TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 24/12/2024

D3.4 – Framework for industry transition modelling

WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs

Disclaimer

Copyright Message

Grant Agreement Number	101137606	**Acronym**	TRANSIENCE
Full Title	TRANSItioning towards an Efficient, carbon-Neutral Circular European industry		
Topic	HORIZON-CL4-2023-TWIN-TRANSITION-01-36		
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action		
Start Date	January 2024	**Duration**	48 Months
Project URL	https://www.transience.eu/		
EU Project Advisor	Fatima GONZALEZ GOMEZ		
Project Coordinator	Institute of Communication and Computer Systems (ICCS)		
Deliverable	D3.4 – Framework for industry transition modelling		
Work Package	WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs		
Date of Delivery	**Contractual** 31/12/2024	**Actual**	24/12/2024
Nature	Report	**Dissemination Level**	Public
Lead Beneficiary	Utrecht University (UU)		
Responsible Author	Li Shen	**Email**	l.shen@uu.nl
	UU	**Phone**	
Contributors	Gergo Suto [UU]; Andrea Herbst, Marius Neuwirth, Luna Luetz, Tobias Fleiter, Simon Lukas Bussmann, Meta Thurid Lotz [Fraunhofer]; Georg Holtz, Mathieu Saurat, Lukas Hermwille, Miriam Ruß [WI]; Panagiotis Fragkos, Maria Iro Baka [E3M]; Jakob Duerrwaechter, Sally Dacie [PIK]; Tom Terlouw [PSI]; Teresa Domenech Aparisi [UCL]; Patryk Bialas, Anna Gorczyca, Agnieszka Ziecina [PNTEC]; Diego Garcia-Gusano, Inigo Munoz, Izaskun Jimenez, Hanna Kuittinen [TECNALIA]		
Reviewer(s)	Konstantinos Koasidis, Alexandros Nikas, Panagiotis Kokkinakos [ICCS]; Maria-Iro Baka [E3M]; Marius Neuwirth [Fraunhofer]; Georgios Xexakis [HOL]; Mathieu Saurat [WI]; Teresa Domenech Aparisi [UCL]		
Keywords	industry transition, modelling framework, research questions		

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

The deliverable is intended for the broader stakeholder community of TRANSIENCE, including policymakers and other IAM-related projects, to provide an overview of the planned capabilities of MIC3 and the modules comprising it, as well as of our overall approach towards modelling decarbonisation vis-à-vis circularity performance. It is also intended for the IAM scientific community to present the added capabilities, expansions, and model linkages/integrations that are planned and/or performed in the project.

3. Short summary of results (<250 words)

This document, Deliverable D3.4 of the TRANSIENCE project, presents the conceptual framework and progress in developing the Model for European Industry Circularity and Climate Change Mitigation (MIC3). The MIC3 framework integrates advanced modelling tools to evaluate pathways for decarbonising and transitioning European industries to a circular economy. Focusing on energy-intensive sectors—steel, cement, and plastics—it will provide a comprehensive, open-source model ecosystem capable of addressing policy-relevant questions related to climate neutrality, resource efficiency, and industrial competitiveness.

The framework features eight satellite modules encompassing diverse modelling paradigms, such as computable general equilibrium, material flow analysis, energy system modelling, techno-economic analysis, and life cycle assessment. These modules enable the exploration of cross-sectoral interactions and the socioeconomic, environmental, and technical impacts of industry transformation. The report outlines the modular structure and interlinkages within MIC3, designed to facilitate scenario-based analyses of decarbonisation and circular economy interventions.

Two illustrative research questions demonstrate the framework's versatility: the economic implications of high R-strategies (e.g., refuse, reuse) and the resilience of industrial symbiosis under varying energy and locational constraints. These case studies highlight the capacity of MIC3 to generate insights into sectoral transitions, material efficiency, and the interdependencies of industrial clusters.

The report also discusses the broader applicability of the framework in addressing the interplay between policy measures, resource utilisation, and industrial dynamics. The development of MIC3 prioritises transparency, stakeholder engagement, and adaptability to regional contexts, aiming to support evidence-based policymaking and sustainable industrial practices across Europe.

4. Evidence of accomplishment

This report.

Funded by the European Union

PROCESSES4PLANET

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

Funded by the European Union
PROCESSES4PLANET

Executive Summary

This document, Deliverable D3.4 of the TRANSIENCE project, presents the conceptual framework and progress in developing the Model for European Industry Circularity and Climate Change Mitigation (MIC3). The MIC3 framework integrates advanced modelling tools to evaluate pathways for decarbonising and transitioning European industries to a circular economy. Focusing on energy-intensive sectors—steel, cement, and plastics—it will provide a comprehensive, open-source model ecosystem capable of addressing policy-relevant questions related to climate neutrality, resource efficiency, and industrial competitiveness.

The framework features eight satellite modules encompassing diverse modelling paradigms, such as computable general equilibrium, material flow analysis, energy system modelling, techno-economic analysis, and life cycle assessment. These modules enable the exploration of cross-sectoral interactions and the socioeconomic, environmental, and technical impacts of industry transformation. The report outlines the modular structure and interlinkages within MIC3, designed to facilitate scenario-based analyses of decarbonisation and circular economy interventions.

Two illustrative research questions demonstrate the framework's versatility: the economic implications of high R-strategies (e.g., refuse, reuse) and the resilience of industrial symbiosis under varying energy and locational constraints. These case studies highlight the capacity of MIC3 to generate insights into sectoral transitions, material efficiency, and the interdependencies of industrial clusters.

The report also discusses the broader applicability of the framework in addressing the interplay between policy measures, resource utilisation, and industrial dynamics. The development of MIC3 prioritises transparency, stakeholder engagement, and adaptability to regional contexts, aiming to support evidence-based policymaking and sustainable industrial practices across Europe.

Contents

Table of Figures

Table of Tables

1 Introduction

This report describes a conceptual version of the Model for European Industry Circularity and Climate Change mitigation (MIC3) framework, which integrates different modelling approaches to provide an enhanced representation of both decarbonisation and circular economy opportunities for industry transitions in Europe. The framework consists of eight satellite modules, spanning across five distinct modelling paradigms. Satellite modules are under development throughout the project's first phase (M1-M18) and bilateral data interfaces will be implemented in the second phase (M19-M36).

Recognising the utility of research questions as guides for effective model development, the project's open model development strategy (D3.2) set out to (i) formulate example research questions based on stakeholder needs, circularity ambitions, and policy development in three focal sectors (steel, cement, and plastics), and (ii) refine the development and planned coupling of modules accordingly. Preliminary research questions are meant to guide the development of modules and interfaces. They are not intended to replace dedicated co-creation activities for understanding policy and industry stakeholder needs (Task 8.1), which will in turn serve as the basis for scenario narratives later on (WP11). The activities relating to the first and second step of the development strategy have been taking and will continue to take place in the coming months.

The present report documents the progress made as of December 2024 (M12). It builds on the outcomes of previous project outputs, notably *Module Interfaces and Data Exchange* (MS5), *Draft Framework for Modelling* (MS7), and *Assessing Needs for Model Applications* (D2.2), and will be used as input for the development of satellite modules in WP4 and for creating the *Operational Version of MIC3* (D7.3) during Phase 2.

The rest of the report is organised as follows. Section 2 clarifies the project's scope including a shared understanding of industry transition in the context of TRANSIENCE. Section 3 proposes a conceptual framework for MIC3 by anchoring the coupling of modules in a general understanding of industry's linkages to well-being, services, and the environment. Section 4 demonstrates the applicability of the MIC3 framework via two example research questions about the potential implications of decarbonisation and circular economy interventions. Finally, Section 5 examines the interactions between (industrial) sectors within each MIC3 module to get a better understanding of the possible indirect effects of said interventions. The knowledge gained from this inquiry will eventually help interpret results when answering research questions.

2 Scope

The TRANSIENCE project aims to produce modelling pathways for the transition of European industries to climate neutrality and circular economy. In this context, aspects of the scope of modelling addressed here include the different dimensions incorporated and planned improvements within the MIC3 framework, including but not limited to spatiotemporal considerations. The precise scope will eventually be determined by specific research questions. Here, we highlight the 'boundaries' of each of these scope-dimensions.

Although the entire manufacturing sector will be covered in MIC3, focal materials (and industry sectors) for the TRANSIENCE project include inter alia *steel*, *cement* and *plastics*. These materials were selected to act as working examples to guide the conceptualisation of the framework as their production corresponds to high energy- and emission-intensive industries. Under the decarbonisation and circular economy ambitions of the European Union, the manufacturing of these materials and products made thereof in Europe is expected to change towards less energy- and emission-intensive technologies and practices. The process of this change is referred to as *industry transition* in the context of this project. How this industry transition will be realised in the coming decades is strongly influenced not only by climate and circular economy policy but also by wider developments, such as socioeconomic trends, global trade mechanisms, or the ongoing energy transition. Therefore, the scope of modelling the industry transition in this project includes assessing the impact of decarbonisation and circularity interventions in the value chains of steel, cement, and plastics, while also considering the interplays with and of the broader factors and trends mentioned.

The geographical scope of MIC3 focuses on European countries, with constituting modules capable of different levels of granularity. Interdependencies to the rest of the world will be addressed via modules that model trade either in monetary (CGE) or physical terms (Global MFA). The spatial resolution of most modules will be national, while others operate at either supra-national or sub-national (e.g. NUTS classification) level, depending on data availability. This resolution is increased for the representation of industrial activities, with the possibility of narrowing down to the level of regional industrial clusters.

The MIC3 framework will cover the time horizon until 2050, with some modules capable of also projecting up to the end of the century. The temporal resolution will generally be either annual or every five years, though some processes will necessarily be modelled at very short intervals (e.g., power system). While the capabilities of the modules will be constant, specific scopes might be selected depending on research questions investigated with the MIC3 model.

3 Conceptual framework

Although there are several pieces in the literature focusing on relevant aspects (e.g., Wesseling et al., 2017, who identify the main barriers of industry transition of relevance to TRANSIENCE), we particularly draw on a recent review of modelling industry transitions under low energy and material demand scenarios offered by Wiedenhofer et al. (2024). This review presents a conceptual framework of how 'service provisioning' connects the satisfaction of human needs with industrial production systems and in turn with the natural environment (Figure 1a). According to this framework, well-being relies on services that are often defined as 'what is actually demanded', such as decent living standards, employment, thermal comfort, or healthy diets. These services are provisioned through physical functions (e.g., transport, housing, heating/cooling, nutrition) and performed via the use of products and energy (e.g., buildings, vehicles, appliances, infrastructure). Since these functions require material products and energy, they drive industrial and energy systems to process natural resources to meet the material basis requirements.

Figure 1b shows a (preliminary) correspondence between this framework and the satellite modules of the MIC3 model. The correspondence should not be interpreted as one-on-one[1], rather MIC3 can be considered as a specific implementation of the above (general) framework. Additionally, Table 1 provides an overview of the modules, including the names of their (software) implementation and the modelling paradigms with which they are associated. Further explanations of each module are given in Section 5.

Table 1. Overview of MIC3 modules, their specific implementations and corresponding modelling paradigms.

MIC3 module	Specific implementation	Modelling paradigm
CGE	OPEN-GEM	Computable General Equilibrium
P&S Database	Product & Service database	Not relevant
Global MFA	SIMSON	Material Flow Analysis
EU MFA	EU MFA	Material Flow Analysis
Energy System	OPEN-PROM	Energy system simulation
Industry	EDM-Invest	Techno-Economic Analysis + Linear Programming
	FORECAST-Industry	Techno-Economic Analysis
LCA	premise	Life Cycle Analysis

The coupling of modules is crucial for the functioning of MIC3, therefore Figure 1c visualises the planned interfaces between modules. Data exchange between modules will be facilitated through common data formats such as IAMC result templates and by building Application Programming Interfaces (APIs) for all modules. The set of connections displayed showcase the possibilities for module communication. Which interfaces and in what order will be employed depends on specific research questions. In the following section, we explore the deployment of MIC3 through two example research questions.

[1] For example, the energy system module includes a simplified representation of *industry* for practical reasons.

Funded by the European Union
PROCESSES4PLANET

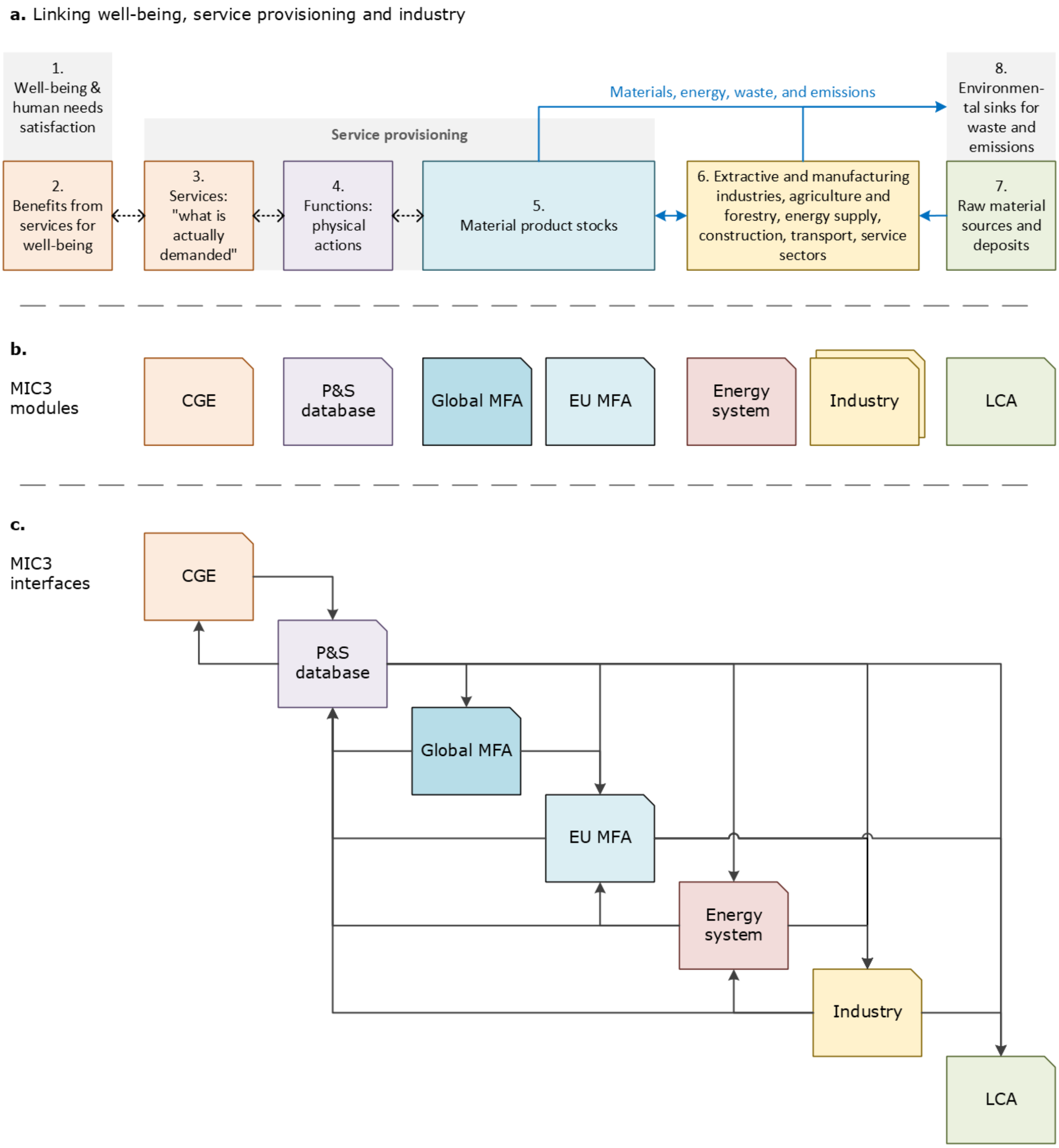

Figure 1. (a) Conceptual framework of the connections between well-being, service provisioning and industry (adapted from Wiedenhofer et al, 2024). Blue arrows represent physical flows of resources and waste, and dashed arrows show interactions of elements. (b) Corresponding MIC3 modules; (c) Planned interfaces among MIC3 modules.

4 Examples of modelling industry transitions with MIC3

Recognising the utility of research questions as guides for effective model development, the project's open model development strategy (Deliverable 3.2) set out to (i) formulate example research questions based on stakeholder needs and circularity ambitions of the three focal sectors, and (ii) refine the development and planned coupling of modules accordingly. These activities have been and will continue to take place in the coming months. The present report documents the progress that has been made until its finalisation (M12).

Several example research questions have been formulated in Deliverable 2.2 'Assessing Needs for Model Applications' based on engagement with stakeholders in industrial regions. A few additional questions have been put forward by partner institutions of Work Packages 3 and 4.

During the project's general assembly on October 23, 2024 (which followed the Brussels policy workshop jointly held with our sister project, AMIGDALA, on October 22, 2024), an internal workshop was held, where consortium members exchanged ideas for addressing a subset of example questions. The discussions were aimed at coming to agreement on the following points (per research question):

1. What are the relevant *final* outputs, and which module(s) deliver them?
2. What are the relevant *intermediate* outputs, and which module(s) deliver them?
3. How are (decarbonisation and circularity) interventions taken up by MIC3, i.e. which module(s) are first affected?
4. Which modules are indirectly affected by the intervention(s)?
5. What are necessary input data?

The limited time available during the general assembly calls for the continuation of this activity. The consortium will carry on with translating early research questions into modelling and data collection efforts in a similar method during the coming months. The remainder of this chapter contains a detailed summary of the discussion outcomes for two questions that have been discussed at the general assembly. The two example questions are different in purpose as well as associated modelling effort and as such were selected to showcase the broad range of possibilities with MIC3. Other potential research questions can be found in Annex A. Note that the list of questions is not exhaustive, nor does the project aim to answer all of them. The final research questions will be selected and prioritised at a later stage, e.g., as part of Task 8.1.

4.1 Example research question 1: economic implications of successful high R-strategies

Context and question

A shift to higher R-strategies, such as 'refuse' or 'reuse'[2], may lead to a reduction in industrial production (in or outside the EU) and to an increase in certain service activities, such as repair and refurbishment. What would be the shift in material and energy use, GHG emissions, and consequently, the implications of these changes for the economic structure, i.e. structural changes in industry and service sectors and employment?

Final output

The economic implications of high R-strategies are best answered by the socio-economic (CGE) module.

[2] For an extensive description and review of R-strategies, see Reike et al. (2018).

Most relevant final outputs include the distributions of value added and employment across economic sectors, particularly any changes between industry and service (sub-) sectors.

Intermediate output

Further relevant indicators could be lifecycle GHG emissions (related module: LCA) and use of energy and materials at different levels of detail and scale, e.g., national, sectoral, product, or industrial process (related modules: Energy System, EU MFA, Global MFA, Industry).

Uptake of interventions and required data

High R-strategy measures would primarily 'enter' MIC3 via the EU MFA module. Relevant modelling mechanisms identified are the modifications of the material intensities of products (e.g., steel use per vehicle), industry process parameters (e.g. efficiency, market share), stock development parameters (e.g. utilisation rate of buildings) and absolute reductions in consumption by material or product category.

Additionally, interventions should also specify, as much as possible, any direct economic effect of the selected R-strategy measures. They could include changes to costs, price elasticities, marginal employment, among others. These changes could be taken up by the CGE module for an even more thorough economic evaluation.

Propagation of interventions

From the perspective of modelling, the sequence of modules influences the eventual impact of an intervention. After its uptake, any intervention will inherently be propagated through subsequent modules. Due to the CGE's double role of intervention absorption and of providing basic socio-economic indicators (e.g., GDP) to other modules, interventions will be directly or indirectly affecting all modules (see Figure 2). The material effects of interventions enter later in the sequence via the EU MFA module, thereby having indirect influence on industrial processes (related module: Industry). After the estimation of new industrial processes, the results will be fed back to the CGE module to derive the induced economic implications of high R-strategy interventions. The modelling sequence will be concluded with this iterative feedback loop.

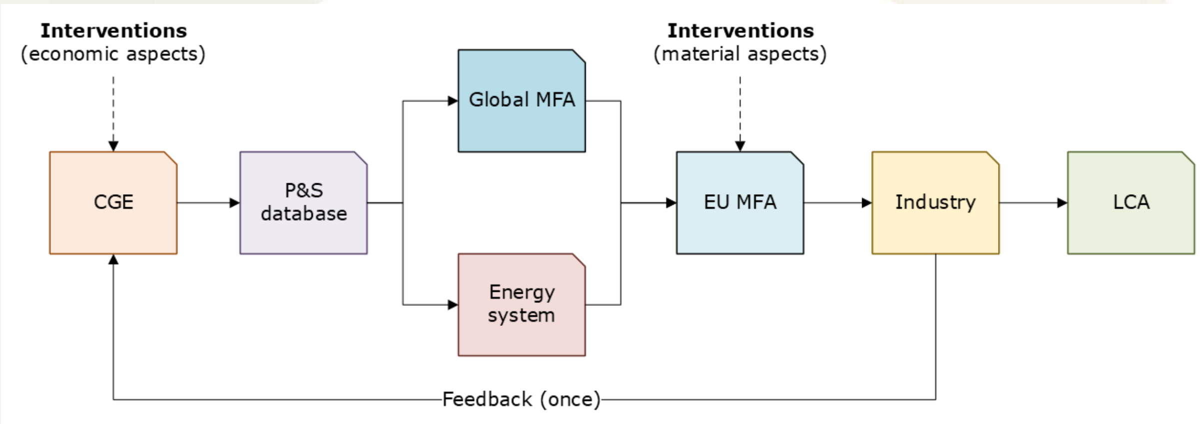

Figure 2. Simplified and preliminary modelling workflow for example Research Question 1.

4.2 Example research question 2: resilience of industrial symbiosis

Context and question

Clustering industrial activities can have benefits for cooperating producers due to better opportunities for industrial symbiosis, such as infrastructure sharing, by-product and waste heat utilisation, shorter transportation distances, etc. Industrial stakeholders in the region of North Rhine-Westphalia, Germany expressed to perceive the benefits of these 'cluster effects' as key for their current and future international competitiveness[3]. At the same time, factors such as the greater availability and lower costs of (renewable) energy supply in other countries within and beyond Europe could prompt the relocation of some industries. The consequences of such relocations for the symbiotic relationships among a cluster's remaining industries is poorly understood. Therefore, a relevant research question is: how potent are the locational advantages of clustering vis-à-vis locational disadvantages related to limited availability and comparatively high cost of energy supply (RE and hydrogen)?

Potential output indicators

Transport costs, distance, and duration; industrial waste and by-product utilisation; manufacturing costs; GHG emissions.

Discussion of approach

Answering this type of research question requires the identification of suitable indicators for quantifying the effects of industrial clustering. Since the industrial model is able to represent individual facilities or industrial clusters, it may be possible to identify potential synergies for some sectors. General evaluation of potential for symbiotic relationships could be measured by the (site-specific) Industry modules through indicators for transport (distance, costs, access to infrastructure such as pipelines and ports) and the utilisation of industrial wastes and by-products. Locational disadvantages related to the relatively high cost of (renewable) energy supply in some parts of Europe could be addressed by the Energy System module and related scenario assumptions. Similarly, some of the labour and capital costs could be evaluated by the macro-economic modules, although not at the scale of the cluster but the sector as a whole. Concepts such as skill development, knowledge sharing, or innovation ecosystems are out of the scope of MIC3 modules.

A limitation can be the geographical resolution of most MIC3 modules, which—with the exception of the Industry modules—operate at national or supranational granularity. Therefore, case study-specific approaches are suggested to best represent clustering effects at the local level. The possibility of building digital twins of industry clusters in case study regions will be subsequently explored. Modelling efforts might also be complemented by qualitative research. This is a highly relevant question but also very broad, posing difficulties towards refining an actionable modelling strategy to approach them. Further refinement, e.g., by a site-specific case, is needed to meaningfully be modelled by MIC3.

[3] See Deliverable 2.2 for detailed outcomes of this and other workshops.

5 Cross-sectoral interactions in modules

After presenting a general approach to the two example research questions, this section delves into the individual modules of MIC3. Where applicable, a description is given about the modelling of interactions between (industrial) sectors along the value chains of steel, cement, and plastics. Since decarbonisation and circular economy measures are often targeted at a single sector, this inquiry into cross-sectoral interactions contributes to a better understanding of the propagation of effects induced by the interventions. The insights gained this way will help interpret final outputs of MIC3 when answering research questions.

5.1 OPEN-GEM: Computable General Equilibrium module

The OPEN-GEM model will be the open version of the GEM-E3-FIT model. The GEM-E3-FIT model is a multi-sectoral, recursive dynamic CGE model, representing the global economy through interlinkages between productive sectors, consumption, price formation of commodities, labour and capital, trade, and investment dynamics (Fragkos & Fragkiadakis, 2022). It formulates the supply and demand behaviour of economic agents with market derived prices to clear markets, allowing for a consistent evaluation of distributional effects of policies. The model is driven by accumulation of capital, equipment, and knowledge, features equilibrium unemployment, energy efficiency standards, and carbon pricing, and can quantify the socio-economic impacts of policies ensuring that in all scenarios the economic system remains in general equilibrium. It is calibrated using the Global Trade Analysis Project (GTAP) database that provides a comprehensive and self-consistent accounting of firms' production structures, households' consumption, trade, gross fixed capital formation, and sectoral value added (Figure 3).

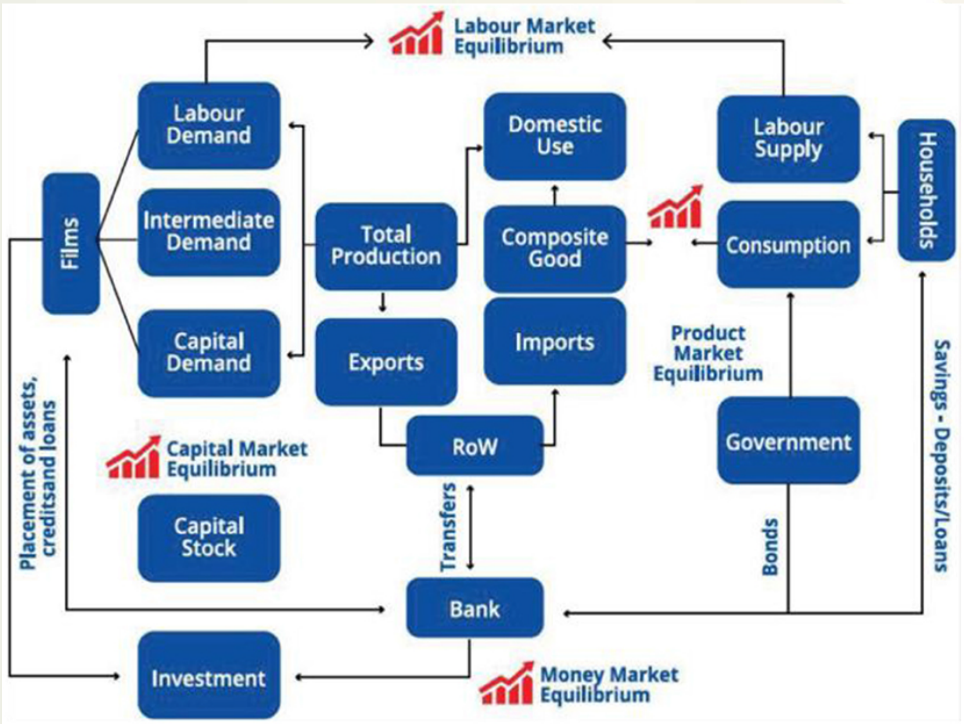

Figure 3. Schematic structure of the GEM-E3-FIT model (Fragkos & Fragkiadakis, 2022).

In the context of the TRANSIENCE project, an open version of the GEM-E3-FIT model will be developed and integrated within the MIC3 framework via appropriate soft-linkages with the other modules. The OPEN-GEM model will be used for two main purposes:

Funded by the European Union

1. To provide the boundary framework conditions for the MIC3 model in terms of broad socio-economic development (e.g., GDP growth, production by sector, investment, household income, employment by sector/activity) via appropriate automated links and interfaces with all modules and visualisation tools of the MIC3.
2. To close the loop of the industry-energy system-climate-economy-trade nexus in alternative scenarios, by quantifying the socioeconomic, trade, competitiveness, and employment impacts of industrial transformation by sector through the appropriate integration of results from other modules (e.g., industrial production costs, investment requirements to decarbonise industry) and thus exploring the broad macroeconomic impacts of climate and industrial policies.

The OPEN-GEM model will cover each EU Member State and major non-EU economies, focusing on the main trade partners and neighbours (UK, Russia, Turkey, USA, China) and major emitters globally (India), while aggregating the other economies into regions. The model will provide estimations of the main macroeconomic indicators in monetary (and not in physical) terms for the period 2020-2060 (up to 2100, if required) at 5-year time steps. The sectoral granularity of the model will include the Iron and Steel, Non-Metallic Minerals, and Chemical products as separate activity sectors. Table 2 presents the sectoral aggregation of OPEN-GEM.

Table 2. Sectoral aggregation of the OPEN-GEM model.

Agriculture	Non-ferrous metals	Other Equipment Goods
Coal	Non-metallic minerals	Consumer Goods Industries
Crude oil	Chemical products	Construction
Oil	Rubber and plastic products	Transport
Gas	Paper products	
Ferrous metals	Transport equipment	

The model focuses on assessing the complex cross-sectoral interactions of various products and economic activities that are captured by the input-output tables; for example, cement is used to build infrastructure, steel is used to manufacture vehicles and other industrial products. Industries also interact with each other through bilateral trade of products, determined endogenously in the model using the Armington assumption (Armington, 1969), and influenced by the relative production costs across countries. The industries are also interlinked via their competition for shared pools of resources, such as labour, capital and energy resources.

5.2 Product & Service Database

Facilitating model linking and development: the database is intended to focus on providing data needed for linking the TRANSIENCE models and supporting model development. This includes enabling data exchange and harmonisation of key data ensuring consistency among the TRANSIENCE models. Priority will be given to interfaces.

Exchanging the most relevant data: the database will document harmonised and non-harmonised data, thereby ensuring transparency. It will include translations of data and define relevant product demands, starting with specific sectors like transport services and vehicles.

5.3 OPEN-PROM: Energy system module

OPEN-PROM is a global energy system model that covers in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level. Final energy demand in OPEN-PROM comes from three main sectors: industry, domestic, and transport.

Industries interact via a (background) energy system, e.g., energy supply. The energy system has limited features, e.g., energy supply availability, which can put industries at competition with one another.

Industrial demand in OPEN-PROM is split into three main categories. The first category, non-substitutable electricity demand, involves energy services that must be met exclusively by electricity (e.g., lighting, cooling). The second category, substitutable energy demand, includes useful energy requirements that can potentially be satisfied by multiple energy forms (e.g., heating, process energy) and is subject to substitution. The last category involves the use of energy products for non-energy uses. The broad industrial sector is further divided into 10 subsectors, including Iron and Steel, Non-Metallic Minerals, and Chemicals, and energy demand is determined at the level of subsector/region. The energy demand of each subsector in each region is assumed to be a function of fuel prices and industrial value added (activity indicator). After the demand in each industrial sub-sector is calculated, different fuels (e.g., coal, oil, gas, electricity, biomass, hydrogen) linked with specific technologies compete to meet the energy demand based on their costs, technology maturity, preferences, and other factors influencing technology uptake. Prices include the effect of carbon prices, and constraints can be applied through emission abatement, pollution permits, and/or energy savings. The model among others represents the mix of technologies and fuels, and possible substitutions between energy forms, technologies, and energy savings.

5.4 EU-MFA: EU material stock and flow module

The material stock and flow module accounts for interactions between industries and value chains through the final demand for composite products, such as buildings or vehicles, which consist of multiple materials. For instance, the development of the building stock and vehicle fleet drive the final demand for cement, steel, and plastics in these categories. The MFA modelling approach measures flows and stocks in physical units rather than monetary terms. However, there are no endogenous interactions between the different materials within the same composite product (e.g., steel and plastics in passenger cars). Instead, these material flows are tracked in parallel, requiring harmonisation of external drivers (e.g., final demand developments from other models in MIC3) and consistent input parameters, such as material intensity factors.

The module incorporates a diverse range of product types, spanning from composite products (e.g., vehicles), to mono-material components that form part of composite products (e.g., moulded polyurethane seats in vehicles or PVC profiles in buildings), and mono-material stand-alone products (e.g., plastic packaging). Depending on the research question, the modelling approach can be sector-based top-down or product-based bottom-up. The module differentiates between broad application sectors (e.g. Automotive, Buildings & construction, Packaging, Electrical & electronics equipment, Agriculture etc.), detailed application sectors that are parts of the broad ones (e.g., “passenger cars” as part of “Automotive”, “Residential buildings” as part of “Buildings & construction”), and a product level (based on PRODCOM categories). A schematic example for plastics is shown in Figure 4. The detailed MFAs will be drawn along the whole life cycle of the selected material systems. For plastics, the detailed MFA will cover from production of primary polymers, to manufacturing of semi-finished products, plastic products and plastic containing products to the systems of application to the final disposal routes.

The model representations of the detailed application sectors modelling may interact - consequently at the end-product level (i.e., buildings and vehicles). There is no further upstream interaction considered in EU-MFA, e.g., between the sub-sectors of non-metallic minerals and iron and steel (use of blast furnace slag as clinker substitute). While stand-alone mono-material products, such as plastic packaging, may interact with other value chains via substitution (e.g., steel, glass or paper packaging), such interactions are not modelled endogenously. Substitution effects are instead assumed exogenously or derived from other MIC3 modules. This flexible modelling approach allows for a detailed and adaptable analysis of material flows across sectors and value chains while maintaining consistency and alignment with external drivers and assumptions.

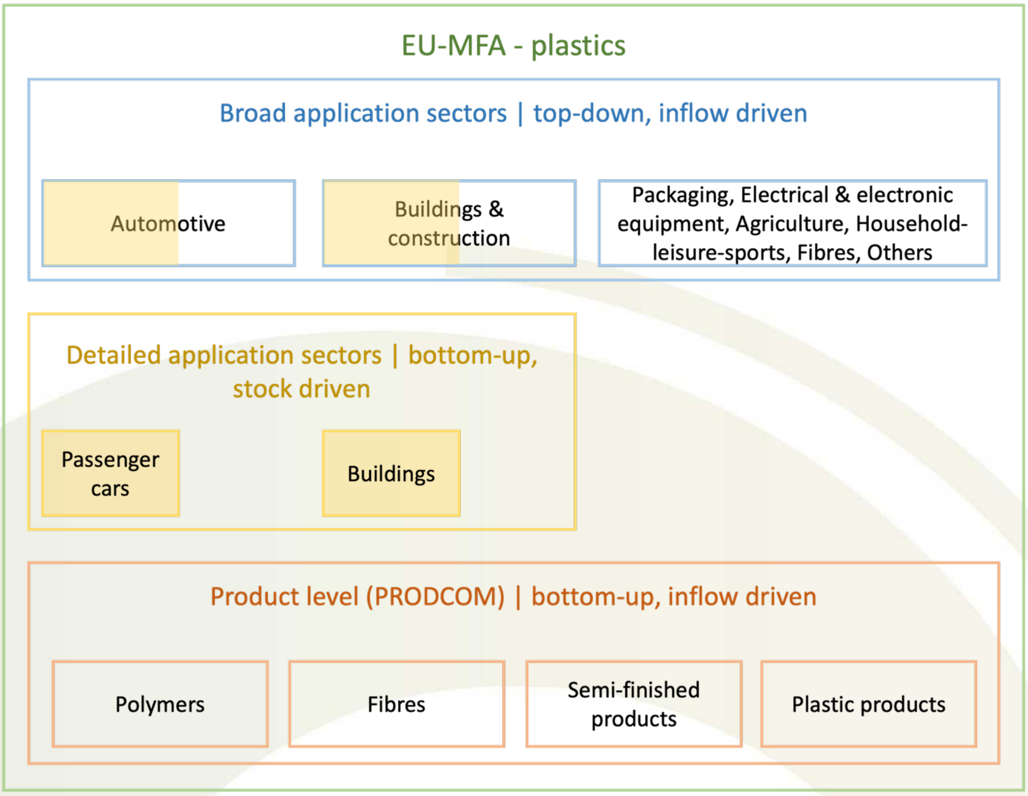

Figure 4. Product and sectoral resolution in EU-MFA for plastics.

5.5 SIMSON: Global material stock and flow module

It is important to assess the EU industry in the global context, since competition and trade are important in determining EU competitiveness. The global material flow analysis (MFA) model focuses on material flows in the steel, cement and plastics industries, and, in the context of the MIC3 framework, specifically on the net trade of these materials and products between regions. Harmonisation will be performed with the EU MFA on values for European production and demand. On the European level, the global MFA model will therefore benefit from the sector interactions implemented in the EU-MFA model. The combined global and EU MFA models will enable to assess challenges in the EU industry transition due to global competition, and possible opportunities corresponding to various policies (minimum recycled content, carbon pricing, etc.).

Outside the EU, the first implemented version of the MFA will have stand-alone models for the three sectors (steel, cement, and plastics). It will be informed with data from the REMIND integrated assessment model. Since the models are stand-alone, cross-sector interactions can only be captured exogenously, via harmonisation and data input from models capturing these interactions.

Funded by the European Union

Full coupling of the model to REMIND and demand being informed from vehicle and buildings stock models is also planned, although it is not part of the work plan of this project. If implemented, this would allow for a common source of material demand, like in the EU-MFA for Europe. Also, production volumes and prices would be linked to REMIND, where they are part of a fully coupled optimisation problem, such that sector interactions could be captured endogenously.

5.6 EDM-Invest: Techno-economic industry module

The WISEE EDM-Invest module is a generic framework for cost optimisation of sectoral transformation pathways across regions, sites (within regions), and plants/technologies that are connected to a production network via their inputs and outputs and transport (costs) between sites. It is/will be applied to each of the three sectors steel, petrochemicals and cement separately through structuring sector-specific input data according to the frameworks needs.

As each sector-specific application of the EDM-Invest module focusses on one sector only, it considers cross-interactions between these sectors only to the extent as represented by the input data. A prime example of how data input can be used to represent cross-sector interactions is to use the amount of blast furnace slag that is produced in the EDM-Invest Steel module as input to the EDM-Invest Cement module.

Beyond that, cross-sectoral interactions can be covered by harmonised input data for the sectoral modules, such as energy and CO_2 prices and upscaling scenarios for H_2 and CO_2 infrastructures.

5.7 FORECAST-Industry: Techno-economic industry module

The FORECAST-Industry module is an open-access framework for techno-economic analyses of industry with high technological and spatial resolution (Neuwirth et al., 2024a, Neuwirth et al., 2024b). It is based on a simulation approach and considers individual industry sites and their production units. Each existing industry site is represented with specific information on geolocation, production units and processes as well as corresponding details such as production capacities and emissions. The investment decisions depend on the scenario-specific assumptions, such as energy carrier prices, policy instruments, and local infrastructures. Some of the necessary inputs, e.g., energy prices, are fed in from other models, such as OPEN-PROM. The decision is modelled as a discrete choice among competing processes with their total cost of ownership as the main decision criterion. The age of production units and their reinvestment cycles are considered the main restrictions on the dynamics of the transition. Especially the integration of circular economy strategies from the MFA modules results in a new level of detail to model upcoming strategies. It is used to consider the general scenario narratives by using socio-economic data from OPEN-GEM and economic data from OPEN-PROM as input within TRANSIENCE. Further, circular economy strategies from the MFA modules are linked to FORECAST-Industry and considered in the development of the industry transition.

The model allows to assess different scenarios for industry transformation pathways and analyse the implications of varying energy prices and policies as well as the spatial distribution, infrastructure access, and the age structure of the current plant stock and its typical reinvestment cycles. The result of the model are projections on the future energy demand, techno-economic results per process, and the stock turnover of industrial processes with georeferenced resolution.

5.8 premise: Life Cycle Assessment module

The Python package *premise* is used to modify background LCA databases based on the model outputs from OPEN-PROM, EDM-Invest, FORECAST, and possibly the EU-MFA model. Those outputs will be harmonised in terms of future scenarios. Selected processes—including those for steelmaking, cement, and plastics—within the LCA background database *ecoinvent* are modified using those model outputs. In premise, there are sub-modules addressing the modification of the steel sector (such as updating efficiencies, power consumption, regionalisation, primary versus secondary steel shares, and integration of carbon capture and storage if needed) and cement sector (such as making new market activities, updating efficiencies, power consumption, regionalisation, and integration of carbon capture and storage if needed). Finally, we will change market activities for the petrochemical and plastic sector (and change secondary vs. primary production rate).

Next, based on the model outputs and the modified background LCA database, we quantify environmental burdens of system imparts of entire energy pathways, or for the sub-sectors mentioned, using Python module *pathways*[4] accounting for both direct and indirect interactions as well as resources and emissions.

Since sectors are interconnected in LCA databases, interactions between the value chains of steel, cement, and plastics are addressed and accounted for in their upstream and downstream processes.

[4] https://github.com/polca/pathways/tree/main

6 Conclusion

In conclusion, the development of MIC3 is intrinsically driven by the research questions it seeks to address, ensuring that the model structure and constituting modules align with the core inquiry. The present report has advanced the model development on three fronts. First, it offered a conceptual framework suitable to inform the meaningful connection of constituting MIC3 modules in the context of the industry transition. Second, it illustrated the diverse application possibilities of MIC3 through two example research questions that cover different policy- and industry-relevant issues. Third, the modelling of interactions between (industrial) sectors was explored to increase understanding about the indirect effects of decarbonisation and circular economy strategies.

Moving forward, the categorisation of research questions will be carried out to enhance the model's applicability. This will involve grouping questions into two key categories: first, by different scenario narratives that reflect varied environmental, economic, and policy contexts; and, second, by the decarbonisation and circular economy intervention 'uptaking' modules, which focus on the specific systems impacted by such measures. Additionally, the incorporation of causal loops diagrams, created based on stakeholder workshops (see Deliverable D2.2), into the model development will help capture dynamic feedback and interdependencies within the (industrial) system. Future developments will also emphasise more site-specific questions, enabling the model to be tailored for local contexts through re-coupling exercises that integrate regional data and assumptions. These advancements will strengthen the model's capacity to address complex, real-world challenges, ensuring its relevance and flexibility in supporting decision-making at various scales.

Annex

A complete list of potential research questions compiled until now. Question 1-9 were put forward in D2.2 'Assessing Needs for Model Applications'.

Q1. How resilient are decarbonisation pathways and strategies against drastic price shocks or supply chain disruptions? Recent history has led to a significantly increased risk/uncertainty perception of industrial stakeholders. They would appreciate more extreme security-informed scenarios reflecting dramatically different prices and/or restricted availability of some resources.

Q2. What are the costs of economic resilience and how can we measure it? From an industrial policy perspective, we might need to subsidise some strategic but potentially uncompetitive industries (e.g. critical raw materials, microchips). The question is which sectors and how much should they be supported? This question is closely related to the need for more extreme security-related scenarios which provide clues as to which sectors are particularly relevant for economic resilience and which ones might be more easily substituted.

Q3. Which effect can circular economy strategies have in enhancing resilience and competitiveness of EU industries? While Europe may have limited remaining natural resources, it is rich in secondary resources. The questions how these can be leveraged to mitigate price and availability concerns related to raw materials.

Q4. Which public investments are key and need to be prioritised? And can we design decarbonisation pathways that minimise (public) investments? Political uncertainty is increasingly perceived as a main barrier for investment decisions. It is partly fuelled by the perception that governments are unable to leverage the required (public) investments and there is increasing competition between different policy areas over scarce public resources. This raises the question of prioritisation.

Q5. What are potential socio-economic impacts (incl. distributive and health impacts) of different decarbonisation and circularity solutions on social acceptance and consumption patterns? Stakeholders acknowledge the importance of the social dimension of transitions. If not addressed, there is a risk that backlash, and resistance will further enhance political uncertainty creating a reinforcing feedback loop with the investment bottleneck highlighted above.

Q6. How fast are markets for green raw materials going to develop under a variety of policy measures to support green lead markets? Current models typically only provide for aggregated demand for specific materials that lacks granularity in terms of the different qualities required, the location of the demand or the production method used. In order to provide a clearer picture models would need to differentiate markets for green vs. conventional energy-intensive commodities.

Q7. How potent are locational advantages of clustering vis-à-vis locational disadvantages related to limited availability and comparatively high cost of energy supply (RE and hydrogen)? Industrial stakeholders perceive cluster effects and industrial symbiosis as key for their current and future competitiveness. Perhaps the question is how these locational advantages of clustering can be represented in models, because if they are not, we are missing an important part of the competitiveness picture and run the risk of creating self-fulfilling prophecies of waning competitiveness.

Q8. What is the impact of different decarbonisation infrastructure investment strategies on emissions reduction, economic competitiveness, and energy security in regions heavily reliant on

Funded by the European Union

PROCESSES4PLANET

fossil fuels? As the insights presented above highlight, infrastructure investments are imminent and key to unlock full decarbonisation. To take investment decisions, the effectiveness and trade-offs of these different investment strategies needs to be explored across key sustainability dimensions: emissions reduction, economic competitiveness, and energy security.

Q9. What are trade-offs between spatial limitations, which can hinder large-scale infrastructure development, and the potential benefits of geographical proximity for fostering industrial symbiosis and circularity? So far, space constraints are hardly taken into account in scenario modelling but may significantly limit the available options to implement specific decarbonisation strategies. This is particularly relevant for the chemical industry where it is clear that from a global or European perspective biobased feedstocks, carbon-rich waste and captured carbon from other processes will all play a role as alternative feedstocks to substitute virgin fossil fuels. But at the site level, tough decisions will have to be made as to which strategy is the right one to convert this specific site.

Q10. How much will a shift to a circular economy with reduced raw material demand, and increased material efficiency, reduce the overall costs of the transition to a net-zero GHG industry in the EU? What does this mean for the role of industrial Carbon Capture and Storage (CCS), negative emission technology, and other expensive mitigation options?

Q11. A shift to a circular economy will result in reduced imports of raw materials to the EU. **How will this affect the trade balance, the resilience of the EU economy, as well as the EU GHG footprint?**

Q12. Certain parts of the industry transformation – in particular electrification and hydrogen use – should to some extent be synchronised with the energy transformation to be beneficial for GHG emission reduction (e.g. in most cases direct electrification of industrial processes does not reduce systemic emissions if electricity is still produced mostly with natural gas and coal). CE may change the picture through reducing the overall energy demand of industry (and other sectors), potentially leading to a swifter increase of renewable shares in the energy mix, paving the way to earlier fuel switches in industrial production. **To what extent can CE accelerate the transition of industrial energy consumption towards renewables?**

Q13. Different policies must align well on the timeline to facilitate a smooth transition of industrial production towards net-zero. For example, if CO2 prices climb very high before CBAM is fully operational or support measures are implemented, imports may replace domestic production, and plants may be decommissioned and no longer be available for turning them "green". Another example would be the creation of green lead markets whose volume and specifications need to match what is technically feasible. **Which timing-related interdependencies exist between CE measures and other policies?**

Bibliography

Armington, P. (1969). A Theory of Demand for Products Distinguished by Place of Production. *IMF Econ Rev 16*, 159–178. https://doi.org/10.2307/3866403

E3-Modelling. (2017). *GEM-E3 Model Manual*. https://e3modelling.com/modelling-tools/gem-e3/

Fragkos, P., & Fragkiadakis, K. (2022). Analyzing the Macro-Economic and Employment Implications of Ambitious Mitigation Pathways and Carbon Pricing. *Frontiers in Climate*, *4*. https://doi.org/10.3389/fclim.2022.785136

Neuwirth, M., Fleiter, T. & Hofmann, R. (2024a). Modelling the market diffusion of hydrogen-based steel and basic chemical production in Europe – A site-specific approach. *Energy Conversion and Management 322*, 119117. https://doi.org/10.1016/j.enconman.2024.119117

Neuwirth, M., Fleiter, T. & Hofmann, R. (2024b). Modelling the transformation of energy-intensive industries based on site-specific investment decisions. *Scientific Reports, 15*. https://doi.org/10.1038/s41598-024-78881-7

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling*, *135*, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Wesseling, J. H., Lechtenböhmer, S., Åhman, M., Nilsson, L. J., Worrell, E., & Coenen, L. (2017). The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, *79*, 1303-1313. https://doi.org/10.1016/j.rser.2017.05.156

Wiedenhofer, D., Streeck, J., Wiese, F., Verdolini, E., Mastrucci, A., Ju, Y., Boza-Kiss, B., Min, J., Norman, J., Wieland, H., Bento, N., León, M. F. G., Magalar, L., Mayer, A., Gingrich, S., Hayashi, A., Jupesta, J., Ünlü, G., Niamir, L., … Pauliuk, S. (2024). Industry Transformations for High Service Provisioning with Lower Energy and Material Demand: A Review of Models and Scenarios. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-110822-044428