and then handed over to the scenario work in WP4 and WP5.

5.2 Progress

Since the start of the task in October 2025, progress has mainly taken the form of conceptual, methodological, and coordination work. This sequencing is consistent with the work plan and with the nature of Task 3.5, which sits at the intersection of several modelling efforts and depends on upstream developments in WP2 and in other WP3 tasks. In particular, the enhanced GTAP database, sectoral disaggregation work, and the clarification of model outputs are important prerequisites for defining meaningful links between macroeconomic models and the physical stock-flow representation developed in DYNERIO model. An immediate implementation of the linking would therefore have been premature before clarifying the scope of the models involved, the information they can provide, and the consistency conditions required for their interaction. For this reason, the first months of activity have been devoted to framing the linking problem in a more operational way and to translating the broad ambition of Deliverable D3.1 into a sequence of manageable steps. This preparatory phase is now being translated into a more operational and accelerated phase, based on dedicated exchanges with the modelling teams and the definition of initial soft-linking tests.

From a methodological point of view, the work carried out so far has further specified the modular architecture initially envisaged in Deliverable D3.1. This refinement aims to better highlight the challenges related to this formalisation, as shown in the Figure 3.

Figure 3: Multi-scale complexity of the challenges related to the modelling link formalisation



Four main groups of challenges have emerged from this first methodological refinement, also driven by recent research stemming out of the project, among others (Keppo et al., 2026).

The first concerns the degree of overlap between the models to be linked. Before any coupling can be formalised, the regional and sectoral scopes of the macroeconomic models and of DYNERIO need to be sufficiently aligned to limit harmonisation problems and ensure consistency. At the same time, a minimum consistency is also required in the "philosophy" of the models, that is, in the way they represent production, demand, trade, and sectoral interactions. Differences such as Multi-Regional Input-Output (MRIO) vs. Supply-Use structures, industry-based vs. product-based technology assumptions, or Armington vs. alternative trade specifications are not merely technical details, since they directly affect the meaning and comparability of exchanged variables across the models. For this reason, an important part of the work carried out so far has been devoted to clarifying the representational structure of the models involved and to identifying the need for concordance matrices across the relevant sectoral and regional classifications, including the GTAP-based developments of WP2.

A second challenge concerns the identification of the variables that can realistically be exchanged between modelling frameworks. A preliminary mapping has confirmed that a first layer of information can be transmitted from macroeconomic models to DYNERIO through variables such as energy demand and commodity trade volumes, while a possible feedback from DYNERIO to macroeconomic models could take the form of structural changes, for instance in the power mix or transport mix. In addition to this preliminary mapping additional variables have been identified: on the macroeconomic side, these may include investments by technology and commodity prices; on the physical side, production capacities, energy services, and demand for critical raw materials become relevant candidates. However, the figure also makes clear that the linking problem becomes more demanding once additional variables are considered and critical, if the link is bidirectional. This has led to the conclusion that exchange variables cannot be defined in an abstract, one-size-fits-all manner. Rather, they must be specified model by model, distinguishing between endogenous, exogenous, and potentially "hybrid" variables, i.e., variables that may become part of the exchange depending on the specific coupling strategy retained.

A third challenge relates to the model coupling strategy itself. At the conceptual level, the consortium has recognised that the link across models may be formulated in different ways, ranging from a one-way, monodirectional transfer of information to a more advanced two-way interaction. A one-way architecture is simpler to manage and does not raise convergence issues, but it does not allow physical constraints to feed back into the economic system. A two-way architecture would be more robust from an analytical point of view, since it would allow material availability, recycling dynamics, or technology stock constraints to influence macroeconomic results, but it would also introduce greater complexity in terms of consistency, iterations, and computational burden. At this stage of the project, the work of Task 3.5 has therefore focused less on selecting a single preferred architecture and more on making explicit the implications of these alternative levels of complexity, so as to create a common basis for discussion with the modelling teams.

The fourth challenge concerns software implementation. Even when the conceptual direction of the link is clear, an additional decision is needed as to whether the coupling should be implemented as a soft or a hard link. A hard link would imply tighter integration of equations and routines within a common modelling environment, with higher internal consistency but also stronger requirements in terms of code harmonisation, maintenance, and coordination across teams. A soft link allows each team to retain control of their own model, while data are exchanged through agreed procedures (that can be automated) and shared repositories. In the light of the current maturity of the task and considering that several relevant model developments in WP2 and WP3 are still ongoing, the work carried out so far suggests that the first route to be tested should be the soft-link approach. This is the most operationally feasible option at the present stage and provides a manageable entry point for proof-of-concept exercises, while leaving open the possibility of later moving towards more iterative or more tightly integrated configurations.

5.3 Next steps

The next phase of the task will translate the conceptual framework into more operational outputs and marks the beginning of an accelerated implementation phase for Task 3.5. A first priority is the systematic review of the model characteristics collected in Deliverable D3.1 and their comparison with the evolving WP2 data work. This will allow the preparation of the first version of the cross-consortium concordance matrices needed to connect the models at sectoral and regional level. Particular attention will be devoted to the consistency between the future extended GTAP structure, the macroeconomic models involved in WP3, and the physical stock-flow representation that underpins Task 3.5. This step will provide the technical basis for moving from general conceptual alignment to concrete model-linking tests.

In parallel, the interaction with the modelling teams will be intensified through bilateral discussions and regular task meetings specifically dedicated to Task 3.5. These meetings will provide a structured forum to discuss the linking options with the relevant model developers, progressively narrow down feasible exchange variables, and identify the most suitable soft-linking configuration for the first proof-of-concept tests. The main objective of this phase will be to define, for each model, a more precise list of exchange variables and to distinguish between variables that remain exogenous, variables that are internally determined, and variables that can realistically be exchanged in a linking exercise. This step is essential to move from a general discussion on model linking to model-specific implementation choices. The regular meetings planned for Task 3.5 will also serve to monitor feasibility, identify emerging bottlenecks, and ensure consistency with the broader modelling developments of WP3.

A further step will be the set-up of conceptual proof-of-concept tests. These tests are expected to start from relatively simple one-way soft-link configurations and then assess, where justified, the conditions under which more articulated feedbacks can be introduced. The purpose is not to deliver a definitive integrated platform at this stage, but to test the plausibility of the alternative linking configurations identified so far and to build a sound basis for the formalisation work that will follow in 2027. Altogether, these activities will prepare the ground for the drafting of Deliverable D3.6 and for the subsequent use of the improved model links in the scenario analysis of WP4 and WP5.

6 Land-use changes and environmental indicators (Task 3.6)

6.1 Objectives

Task 3.6 aims to improve the representation of land-use changes and environmental indicators in the ENTICE modelling framework, with a particular focus on the land-use and environmental effects of trade in agricultural and land-based products. In line with the work plan defined in Deliverable D3.1, the task addresses a key limitation of many macroeconomic and GTAP-based models: while these models are well suited to assess production, price, demand and trade responses, they generally represent land in an aggregated way (or not at all) and therefore cannot directly capture where land conversion takes place or what environmental impacts follow from this conversion.

The main objective is therefore to develop a more spatially informed bridge between changes in production and trade, land-cover change, land use, land use change and forestry (LULUCF) emissions and biodiversity impacts. This is pursued through two complementary routes. First, response-curves and lookup-tables are currently being developed, using GLOBIOM and spatial land-cover data to quantify how changes in agricultural production, especially livestock and feed-related production, translate into changes in land cover, emissions and biodiversity indicators, such as the Mean Species Abundance (MSA) index and the Biodiversity Intactness Index (BII). Second, the task explores a prototype route for embedding land-use change and environmental accounting more directly in macroeconomic/CGE models through explicit tracing of land cover changes within these models, inclusion of Global Trade Analysis Project – Agro-Ecological Zone (GTAP-AEZ) where feasible, and post-model environmental accounting.

Specific emphasis is placed on livestock and grassland dynamics, because animal-source foods require land directly through grazing and indirectly through feed production. This makes livestock production a central channel through which land cover and environmental impacts are altered. The empirical work initiated since the beginning of the task also focuses on developing a more recent land-cover baseline than the current GLOBIOM base year of 2000, which is outdated for the analysis required in Task 3.6.

6.2 Progress

Since the start of the task, progress has concentrated on three fronts: (*i*) conceptualisation of the modelling approach, (*ii*) identification of feasible routes for integration with macroeconomic and CGE models, and (*iii*) empirical data preparation for a new land-cover baseline. The two main blocks of work carried out in between the Deliverables D3.1 and D3.2 reporting periods are described below. These include the conceptual work consolidated around a dedicated workshop and the construction of an updated land-cover map for GLOBIOM.

6.2.1 Conceptual work on T3.6

During the ENTICE project's March 2026 General Assembly, a workshop on the conceptual work around Task 3.6 was held. The workshop brought together the macroeconomic modelling teams with potential interest in the task, including ENVISAGE, ICES, NEMESIS World, and GEM-E3. Its purpose was exploratory: to explain the proposed Task 3.6 framework, clarify the data and modelling requirements for the CGE prototype route, and identify the inputs needed from modelling teams for the lookup-table route. Rather than fixing final design choices, the workshop served to build a common understanding of the state of the art in LULUCF and biodiversity accounting in CGE/GTAP-based models, to clarify the limits of existing approaches, and to scope which improvements are realistic within ENTICE.

The discussion confirmed that CGE and GTAP-based models provide a strong basis for analysing economy-wide interactions, prices, factor substitution possibilities, resource constraints, bilateral trade, and indirect effects across sectors and regions. At the same time, it highlighted the main weakness that motivates Task 3.6: land is often too aggregated, non-productive land such as forests and natural land is generally not included; the land that is included, has limited spatial detail, and LULUCF and biodiversity accounting are usually added ex post rather than represented as endogenous native model components. Because environmental and biodiversity impacts depend strongly on where land conversion takes place, what land cover is converted, and how the land is managed, the task requires a more granular land-cover and land-cover-change representation.

On this basis, two methodological pathways were structured. The first is a modelling-chain (lookup-table) approach, in which production shocks from GLOBIOM are translated into spatial land-cover change, after which LULUCF emissions and biodiversity indicators are calculated. This route is most suitable for CGE models that do not have land as an explicit production factor or only at a very aggregate level. GLOBIOM has quite an extensive experience with model emulation and response curves (so called 'lookup-tables') with respect to greenhouse gas (GHG) emission reduction potentials from agriculture, forestry and other land use (AFOLU) and land-based biomass potentials for bioenergy. This generally takes the form of a two dimensional scenario matrix combining different carbon price and biomass price trajectories (Frank et al., 2021). The Lookup Table structure is formulated in a dedicated GitHub page[13]. In T3.6 we aim to go beyond this by calculating the response curves directly from production and using a multi-dimensional matrix.

The second is a direct CGE-workflow (prototype) approach, in which land is made more explicit in the production structure of the CGE models, land transformation or land supply modules are introduced, non-productive land is considered where possible, and environmental accounts are added so that land transitions can be translated after each solve into emissions and biodiversity indicators.

To make these pathways operational, structured templates describing the modelling assumptions, drivers, and simulation dimensions were prepared and discussed with the modelling teams. For the lookup-table route, the cards specified the need to distinguish disaggregated land-use production sectors, including ruminants, non-ruminants and cropland, and to define the key drivers spanning the response surface. Suggested drivers include demand and productivity changes, trade-policy changes ranging from liberalisation to higher tariff barriers, climate and SSP-related productivity impacts, conservation policies, bioenergy policies, and carbon tax or mitigation technology assumptions. The cards also proposed illustrative sampling levels for crop, non-ruminant and ruminant production, yields, and conservation policies, which together would define a structured set of GLOBIOM simulations for estimating response curves.

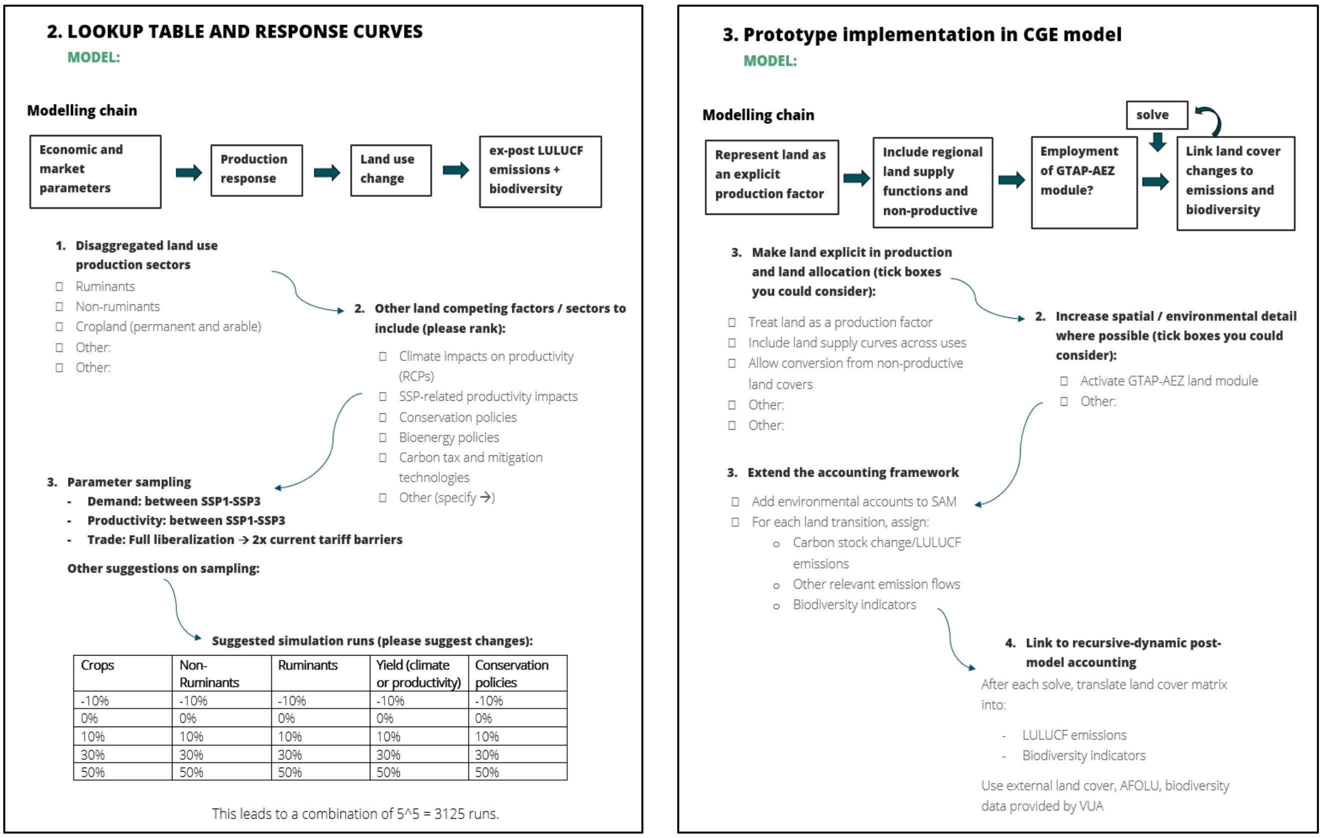
For the CGE prototype route, the response cards identified the implementation elements that need to be assessed with each interested modelling team: whether land is already treated as a primary production factor, whether regional land supply functions can be introduced, whether conversion from non-productive land covers can be represented, whether the GTAP-AEZ module can be used, and whether the accounting

[13] https://github.com/iiasa/GLOBIOM-G4M_LookupTable

framework can be extended with environmental accounts. The envisaged accounting extension would assign carbon stock changes, other relevant emission flows, and biodiversity indicators to land-cover transitions, and then translate the post-solve land-cover matrix into LULUCF emissions and biodiversity impacts. Among the participating teams, those that already treat land as an explicit production factor are the most natural candidates for the prototype, and we are currently continuing bilateral technical discussions with candidate models.

Progress was also made on the selection of environmental indicators and land-cover classes. The discussion distinguished between indicators that can be calculated from land-use shares and indicators that are more naturally tied to land-use transitions. The Biodiversity Intactness Index (BII), Mean Species Abundance (MSA) and a composite habitat or land-cover goodness index can be computed through area-weighted land-use shares. Species–area relationship (SAR) indicators are more directly linked to habitat loss relative to a baseline. The response cards also asked modelling teams to rank wider environmental indicators such as water stress, soil degradation or erosion risk, and nitrogen pressure, which can inform later prioritisation once the land-cover and emissions components are more advanced.

Figure 4: Illustration of the structured templates shared with modellers during ENTICE project's March 2026 General Assembly



6.2.2 Empirical and data work, creating a new land cover map

In parallel with the workshop-based conceptual work, empirical work has focused on developing an updated global land-cover map for Task 3.6. This work addresses an important limitation in GLOBIOM: the model's current land-cover base year is 2000, which is too outdated for analysing recent trade- and livestock-related land-use dynamics. The updated map will also support the construction of a land-cover-change matrix that can be linked to GLOBIOM production responses.

The new map is being developed at global scale and will be harmonised with the spatial and regional structure used in GLOBIOM, so that it can be integrated directly into the model workflow. After comparing available datasets in terms of consistency, resolution and land-cover detail, the Copernicus Climate Change Service Land Cover Classification Gridded Maps were selected as the main data source (Copernicus Climate Change Service, 2019). This dataset provides annual global land-cover maps from 1992 onwards at 300 m resolution, using 22 classes based on the FAO Land Cover Classification System (Di Gregorio & Jansen, 2001). Because grassland is central to livestock production and is difficult to represent accurately in global land-cover products, the Copernicus data will be complemented with annual grassland maps from Parente et al. (2024). These maps distinguish between cultivated grassland and natural or semi-natural grassland, which is particularly useful for analysing livestock-related land-use change. They cover the period 2000–2022 at 30 m resolution. Where relevant, additional layers on permanent cropland and wetlands may also be included to improve the representation of land cover types important for livestock production and environmental impacts.

The data processing workflow is designed to create two outputs. The first is a raster-based dataset at pixel level, which enables detailed spatial analysis of land-cover change between 2000 and 2020. The second is a vector-based dataset aggregated to the national level, which allows for more efficient country-level analysis and visualisation. The main processing steps are as follows. First, all raw datasets are imported and standardised, including land-cover maps for 2000 and 2020, grassland maps for 2000 and 2020, country boundaries, and relevant socio-economic, livestock and biophysical variables. Second, all datasets are cleaned and harmonised by reprojecting them to a common coordinate reference system, addressing missing or inconsistent values, and assigning a country identifier to each spatial unit. Third, the land-cover and grassland datasets are combined into new reclassified land-cover layers for both 2000 and 2020. This involves harmonising spatial resolution, creating binary maps for individual land-cover classes, aggregating them to the final resolution, and combining them through a decision-tree approach.

The final raster dataset shows land-cover transitions at pixel level, while the national-level dataset will aggregate the area of each land-cover transition by country. This will result in a land-cover-change matrix indicating, for example, how much forest, cropland, grassland or wetland area changed between 2000 and 2020 in each country. This new land cover map will be integrated in GLOBIOM to update the base year.

Building on this baseline, the next empirical step is the construction of a land-cover-change matrix capturing transitions between forest, cropland, grassland, other natural land, wetlands and built-up land. The matrix will form the empirical backbone for linking GLOBIOM production responses to land-cover transitions and, subsequently, to LULUCF emissions and biodiversity indicators. Particular attention is being given to grassland, pasture, and feed-crop dynamics, given the centrality of livestock-related land pressures to the task.

Overall, the work remains aligned with the work plan outlined in Deliverable D3.1, and no substantive deviation from the initial objectives has been identified. The main refinement concerns sequencing: given the importance of the outdated GLOBIOM base year, early effort has been placed on land-cover data preparation and conceptual design before full response-curve generation. This sequencing mitigates the risk of building response functions on an outdated or insufficiently detailed baseline and creates a stronger basis for later integration into GLOBIOM and for the transfer of results to other ENTICE models.

6.3 Next steps

The next phase will consolidate the conceptual choices made during the workshop into an operational Task 3.6 workflow. The first priority, from May to November 2026, is to complete the construction and validation of the updated 2020 land-cover global map and to integrate this in GLOBIOM. This will include harmonising spatial land-cover datasets to the spatial and regional structure required by GLOBIOM, checking consistency with available emission and land-use data, and preparing the matrix in a format suitable for scenario and response-curve analysis.

The next step will be to design and run the first set of GLOBIOM simulations for the lookup-table approach, from November 2026 to March 2027. These simulations will test how changes in ruminant production, non-ruminant production, crop production, productivity, trade assumptions and land-competing policies affect land-use and land-cover outcomes. The results will be used to derive the first response curves linking changes in production and trade to land-cover transitions, LULUCF emissions, and biodiversity impacts.

In parallel, the task leader will continue engaging with interested macroeconomic modelling teams to assess the feasibility of the CGE prototype route, up to November 2026. This will involve identifying which models can treat land as an explicit factor, which can include land supply or land transformation functions, which can use GTAP-AEZ information, and which can implement post-model environmental accounting. Based on these discussions, a minimal prototype specification will be prepared, by April 2027, for translating land-cover changes after each model solve into LULUCF and biodiversity indicators.

A last important step, December-April 2027, is the work on a biodiversity indicator related to land-use changes that can be used for integration in CGE models and for translation of land-cover changes to biodiversity impacts.

The final months, May and June will be used to finalize the database with response functions, and to develop and finalise the deliverable including both the GLOBIOM related results as well as the CGE prototype.

By the end of the task, these activities should deliver a coherent and operational link between production and trade changes, land-cover transitions, emissions and biodiversity impacts. The outputs will provide the empirical and methodological basis for integrating Task 3.6 results into the broader ENTICE modelling framework and for using the improved land-use and environmental indicators in subsequent WP4 and WP5 scenario analysis.

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7 Summary

Sections 3–6 report progress across four complementary strands of WP3, moving from methodological foundations to concrete implementation pathways in large-scale models.

Task 3.2 (sector disaggregation) focused on building the methodological foundations for extending sectoral coverage in macroeconomic models, using GEM-E3 as a reference framework to formalise a generic and accounting-consistent approach for introducing new sectors once the disaggregated WP2 datasets become available. Progress includes defining how newly introduced sectors can be connected to production structures, demand components, investment, household consumption, and trade, while preserving consistency with existing model equations and macroeconomic interactions. Next steps will shift toward cross-model coordination and implementation, starting with a survey of modelling teams, the preparation of a cross-model integration matrix, and the progressive development of methodological guidance and first model-specific applications.

Task 3.3 (trade theory integration) delivered a unified analytical and computational framework comparing Armington, Krugman and Melitz trade structures, and clarified the additional equations, variables and data requirements implied by richer trade mechanisms. It also advanced a scalable calibration strategy together with a GTAP-based GAMS calibration toolkit shared with partners, thereby lowering the practical barriers to embedding heterogeneous-firm features in large-scale CGE models. Next steps will focus on translating this toolkit into concrete implementation in selected consortium models (Step 2 proof of concept), followed by model-specific guidance for broader uptake (within and beyond ENTICE) and preparation of the related deliverable.

Task 3.4 (technological change) strengthened both the empirical basis and modelling options for endogenising innovation and technological change in large-scale models. Progress includes consolidating the review of how macroeconomic models and IAMs represent technological change; advancing the construction of R&D and knowledge-spillover datasets (exploring GMRIO-based transaction, patent-citation matrices and FDI-based indicators as proxies); and developing two complementary modelling templates: a first R&D/knowledge-stock framework designed for broad uptake across the modelling ensemble, and a proof-of-concept directed technological change model with endogenous market structure (Cournot competition with free entry) and explicit upstream–downstream energy-system linkages, calibrated to observed energy use, markups and patenting patterns. Next steps will prioritise finalising and comparing knowledge-flow proxies, sharing an initial dataset internally by early autumn 2026, and releasing reusable implementation code to support adoption of the general framework by ENTICE models and beyond, while extending the DTC model to a multi-regional setting aligned with Task 3.3.

Task 3.5 (materials and mineral resources) focused on operationalising the linkage between macroeconomic models and the DYNERIO physical stock–flow tool. The work clarified the main consistency conditions (alignment in sector/region coverage and modelling “philosophy”, including MRIO vs supply–use structures and trade specifications), mapped feasible exchange variables and their status (endogenous/exogenous/hybrid), and structured coupling options (one-way vs two-way; soft-link vs hard-link). Given current maturity and ongoing upstream developments, a soft-link proof-of-concept was identified as the most feasible entry point to test exchange protocols and prepare concordance matrices before moving to more iterative feedbacks. Next steps will develop first cross-consortium concordance matrices consistent with WP2 data work, agree on model-specific exchange variable lists with partners, and launch initial one-way soft-link tests that can later be scaled to two-way configurations where feasible.

Task 3.6 (land use and environmental indicators) structured two implementation pathways: a lookup-table/response-curve approach based on GLOBIOM outputs, and a CGE prototype route with more explicit land representation combined with post-solve environmental accounting. A dedicated workshop engaged interested modelling teams to scope feasible integration choices, refine response-card designs (drivers, sampling strategy, sector detail), and prioritise indicator needs. In parallel, empirical work progressed on building an updated land-cover baseline, combining Copernicus land-cover with improved grassland information, and on defining a land-transition matrix that will underpin LULUCF emissions and biodiversity impact assessment, with particular attention to livestock- and feed-driven land pressures. Next steps will complete validation and integration of the updated land-cover baseline in GLOBIOM, run a first set of simulations to estimate response curves for key production/trade drivers, and define a minimal prototype specification (with interested models) for translating post-solve land-cover changes into LULUCF and biodiversity indicators.

As already highlighted in Deliverable D3.1, the WP3 model-improvement tasks follow distinct timelines: some strands have already produced tangible outputs, while others are only now entering their main implementation phase. In particular, Task 3.3 has delivered both a detailed theoretical background paper and an operational calibration toolkit, and Task 3.4 has made substantial progress on the modelling approaches for endogenous technological change, with first data outputs expected in the coming months. Task 3.6 has also advanced markedly by defining two structured implementation pathways to integrate land use and environmental indicators in macro-models aligned with the capabilities of participating macroeconomic/CGE models and by initiating the update of the land-cover baseline that will serve as the empirical reference for subsequent work. Tasks 3.2 and 3.5 follow a sequencing that is more directly dependent on WP2 dataset developments and on cross-model alignment. Their first phase has therefore focused on methodological framing, consistency conditions and implementation planning, creating the basis for the more operational phase that is now starting.

Overall, implementation remains aligned with the work plan set out in Deliverable D3.1, with no major deviations to date and only minor adjustments. For Task 3.2, the initial plan to deliver generic methodological guidelines for sector implementation by December 2026 is maintained; however, these guidelines will be iteratively updated and complemented thereafter to support the full roll-out of the new sectoral disaggregation across participating models, in line with model-specific capabilities. For Task 3.4, the review of existing modelling approaches will be expanded to include parameter estimates and/or calibration evidence, while work on the general framework to endogenise technological change, through R&D investment and knowledge spillovers and/or via directed technological change, has progressed faster than initially anticipated. This progress has been enabled by sustained coordination, notably through a monthly one-hour meeting launched in January 2026 to review progress and next steps for the model-improvement tasks and to address broader WP3 implementation issues, complemented by a series of technical workshops, including two task-specific sessions at the Milano General Assembly in March 2026 (Tasks 3.3 and 3.6) and an earlier workshop on Task 3.3 in February 2026. This coordination will continue through to the end of the model-improvement activities (M30), following the initial WP3 monthly-meeting plan and complemented by targeted workshops; two are already planned for May 2026 (Tasks 3.2 and 3.5). For Task 3.5, these dedicated exchanges will support the transition from the preparatory phase to the operational testing of soft-linking options, including the definition of model-specific exchange variables, concordance matrices, and initial proof-of-concept exercises.

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