TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 30/10/2025

D7.1 – Updated open data management plan

WP7 - Operationalisation of the open modular framework

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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	D7.1 – Updated open data management plan		
Work Package	WP7 - Operationalisation of the open modular framework		
Date of Delivery	**Contractual** 31/10/2025	**Actual**	30/10/2025
Nature	Report	**Dissemination Level**	Public
Lead Beneficiary	Institute of Communication and Computer Systems (ICCS)		
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Keywords	Data management plan; FAIR data; machine-actionable; data handling		

EC Summary Requirements

1. Changes with respect to the DoA

The I2AM PARIS web platform is now referred as IAM PARIS web platform. No other changes with respect to the work described in the DoA.

2. Dissemination and uptake

This report shall serve as a guide for all consortium partners on how to handle project datasets. It can also be used by external users to understand how data in the TRANSIENCE project is collected, processed, and disseminated.

3. Short summary of results (<250 words)

This report presents the updated version of the open Data Management Plan (DMP) for the TRANSIENCE project. The DMP continues to evolve alongside the project, reflecting progress made in data generation, curation, and sharing during the first project phases. It describes the datasets produced and used within TRANSIENCE, outlines how they are made findable, accessible, interoperable, and reusable (FAIR), and details the measures ensuring data quality, security, and ethical compliance.

The project maintains a machine-actionable Data Management Plan (maDMP) through the ARGOS service developed by OpenAIRE and EUDAT. The maDMP is regularly updated with metadata, access conditions, and links to datasets generated during the project.

The current version of the DMP documents the integration of open databases and modelling outputs that support the MIC3 framework. These include datasets on policies and technologies for industrial circularity and decarbonisation, product and service specifications, ontologies for data interoperability and industrial pilot modules for key sectors such as steel, cement, and plastics. Also, open science protocols from D3.8 are presented. All public datasets are accessible through the TRANSIENCE Zenodo community and the IAM PARIS web platform, ensuring long-term availability, transparency, and reuse. This DMP will continue to be refined and expanded, with the final update planned for Phase 3 of the project (Deliverable D11.2).

4. Evidence of accomplishment

This report and the machine-actionable DMP in ARGOS (link).

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 – Fundacion 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

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Executive Summary

The TRANSIENCE project generates and uses a large volume of data through its model development and scenario analysis activities. This updated report presents the second version of the project's Open Data Management Plan (DMP), which documents how data are collected, organised, stored, and shared across the consortium. The DMP outlines the measures adopted to ensure that all data produced in TRANSIENCE are findable, accessible, interoperable, and reusable (FAIR), while also addressing resource allocation, data security, and ethical aspects.

This updated version reflects the progress made after the first DMP was published and incorporates new datasets and practices developed in the project's ongoing phases. These include the open databases on policies and technologies for industrial circularity and decarbonisation, the product and service database, and the EU industrial pilot modules integrating the FORECAST-Sites and ITOM models. All public datasets are made available through the TRANSIENCE Zenodo community and the IAM PARIS web platform, ensuring open access, transparency, and long-term preservation.

In parallel, TRANSIENCE continues to maintain a machine-actionable Data Management Plan (maDMP) through the ARGOS service of OpenAIRE and EUDAT. The maDMP is continuously updated with metadata, access conditions, and links to datasets, model repositories, and publications generated by the project.

The report also introduces the open science protocols developed in Deliverable D3.8, which provide practical guidance for implementing open and FAIR practices in data sharing, model development, and documentation. In addition, the DMP now includes the first steps toward building project-wide ontologies for data sharing, designed to support interoperability between models and datasets within the MIC3 framework.

The report begins with the working definitions of data, DMP, and machine-actionability used in TRANSIENCE (Section 1), followed by an overview of the project's data scope, collection purposes, and formats (Section 2). Section 3 outlines the FAIR data strategy, and Section 4 details the allocation of resources to support its implementation. Section 5 describes data storage, security, and recovery procedures, while Section 6 addresses ethical considerations in data handling. Section 7 introduces the TRANSIENCE Zenodo community, and Section 8 presents the machine-actionable DMP in ARGOS. Section 9 discusses the open science protocols developed under D3.8, and Section 10 documents the new datasets and repositories created during this phase, including the policy and technology datasets, ontologies, and the product and service database.

Contents

Table of Figures

Table of Tables

1 Introduction

This report presents the updated version of the Open Data Management Plan (DMP) for the Horizon Europe project TRANSIENCE. It describes how research data are collected, processed, shared, and preserved, and it sets out the principles and procedures governing open and FAIR data management throughout the project. The DMP provides a transparent framework for ensuring that all data produced within TRANSIENCE are Findable, Accessible, Interoperable, and Reusable (FAIR), supporting effective knowledge exchange across partners and contributing to open science practices.

A DMP is a structured document that defines how research data are managed across their entire lifecycle. It outlines the methods, measures, and responsibilities that ensure the quality, security, and long-term accessibility of research data. By describing how datasets are documented, stored, and shared, the DMP helps maintain both the scientific value and the reusability of project outputs.

Building on the first version of the DMP, this updated report reflects new developments in data management, including the integration of open datasets, model documentation, and ontology-based structures that support interoperability among the project's modelling components.

Alongside this report, TRANSIENCE maintains a machine-actionable Data Management Plan (maDMP) using the ARGOS service developed by OpenAIRE and EUDAT. A machine-actionable DMP can be automatically processed and updated by computational systems, allowing continuous integration of metadata and dataset links. This ensures that the plan remains current and interconnected with the project's evolving research outputs. The ARGOS platform enables the creation, versioning, and publication of maDMPs, supporting both private drafting and open sharing. It also integrates with Zenodo, allowing DMPs and datasets to be published and assigned a Digital Object Identifier (DOI), ensuring long-term accessibility and traceability.

This DMP, together with the ARGOS-based maDMP, forms the foundation for open data management in TRANSIENCE and complements the project's open science protocols and ontology development efforts, which aim to promote transparency, interoperability, and reproducibility across all modelling and data-sharing activities.

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2 Data summary

2.1 Project objectives and implications for data collection and generation

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. Towards this goal, it will develop an open-source, user friendly, and validated modelling framework that meets these requirements and can address the questions arising in the next phase of Europe's industry transformation.

The proposed framework will be the Model for European Industry Circularity and Climate Change mitigation (MIC3) and will allow the enhanced representation and full integration of six key dimensions of the transition to a climate-neutral, sustainable, and circular industry in Europe: the socioeconomic, the product and end-use/service, the material, the industrial, the energy system, and the environmental dimensions.

To capture these dimensions, a series of interoperable modules will also be developed and integrated, focusing on energy intensive industries and process industries, by combining different modelling paradigms, including system dynamics, industrial metabolism, agent-based, bottom-up techno-economic, and macro-economic modelling, while building on and opening the code of leading modelling tools. The project will generate an open database of circular economy measures, costs, and potentials (MS10) which will be publicly shared and used for modelling activities within TRANSIENCE. Similarly, we will develop a service and product database of key components for the carbon neutrality of European economy and society, containing product and service characteristics and specifications as well as material composition and supply chain-related information (D4.2).

Our flagship output, MIC3, the 'satellite' modules comprising it, and the scenario exercises stemming from it will be co-developed and validated with relevant stakeholders from industry, policy, and civil society, as well as used to inform assessments and transition strategies, at EU and country level, at global level, and within four heterogeneous regional industry clusters in Europe, to ensure their usability and exploitation in real-world use cases.

To support the development of MIC3, open-source and FAIR data principles and established practices from the broader software development community will be followed. We will create guidelines and tools for collaborative model development and APIs (Application Programming Interfaces) to enable communication among satellite models. The APIs will be based on clear, robust rules agreed with partners, enabling the required exchanges for MIC3 operation, extensively documented in a report (D7.2) and an online service (Swagger), and explicitly designed to ensure modularity beyond the project context, allowing third party models to connect with modules (in tandem and individually). Executable containers of the modules will be provided to enable exploitation of the APIs by others. Automated error checking routines to ensure quality of data transfers between modelling tools will be built, to ensure quality of data transfers between modelling tools, create protocols to guide modelling exercises and activities of the project based on input from partners and external stakeholders, and program validation routines for evaluating the feasibility of produced scenarios against a variety of indicators (MS16). Validation diagnostics will be developed to enable consistency and robustness of results for all modules individually as well as for MIC3.

The entire model code will be open source and model development will follow an open development strategy (D3.2). We will also define diagnostics and open science protocols to ensure smooth module

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integration and create a clear documentation of all variables, parameters, concepts, and assumptions used in the models (D3.8). We will provide guidelines for opening our work via GitHub and Docker using established open-source practices from the wider software development community (D7.2). Apart from open practices, we will secure models' accessibility by stakeholders, providing extensive documentation and APIs to online, running versions of all modules, and promote the simplified version of MIC3 among industry actors, along with tutorials and a helpdesk service during the project and for two years afterwards (D12.4)

All input data of TRANSIENCE models, and outputs of scenario analysis, will be hosted in the data sharing platform IAM PARIS[1], along with extensive documentation of the satellite modules and MIC3, links to model code in GitHub, and user-tailored libraries for each stakeholder group (industry, policymakers, researchers) to interactively visualise our model results. Apart from hosting detailed documentation for models and interactive visualisations to describe the results of modelling exercises, TRANSIENCE will also include fit-for-purpose information and input data, user guides and training kits, as well as explanatory components to discuss results in non-expert language, highlighting key takeaways.

Our maDMP will provide rich metadata for datasets along with their links in Zenodo and IAM PARIS, further increasing their findability and transparency, which in turn could enable results verification, synergies between research projects, leveraging on existing work, and identification of errors or biases (Alvarez-Romero et al., 2022), and thus contribute on TRANSIENCE goal towards understanding the pathways of European industries to decarbonisation and increased circularity performance.

2.2 Types and formats of data

To achieve the projects objectives outlined in Section 2.1 requires the generation and collection of various types of data. Data used for modelling inputs will be mostly quantitative and based on datasets in spreadsheet format (e.g., xlsx or csv) or prebuilt data (e.g., Rda format used for the R language). New model code will be in the format of the programming languages used to develop these models. For instance, ITOM is programmed in Python and, thus, its code will be provided in the Python file format.

Qualitative insights from existing body of knowledge and from stakeholder co-creation activities such as interviews and surveys will also be used to inform modelling. Examples of such qualitative insights could be potential barriers in the development of technologies used for industrial circularity or decarbonisation based on interviews with experts. Our shared database of policy measures and technology costs for mitigation, circularity action, and sustainability will allow qualitative analysis to proceed systematically and explore transformation opportunities, challenges, and appropriate policy packages or technologies in sectors with significant potential. The database will be provided in csv format in Zenodo and as an online interactive application. The latter will allow for different searches and filtering of outputs and potential translation into either exogenous or endogenous variables to increase flexibility of adaptation to generate input that is appropriate for the diversity of our models.

Our scenario results will also be quantitative and exported in a spreadsheet format or other formats that are easily converted to spreadsheets, and available on IAM PARIS. These output datasets will inform the scientific and policy publications of the project which will be provided in pdf formats. Table 1 shows a non-

[1] https://www.i2am-paris.eu/

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exhaustive list of the data types and formats that will be used for different project activities.

Table 1. Data types and formats per project activity

Project activity	Data collected and generated	Data formats
Develop the new modules and models	**Collect**: Code from previous versions of models, feedback from project stakeholders and communities of practice for the different models **Generate**: New model code and documentation	File formats related to the programming language of each model (e.g., py, R, h, cpp, GAMS), reports documenting the model and stakeholder feedback in pdf
Compile the input data for the new models	**Collect**: National and sectoral statistics on socioeconomic parameters, macroeconomic indicators, energy use and supply, industrial indicators, physical demand for products, policy options; technological cost and innovation data; investment costs; global material demands, supply, and circularity; global material demands, supply, and circularity; and other modelling inputs **Generate**: Curate the raw data into a format and data structure that is usable by project models	Spreadsheet-like formats, e.g., xlsx and csv, as well as other formats such as txt, json, sqlite databases etc.
Develop two open databases, one on circular economy measures and another on products and services needed for climate neutrality	**Collect**: Information about circular economy measures from policy and scientific documents, including their costs and potentials/effectiveness in terms of achieving circularity and climate neutrality; characteristics of products and services that are used for the transition towards climate neutrality, e.g., wind turbines, PV panels, EVs, etc. **Generate**: Curate the raw data into a consistent format and data structure that is usable by the project's models and can be easily understood by external users. Both databases will be accessible through online interactive interfaces in IAM PARIS.	xlsx, csv, txt, json
Scenario analysis using the new models	**Collect**: Scenario definitions based on the stakeholder engagement activities of the project **Generate**: GHG emissions, industry relocation, material imports, circularity, sufficiency, future energy demand, fuel mix, jobs creation, resilience to shocks, costs, and other social, economic, and environmental indicators	Reports documenting results and stakeholder feedback in pdf; results in xlsx, csv, txt, json. Scenario results will be also uploaded to the IAM PARIS platform as interactive tables.

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2.2.1 Data processing tools

The main data processing tools used in the project will be the satellite modules comprising MIC3 (Table 2), and MIC3 itself. To develop a hybrid model ecosystem that helps promote the strengths and overcome the weaknesses of each of these modules, efforts will be put on creating interfaces among them to enable firm links in terms of data flows, time, structural differences, and solutions. Dedicated data exchange interfaces will be developed to couple the satellite modules, so that further features and higher fidelity modelling can be achieved, while maintaining their modularity and standalone operational capacity. This entails creating tools for processing the outputs and state-of-the-art visualisation that draws from the best available options, such as those featured by the JRC's Energy and Industry Geography Lab, a tool which maps energy, industrial and other relevant infrastructure required for a climate-neural EU industry (JRC, 2023).

Table 2. Satellite modules of MIC3

Module	Partner	Focus	License	Code repository
OPEN-GEM	E3M	Socioeconomic impacts	GNU AGPL 3.0[2]	https://github.com/e3modelling/OPEN-GEM
P&S Database	PSI	Products & services	CC BY 4.0[3]	https://zenodo.org/records/15517592
EU MFA	WI & Fraunhofer	Material and sectoral flow in EU	GNU AGPL 3.0[2]	https://github.com/wupperinst/transience-eu-mfa/
ITOM	WI	Industrial transformation optimisation	GNU AGPL 3.0[2]	https://github.com/wupperinst/itom
FORECAST-Sites	Fraunhofer	Industrial technology diffusion	GNU AGPL 3.0[2]	https://github.com/fraunhofer-isi/forecast-sites
REMIND-MFA	PIK	Global material flow and trade	GNU AGPL 3.0[2]	https://github.com/pik-piam/remind-mfa
OPEN-PROM	E3M	Energy system	GNU AGPL 3.0[2]	https://github.com/e3modelling/OPEN-PROM

[2] https://www.gnu.org/licenses/agpl-3.0.en.html
[3] https://creativecommons.org/licenses/by/4.0/legalcode

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LCA	PSI	Environmental life cycle assessment	BSD 3-Clause[4]	https://github.com/tomterlouw/lca_transience

Detailed model names: OPEN-GEM = Open General Equilibrium Model for Economy-Energy-Environment, P&S Database = Product & Service Database, EU MFA = Material Flow Analysis for the European Union, ITOM = Industry Transformation Optimization Model, FORECAST-Sites = Technology Diffusion Model in Energy-Intensive Industries, REMIND-MFA = Regional Model of Investment and Development - Material Flow Analysis, OPEN-PROM = Open Prometheus, LCA = Environmental Life Cycle Assessment Model.

In addition to models, other data processing tools will be utilised in the project, including (but not limited to) Microsoft Excel, for reading and editing xlsx and csv files, Microsoft Word for writing reports and manuscripts based on project outcomes, and Adobe Reader/Acrobat for generating publications in pdf format. Additional tools and scripting languages, such as Python and R, are also expected to be used for data processing and curation purposes.

The integration of different sources of input and output data in the MIC3 framework poses challenges to data consistency. In this context, methods to ensure interoperability, smooth integration, and quality of model inputs and outputs, despite heterogeneity of data sources across modules will include dedicated quality checks for all modules. All tasks share a common milestone to define interfaces for data exchange among satellite modules (MS5), and one (MS8) on internal data exchange and validation. Modelling teams within the consortium will serve as pilot users to identify any shortcomings and devise effective quality enhancements for the final release of the MIC3 framework, and validation feedback from stakeholders will be incorporated. Typical quality checks in this respect will include inspections of individual time series and indicators for outliers and anomalies, pre-feasibility assessments of each module separately, evaluation of the modules' accuracy based on their ability to recreate historical developments and contrasting internal consistency across scenarios. Therefore, the project will invest in developing additional tools to facilitate compatibility and consistency and ensure that key indicators are within reasonable ranges (Guivarch et al., 2022) via interfaces for automated vetting in the IAM PARIS platform, thus securing that the individual modules produced as part of the fully integrated MIC3 model can be used to directly feed into international scientific assessments, notably those of the IPCC AR7 cycle.

2.2.2 Data inputs and outputs for models

In terms of data inputs, we will use fully open datasets when possible or at least provide flexible options for defining inputs, allowing users to choose between open or proprietary datasets for simulations. Data outputs will be fully open access based on the FAIR data guidelines provided in this report and its updates (Section 3). These guidelines will be also added in the maDMP to facilitate the uptake and reuse of all outputs via automatic parsing of metadata. Insights from scenario modelling will be publicly available via Zenodo in the form of scientific papers for academics, guides for industrial actors, and policy briefs for policy and other stakeholders (D9.3, D12.3). Datasets will be presented via interactive visualisations in IAM PARIS, offering customised interfaces for all audiences and key policy- and industry-relevant insights/clarifications.

[4] https://opensource.org/license/BSD-3-clause

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All publications and datasets will be open access via a Zenodo community while all project code will be open source via GitHub. All papers and relevant datasets will be shared at the latest upon publication, using Creative Commons licenses for reusability and DOIs for findability. Table 3 shows an indicative list of data inputs and outputs for models.

Table 3. Indicative input and output data for project models (Giarola et al., 2021; Pauliuk et al., 2017)

Data type	Category	Input/output
Population	Socioeconomic	Input
GDP	Socioeconomic	Input & output
Interest rates and exchange rates	Socioeconomic	Input
Labour participation and productivity	Socioeconomic	Input
Household income	Socioeconomic	Input & output
Macroeconomic and sectoral activity data	Socioeconomic	Input & output
CO_2 emissions	Emissions	Input
CH_4 emissions	Emissions	Input & output
N_2O emissions	Emissions	Input & output
F-gases	Emissions	Input & output
Other pollutants	Emissions	Input & output
Fuel efficiency	Energy	Input
Industrial energy demand	Energy	Input & output
Sectoral energy intensities	Energy	Output
Energy/electricity trade	Energy	Output
Vintage tracking	Industry / Energy	Input
Production volumes	Industry	Input
Material stocks and flows	Industry	Input & output
Recycling potential	Industry	Input
Waste generation and use	Industry	Input
Waste flows	Industry	Input & output
Fossil fuel prices	Prices/costs	Input & output
Technology costs (capital, operating and maintenance)	Prices/costs	Input & output

2.2.3 Data used in scenario analysis

In addition to the data inputs outlined in the previous section, TRANSIENCE modules will require inputs specific to exploratory scenarios, to ensure that MIC3 is able to respond to real-world questions supporting policy and industry decision-makers with relevant information. The desired functionality of MIC3 will be specified in close coordination with relevant stakeholders and in respect to the identified needs, developed typologies, interfaces, and data flows. We have organised four workshops, one in each cluster region, to synthesise in four cognitive maps of systemic interdependencies and feedback loops inhibiting/promoting industrial transition to decarbonisation and circularity. These maps serve as a canvas for the open development strategy, enabling to identify entry points for MIC3 modules and the joint application of their integration to offer analysis relevant to identified challenges and provide a starting point for identifying key policy and industrial questions. We will also organise a workshop to evaluate overlaps & divergences of

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modelled pathways with the ones envisioned by stakeholders and identify assumptions for new pathways to reduce these divergences.

A survey (D11.5) will reach an even wider pool in Europe; survey participants will view results tailored to their context (e.g., region, sector), before assessing whether these results are informative, comprehensible, and can be used directly for their policies, industrial strategies, or research. The findings will guide the final stages of pathway modelling. Additionally, all survey and workshop participants will provide their views on the design of the simplified mode, such as on features and functionalities they would like to see on the tool, format of the results, questions they would like to answer using this tool, etc.

Most of these inputs will be produced during the engagement and outreach activities of the project and will relate to pertinent policy and research questions that stakeholders want to explore with the new models. An example of policies that could be included in our scenario analysis is shown in Table 4.

Table 4. Examples of policy categories and objectives used in scenario analysis (Böck et al., 2020).

Policy category	Policy objective
Climate action	Reduced GHG emissions
	Improved carbon pricing
	Carbon sequestration
Economy & Society	Green growth
	Reduced poverty and inequality
	Unemployment reduction
Energy Efficiency	Nearly Zero Energy Buildings
	Electrification
Resources & Materials	Treatment of landfill gas
	Reduced use of fertilisers
	Increased use of alternative cement
Energy generation, storage & transmission	Energy system flexibility
	Fossil fuel phase-out
	Fuel shift: Green H_2 production & use

Other inputs for explorative scenario modelling will be based on assumptions on the variables mentioned in Table 3, such as whether some technologies are available or not and various assumptions on their costs and other characteristics, and on harmonisation parameters shown in Table 5.

More details on potential scenario inputs will be provided in the Open Model Development Strategy (D3.2) and the Open database of policies & technologies (D3.5).

2.3 Origin, expected size, and utility of data

2.3.1 Origin

As discussed in the previous sections, the development of the new models will be based on the existing code of their base models while their inputs will be based on existing data sources. Strategies to achieve fully open-access data inputs will be drawn out during the project in a case-by-case basis and will aim to substitute proprietary datasets with similar open-source data. In case this is not possible, another potential solution will be to convert input data in a prebuilt, binary format which can be only read by the models and

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can be potentially shared openly. An indicative list of the origin of harmonisation data that may be required is adapted by the Broad Scenario Logic[5] of the IAM COMPACT project and shown in Table 5.

Table 5. Indicative harmonisation data, their origin, and format

Topic	Variable	Context	Indicative data origin	Data format
Socioeconomics	**Population**	EU27+Norway	Population data from Eurostat: Historical statistics through 2018 (Eurostat, 2023); EUROPOP2019 projections from 2019 through 2100 (Eurostat, 2022a, 2022b)	csv
		OECD+7 except EU27/Norway	Population data from OECD Economic Outlook 109 Long-term baseline projections (available for 199 through 2060), to ensure consistency with GDP projections (OECD, 2021). Extend with growth rates from UN WPP2022 after 2060 if necessary (see below).	csv
		Rest of World	UN World Population Prospects 2022 figures for all years (available from 1960 through 2100, with historical data until 2022) (United Nations, 2022)	csv
	GDP	All regions, through 2028	GDP from IMF World Economic Outlook (IMF, 2023) in constant 2017 international dollars unless otherwise indicated by the research question	csv
		EU27+Norway, from 2029	Extend IMF forecast with linearly interpolated real GDP growth rates from the 2021 Ageing Report (European Commission, 2021b, 2021a)	csv
		OECD+ except EU27/Norway, from 2029	Extend IMF forecast with real GDP growth rates from the OECD Economic Outlook 109 long-term baseline	csv
		Rest of World	Extend IMF forecast with GDP growth rates per working age capita from SSP2 (must be calculated using the projected population figures) multiplied by population growth rate from the harmonised population time series	csv
Techno-economics	Technology costs (for reference scenarios)	EU27 and comparable countries	The EU Reference Scenario 2020 (European Commission, 2021; European Commission et al., 2021).	csv
		Other regions, power-sector technologies	Most suitable option are cost assumptions from IEA's World Energy Outlook 2022 (International Energy Agency, 2022).	csv
		Other regions, non-power technologies	Options include adapting costs from the EUR Reference Scenario 2020.	csv
	Fossil fuel prices	Historical prices	Regional prices from IEA datasets (International Energy Agency, 2023a). If	csv

[5] https://iam-compact.eu/sites/default/files/2023-05/D4.3_Broad%20Scenario%20Logic_v1.00_SUBMITTED.pdf

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			participating modellers do not have access to proprietary IEA data, data for some years and regions can be extracted from the freely available World Energy Outlook 2022 report (International Energy Agency, 2022), or if global benchmarks are sufficient, some of these are available for free from the World Bank "pink sheet" (World Bank, 2023)	
		Price projections	Regional price forecasts from the World Energy Outlook 2022 extended dataset (International Energy Agency, 2023), requires subscription. Participating modellers who do not have a license can extract some prices visually from charts in the World Energy Outlook 2022 report (International Energy Agency, 2022). For long-term EU-specific exercises that do not need short-term trends, price projections from the EU Reference Scenario 2020 may be used (European Commission, 2021).	csv
Energy	Energy production and consumption	Historical data	IEA World Energy Balances (International Energy Agency, 2023c)	csv
Emissions	Energy-related CO_2, CH_4, N_2O	Historical data	IEA Greenhouse Gas Emissions from Energy dataset (International Energy Agency, 2023b), if modellers have or can acquire access. Alternatively use EDGAR v7.0 (Branco et al., 2022) which is consistent with IEA but with less detailed breakdowns. Emissions can also be calculated from energy consumption data using default Tier 1 emission factors from the 2006 IPCC guidelines for GHG inventories, which are consistent with IEA emission factors.	csv
	IPPU CO_2 from cement	Historical data	Production data and emission factors from (R. Andrew, 2018). Updated data available on Zenodo (R. Andrew, 2023).	csv
	F-gases and non-energy CO_2, CH_4, N_2O	Historical data	EDGAR v7.0 (Branco et al., 2022)	csv
	Other emissions	Historical data	CEDS (O'Rourke et al., 2021)	csv
	Land-use change emissions	Historical data	Check that used or generated data falls within or close to range spanned by 3 bookkeeping models in the Global Carbon Budget 2022 (Friedlingstein et al., 2022). Use an average of the three models if a single harmonised dataset is required and no other constraints are implied by the research question.	csv

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	All emissions	Infilling of historical and future emissions	Use Silicone software package to infill missing emission components, if required by the modelling exercise (e.g., for climate impact assessment) (Lamboll et al., 2020, 2022b, 2022a)	csv

2.3.2 Size

Based on previous modelling-based projects such as PARIS REINFORCE[6], the total size of data that is expected to be collected, processed, and produced will be around 500GB. Most of this size is expected to result from the data inputs that will be used in the new models, and, especially, from the sheer amounts of data outputs that will be produced. Other types of data that can be relatively heavy include the audio and video recordings of consortium and stakeholder meetings, which should be at a scale of hundreds of MB for each meeting, multiplied by a few dozens of meetings that will be organised. The minutes of these meetings will be documented in a small number of reports which will not be more than a few MB each. Model publications are also expected to not take too much space, considering that they will be around 70 pdf documents. More accurate estimations will be available during the project and the next revisions of the DMP.

2.3.3 Utility

The data outputs that will be produced by TRANSIENCE are expected to be useful to all expected audiences of the project. The new models will be directly useful to climate-economy modellers, circular economy modellers, and other researchers of relevant topics while they will be also indirectly useful to policymakers, industry, and civil society representatives. The results of the scenario analysis will be useful to the same target audiences and inform their policies, strategies, research, and other activities. We will especially focus our efforts to disseminate project data to the European Commission and EU agencies, national/local governments, businesses, industrial clusters, energy-intensive industries, financial institutions, and researchers of the broader climate, energy, and circularity modelling landscape.

[6] https://paris-reinforce.eu/

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3 FAIR data

As the significance of open data continues to grow, a consortium comprising stakeholders from academia, industry, and government collaborated to formulate the FAIR Principles as a benchmark for evaluating the extent to which scientific data exhibits characteristics of being Findable, Accessible, Interoperable, and Reusable (Wilkinson et al., 2016). Embracing the FAIR principles empowers researchers to leverage and expand upon existing knowledge, fostering novel discoveries and technological advancements. Instead of prescribing specific technical requirements, these principles offer a flexible framework that supports a spectrum of enhanced reusability across diverse implementations. The core guidelines for assessing the FAIRness of research data are described in Box 1.

Box 1: FAIR principles for research data

1. **Findability:** Findability enables easy location and access of data by interested parties. To achieve findability, data must be allocated a distinct and enduring identifier known as a Persistent Identifier (PID). PIDs provide unique and long-lasting references to digital objects and serve as standardised references linked to the data, even if its location or access method changes over time. PIDs are a crucial component of findability, enabling anyone possessing the identifier to discover and access the data irrespective of its storage location. While PIDs are essential for ensuring findability, comprehensive machine-readable metadata are also important for the automated discovery of relevant datasets and services. They must clearly and explicitly include the identifier of the data they describe and be registered or indexed in a searchable resource, thus forming a vital aspect of the FAIRification process (Jacobsen et al., 2020).

2. **Accessibility:** Accessibility ensures that data are readily available and can be accessed and used by both humans and machines. The (meta)data should be accessible, even when the data are no longer available. They should also be retrievable by their identifier using a standardised communications protocol, which is open, free, universally implementable, and allows for an authentication and authorisation procedure, where necessary. Accessible does not necessarily mean open, as accessibility stands for "accessible under well-defined conditions", which includes shielding data for personal privacy or national security reasons and assuring the proper data protection (Mons et al., 2017).

3. **Interoperability:** Ensuring interoperability is vital for seamlessly integrating and analysing scientific data across various systems and tools. Achieving this requires structuring scientific data in open and standardised formats that are easily understandable and usable by different software and applications. This approach facilitates data sharing and reuse across diverse disciplines and domains, promoting collaboration and interdisciplinary research efforts. Utilising standardized formats and protocols enables the integration of data into analysis workflows, enabling researchers to extract insights and knowledge from varied datasets (Ravi et al., 2022). This is accomplished through the exchange of data and metadata among different software packages via application programming interfaces (APIs), adhering to relevant community standards and incorporating references to other objects. As a result, metadata should use vocabularies that follow FAIR principles and include qualified references to other (meta)data (Calamai & Frontini, 2018). When effectively utilised, metadata can enable research data to function as "mobile" objects (Latour, 1987) indicating their ability to transition between diverse production contexts while maintaining significant evidential value (Pasquetto et al., 2019).

4. **Re-usability:** Reusable data should be structured and documented in a manner that facilitates its effective reuse for different purposes. This includes providing detailed descriptions of the data's

provenance, quality, and usage rights, as well as adhering to clear and standardized data formats and structures. Enhancing reusability optimises the value and impact of scientific data, given they are thoroughly documented, structured, and annotated with metadata in a way that enhances comprehensibility and usability (da Silva Santos et al., 2023). This involves providing details about the origin, quality, and accessibility of data as well as adopting transparent and standardised data structures and formats of widespread recognition and acceptance. By ensuring data's reusability over time, researchers can leverage existing knowledge, generate results more quickly, and establish connections among researchers and scientific fields.

In the context of TRANSIENCE, we will implement open science principles and establish an open pipeline for model development, opening the 'black box' of scientific assumptions, processes, and results, providing full access to the new modules and model produced (including code, interfaces, and data). Data used and produced will be FAIR, allowing to build and sustain a vibrant community of practice on industry-academia collaboration for knowledge valorisation, yielding benefits for both creators and users (Mons et al., 2017), and to document new modelling capacity for expert and non-expert audiences. The FAIRness of research data involves evaluating various aspects of the data's characteristics and infrastructure.

3.1 Making Data Findable

We will make all project outputs findable through PIDs, adequate metadata, and keywords to facilitate document retrieval via search engines. All deliverables, policy briefs, and business guides will be uploaded in the project's Zenodo community[7] and receive digital object identifiers (DOIs). In the case of scientific publications, a DOI will be provided by the publishing journal, although we will still upload publications, accepted manuscripts, or preprints on Zenodo to keep a full archive of our work there. We will also use the versioning system of Zenodo to keep track of the different versions of the documents that we upload; each version will get a separate DOI, but a top-level DOI will be also available, resolving to the latest version. Additionally, we define a consistent naming system for each type of output:

- Scientific publications: "{author(s)}_{year}" (e.g., Smith_et_al_2023.pdf)
- Policy/Business briefs: "TRANSIENCE_{title}" (e.g., TRANSIENCE_Policy_Brief_on_CE_Principles.pdf)
- Deliverable: "TRANSIENCE_DX.X_{title}" (e.g., TRANSIENCE_D3.1_Open_Data_Management_Plan.pdf)
- Datasets: "{author(s)}_{year}_{dataset_name}" (e.g., Smith_et_al_2024_Cost_Assumptions.csv)

All datasets developed during the project will also be archived in Zenodo and fitted with a DOI. After uploading a dataset in Zenodo we will also link it to the maDMP in ARGOS and describe it with rich metadata and keywords, using the Horizon Europe template provided in ARGOS (see Chapter 7). Similarly, all final model code will be publicly stored in GitHub which will be then linked to Zenodo and the maDMP.

All model documentation, inputs, and outputs will be also published in the IAM PARIS modelling platform to further promote them among the climate-economy modelling community that have been using the platform since its development in 2020. For each dataset, we will include links to all related project publications to further increase findability. Finally, both the platform and the project website will include adequate content

[7] https://zenodo.org/communities/transience

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and an optimised sitemap to ensure findability in search engines like Google and Bing.

3.2 Making Data Accessible

We will use Creative Commons licenses for all deliverables, policy briefs, business guides, and datasets produced in TRANSIENCE. Most project outputs will be published using the highly permissive CC BY license (version 4.0). Exceptionally, we may also consider less permissive licenses such as CC BY-SA to ensure that derivative works will be made available with the same open license. For instance, this will be useful for model code developed in TRANSIENCE to ensure that any derivative software will stay open and free to support industrial decarbonisation in Europe.

Scientific publications will be also published in journals offering open-access options in compliance with the Horizon Europe rules. When possible, we will publish in fully open-access journals, also considering the Open Research Europe publishing platform. In case that the available fully open-access options do not align with the scope of a publication, we will select a journal that offers a gold open-access option from the list of journals that the organisations of project partners have a publishing agreement with.

All modules that will be developed in the project, along with the integrated MIC3 framework, will be published under open-source licenses (see Table 2 above for the license of each module). It is noted that we may use different licenses for model code and input data. Even in case that some of the input data in a module is not open access, we will suggest alternative datasets that can be used in their place.

In terms of file formats, we will strive to use well-known formats that can be opened by freeware software such as pdf, csv, txt, mp3, and mp4 files. When this is not feasible (for instance, when we need to publish an Excel spreadsheet file featuring multiple tabs), we will accompany files in proprietary formats with links to compatible freeware software such as the Open Office suite.

We will also ensure that all open project outputs will remain available for as long as possible. All project publications and datasets will be published in established online repositories such as Zenodo and GitHub where high availability is expected for many years to come. The project website will be also kept online for at least three years after the project's end to support the dissemination and findability of project outcomes. HOLISTIC will also ensure the longevity of the IAM PARIS platform for at least four years after the project ends (till around 2032).

3.3 Making Data Interoperable

We will achieve high interoperability of project data by using adequate data formats and providing informative metadata. As suggested in Section 3.2, all project datasets and reports of the project will be shared through widespread formats such as pdf, csv, and txt, avoiding proprietary formats when possible. The documentation of all new modules along with the results of the scenario analysis will be formatted based on the IPCC AR6/AR7 reporting templates, ensuring that the wider climate-economy modelling community can use them, while also achieving interoperability with other relevant software of the community such as the pyam Python package. However, we will also explore other formats used in the field of industrial ecology, to ensure that our results would be readily usable by circular economy researchers. Metadata for all project datasets will be added in TRANSIENCE's maDMP in ARGOS, using the format template of Horizon Europe. As all information in ARGOS is machine actionable, all metadata can be potentially converted to another format template, further ensuring the interoperability of project datasets.

3.4 Making Data Reusable

As suggested in the previous section on open access, by releasing all deliverables and datasets through CC BY license we will support their uptake by a wide range interested parties. Similarly, all scientific papers will be published under open-access licenses and will be made available to the research community directly after acceptance by the journals. We will also ensure the reusability of datasets by using the Horizon Europe metadata scheme in the maDMP of the project. For each dataset, the scheme will provide a short description of the data, links with publications and other datasets, and guidelines for the specific dataset related to FAIR practices, allocation of resources, and security and ethical aspects. This scheme will be thus similar to the format of this report, although it will provide more specific information for each dataset. Lastly, all modelling documentation and results will be formatted using the reporting templates of IPCC AR6 and, potentially, relevant templates from industrial ecology research, ensuring reusability by the wider modelling community of climate change mitigation and circular economy.

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4 Allocation of resources

Most of the FAIR practices described in Section 3 do not require any costs from the project. All deliverables and datasets will be uploaded in Zenodo which is free to use, and we will also use the free version of GitHub to store project code. Similarly, the documentation of datasets in the maDMP in ARGOS is also free of charge.

Additional activities for the implementation of our open data management plan and require resources have been considered in the project's Grant Agreement. The extension and hosting of IAM PARIS requires funds that have been budgeted under WP3, while funds on the development and maintenance of the project website have been considered in the budget of WP1 and the defined purchase costs for ICCS. We have also earmarked a part of the budget for publishing in open access journals. Most of this budget is managed by the project coordinator ICCS while all partners have some funds available for individual open access publications related to their work in the project. Suggested options for publishing in open access journals are shown in Table 6.

Table 6. Suggested publishing options

Access type	Funder	Fees	License
Publish in a fully Open Access journal	TRANSIENCE Grant	Article Processing Charges; ranging between ~200€ (e.g., Elsevier Societal Impacts[8]) to over 10,000€ (e.g., Nature[9])	CC BY 4.0 CC BY-NC-ND 4.0
Publish in a journal that has the option of Gold Open Access	Publishing agreements between the organisations of project partners and the publisher		

On data curation, storage, and preservation, the project coordinator and quality manager will be responsible for data management and quality control. ICCS and HOLISTIC will jointly take up associated costs and put together (and frequently update) the present DMP report.

All project partners will be responsible for correct data handling and curation based on the guidelines of the DMP, including that model code is frequently uploaded in the TRANSIENCE community in GitHub. As also mentioned above, HOLISTIC will be responsible for keeping the website and the platform online and all related project data available for at least three years after the end of the project. For the platform, both ICCS and HOLISTIC are exploring ways to further extend its lifetime.

[8] https://www.elsevier.com/about/policies-and-standards/pricing
[9] https://www.nature.com/nature/for-authors/publishing-options

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5 Data security

Data assets collected, processed, or stored during the research project have been identified in Section 2, are classified based on sensitivity and importance, as they require different levels of protection. All measures to ensure the security of all project data are taken through robust data storage and secure platforms for communication and data exchange.

ICCS has established a dedicated workspace within its enterprise version of Microsoft Teams to facilitate internal communication, including video calls and chats among project partners, as outlined in Milestone 3. Access to this platform is restricted to authorised users, namely consortium members, ensuring confidentiality. Additionally, this system is seamlessly integrated with a secure instance of Microsoft SharePoint, serving as the exclusive data exchange platform for the project. The management and security of these systems are overseen by ICCS administrators and the Data Protection Officer (DPO), with servers located within the EU (Greece), ensuring compliance with GDPR and relevant EU regulations. This adherence to GDPR standards is particularly vital as SharePoint will also store contact details of project stakeholders, necessitating robust security measures. Likewise, personal data of newsletter subscribers will be stored in HOLISTIC's MailerLite account, which is GDPR-compliant.

Apart from the SharePoint, other data storage systems used in the project include the databases of the project website and the IAM PARIS platform. For both databases, HOLISTIC and ICCS have implemented disaster recovery and backup policies to ensure that the data is safe from loss caused by a disaster such as a critical systems failure, fire, theft, or natural disaster. A similar process is followed by ICCS for the SharePoint system while there is also a versioning system in place that protects the users from accidentally deleting or modifying data.

The project's communities in Zenodo and GitHub will be also used to store data during the process, and, most importantly, to preserve all created datasets and publications after the end of the project. For each dataset, only the minimum amount of data necessary for achieving the intended purpose of the dataset will be released. The likelihood of experiencing data loss within these repositories is minimal, given that all files and documents are stored across multiple online servers to guarantee redundancy. Furthermore, the prospect of these repositories ceasing operations is highly unlikely. However, in such an unlikely event, they have contingency plans in place to migrate all content to appropriate archives, such as the servers managed by the Software Heritage Foundation and Internet Archive.

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6 Ethical aspects

All data collection and management activities within the project will adhere to the EU GDPR regulation and the national privacy and data protection laws of each partner country. This entails implementing appropriate measures to protect the privacy and confidentiality of personal data collected or processed during the research, obtaining consent for data processing where required, and ensuring that data is stored and handled securely. For most activities related to model development, ethical and legal considerations are minimal, primarily focused on honouring the licenses of databases serving as sources for modelling inputs. Conversely, ethical considerations take precedence in all co-creation activities of the project (WP2 – Phase 1), where diverse perspectives of project stakeholders will be gathered through workshops, interviews, and surveys.

During workshops, the Chatham House Rule (Chatham House, 2024) will be applied, ensuring anonymity of speakers and participants. Workshop minutes will strictly adhere to this rule, avoiding any linkage between individuals and specific statements. Similar procedures will be followed for documenting interviews, while surveys will only inquire about personal details necessary for research purposes, such as academic or policymaking affiliation. Explicit and clear informed consent will be sought from all participants in engagement activities, with details on ethical aspects included in WP2 deliverables.

As outlined in Section 5, all contact details and feedback from project stakeholders will be securely stored within the project's SharePoint instance, while newsletter subscriber contact details will be kept in HOLISTIC's MailerLite account. Both platforms are hosted within the EU and are GDPR compliant. Measures will be taken to prevent bulk exchange of contact details through insecure channels like emails. No transfer of personal data will occur between EU and non-EU countries. The sole information collected will be lists of research questions voiced by project stakeholders, maintaining anonymity to ensure anonymisation.

Finally, TRANSIENCE will consider the broader societal implications of our research and strive to maximise its positive impact on society. This involves engaging with stakeholders to ensure that research outcomes are socially beneficial and address pressing societal challenges.

7 TRANSIENCE Zenodo repository

A dedicated Zenodo community have been created for the TRANSIENCE project[10] to ensure that all project outputs are safely stored, preserved, and shared in accordance with FAIR data principles. Zenodo, as an EU-supported open-access repository, issues a Digital Object Identifier (DOI) for each upload, ensuring long-term access, version tracking, and clear citation.

The TRANSIENCE community includes public deliverables such as reports on model development linked to GitHub repositories, open science protocols, stakeholder engagement outcomes, and will include the documentation of the MIC3 framework. It also hosts the project's Data Management Plan and its machine-actionable version, together with open datasets and scenario documentation from the modelling activities. The repository serves as a central access point for open and FAIR outputs produced under all project activities, particularly those related to open model integration, data interoperability, and validation.

In addition to official deliverables, the TRANSIENCE Zenodo community (Figure 1) includes or is expected to include scientific publications, training materials, and guides co-authored by the consortium partners, thus strengthening the link between research, policy, and industry. Each upload includes clear metadata, licensing information, and references to the related data or tools, ensuring that all project resources remain findable, accessible, interoperable, and reusable, while supporting long-term visibility and uptake within the European and international modelling communities.

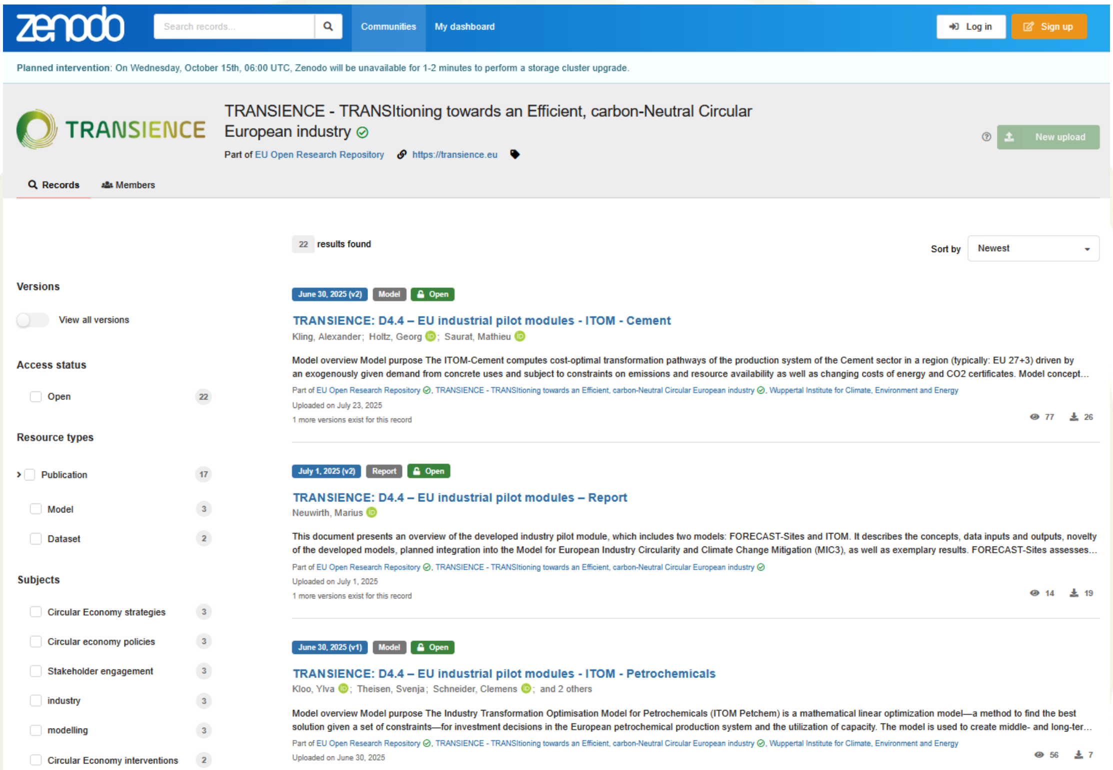

Figure 1. TRANSIENCE Zenodo repository homepage. Most recent uploads are depicted.

[10] https://zenodo.org/communities/transience/

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8 maDMP in ARGOS

In parallel with this report, a machine-actionable Data Management Plan (maDMP) has been created[11] using the ARGOS service developed by OpenAIRE and EUDAT. ARGOS provides an online platform for preparing, updating, and sharing DMPs in a structured format that can be read by both humans and machines. By applying community standards for metadata and interoperability, ARGOS supports the implementation of the FAIR principles and facilitates alignment with the European Open Science Cloud.

DMPs serve as awareness tools, helping researchers handle their data effectively and ensuring its quality, accessibility, and reusability beyond the lifetime of the project. A DMP outlines the digital research methods that evolve throughout the project's duration. Therefore, to remain a useful resource for researchers and stakeholders, the content of the DMP must be regularly updated to reflect the methods applied and the data generated. While maintaining a human-readable narrative remains essential, there is growing recognition of the value of complementing it with machine-actionable details that can enhance transparency and interoperability.

The TRANSIENCE maDMP in ARGOS serves as the central reference framework for all data-related activities in the project, covering data collection, processing, storage, dissemination, and reuse. Each dataset produced within TRANSIENCE is described through detailed metadata, including information on access conditions, licences, and links to related deliverables, model repositories, or publications. The maDMP is continuously updated, for example when a dataset or codebase is deposited in Zenodo, ensuring that the plan remains accurate and up to date throughout the project lifecycle.

For this reason, the TRANSIENCE maDMP in ARGOS provides a detailed overview of all datasets generated, curated, or managed during the project. The maDMP will be updated whenever a project dataset is created or modified, and a summary of its contents will be provided in the updates of this report (D11.2). Personnel from ICCS and HOLISTIC will be responsible for creating entries for new datasets in the maDMP, while all project partners will ensure that the metadata describing their datasets are correct and complete. The full DMP lifecycle in ARGOS is shown in Figure 2.

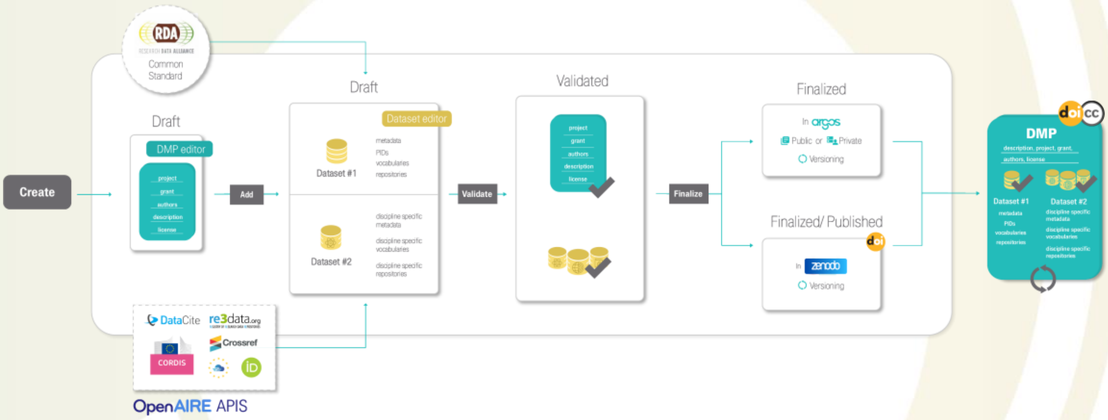

Figure 2. DMP publication lifecycle (OpenAIRE, 2024)

[11] https://argos.openaire.eu/explore-plans/overview/public/30df1ce9-5077-4f28-bfdc-31902af8d910

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The following process is used for creating a new dataset in the TRANSIENCE maDMP:

- The project partner(s) that created the dataset (henceforth called "data creators") share it with ICCS and HOLISTIC ("data managers").
- The data managers upload the dataset on Zenodo.
- The data managers also create a new dataset entry in the maDMP and prefill it by searching the dataset name through the ARGOS interface.
- The data managers complete the metadata for the dataset based on guidance from this report and its updates and also link the dataset to relevant deliverables or scientific publications.
- The data creators are invited to check these metadata and ensure their accuracy.
- The data managers update the maDMP with the new dataset.

A similar process is followed for any new model code, where links are created between the model repositories in GitHub and Zenodo to ensure that each code base receives a unique DOI. This Zenodo entry then is linked to the maDMP (Figure 3), which includes complete metadata, following the same approach as for datasets. These processes are evaluated based on the experience of data managers and creators and may be adapted and improved further during the course of the project.

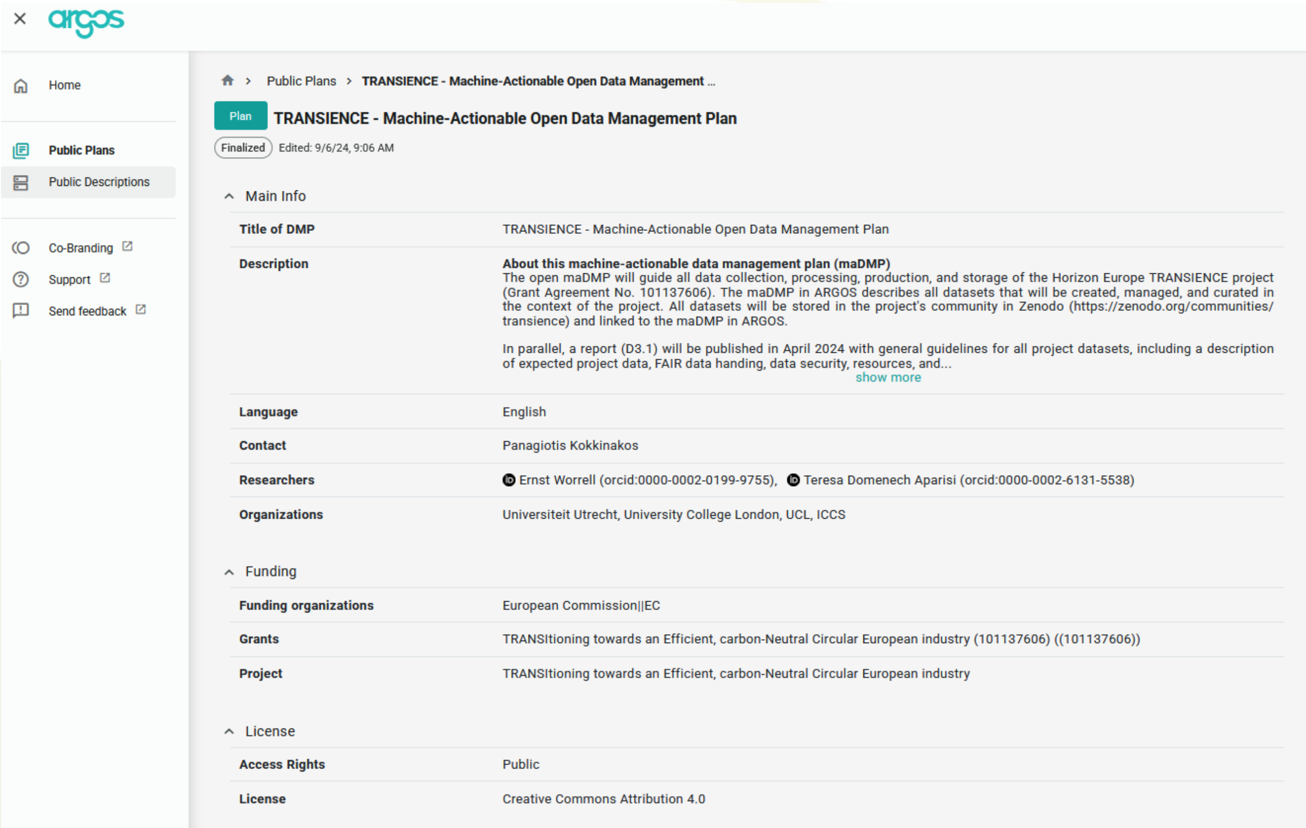

Figure 3. TRANSIENCE maDMP in ARGOS OpenAIRE platform

9 Open science protocols

9.1 Introduction

Open science refers to a set of principles and practices that promote transparency, accessibility, and collaboration in scientific research (Figure 4). Its goal is to make scientific knowledge openly available through unrestricted access to publications, research data, software, and educational materials, while also encouraging the participation of diverse stakeholders throughout the research process. Open science is not limited to sharing results but also includes engagement with different knowledge systems and social actors, supporting collaboration, reproducibility, and inclusiveness in science.

Figure 4. The four main pillars of open science, reproduced from UNESCO (2022)

In TRANSIENCE, open science is implemented through concrete guidelines and actions described in Deliverable D3.8 “Open Science Protocols”[12]. This deliverable was prepared under Task 3.1 “Open and FAIR Data Management (Phase 1)” and complements the project’s Data Management Plan (D3.1) by focusing on the practical application of open science principles, particularly in relation to modelling activities. D3.8 identifies how project outputs such as data, code, and model documentation, can be shared in open-access formats through platforms like Zenodo and GitHub, while ensuring proper licensing, attribution, and long-term accessibility.

The open science protocols developed in D3.8 provide guidance for model development, linking, and use

[12] TRANSIENCE: D3.8 – Open science protocols

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within TRANSIENCE, as well as for structuring and exchanging model data through the use of ontologies. These protocols serve as a reference framework to ensure that all scientific processes within the project remain transparent, reproducible, and aligned with FAIR principles. They will continue to evolve alongside the project, supporting future phases of model integration and application in the MIC3 framework.

9.2 Open science guidelines

All research activities are documented through open-access publications, while input and output data are shared according to FAIR principles. Model code and supporting scripts for data processing and visualisation are being made openly available and stored in online repositories that follow the TRUST principles, such as Zenodo. Table 7 summarises the main inputs, processes, and outputs of the research activities and links them to relevant open science principles.

Table 7. TRANSIENCE research activities and relevant open science principles (Xexakis, 2025)

<table>
<tr><th colspan="2">TRANSIENCE research activities</th><th>Relevant open science principles</th></tr>
<tr><td rowspan="3">Understanding stakeholder needs for new capacities (WP2)</td><td>Inputs: workshops and interviews with stakeholders</td><td rowspan="9">Document all processes through open-access publications (deliverable reports, scientific publications, media articles)

Share raw and processed data (e.g., model inputs and outputs in WPs 4 and 7 or workshop minutes in WP2) along with databases based on the FAIR data principles

Provide as open source the MIC3 model (simplified and full version), its modules, and all relevant scripts (e.g., pathways? for data processing)

Store data and code using TRUST-compliant data repositories</td></tr>
<tr><td>Processes: Three Horizons dialogue framework, cognitive mapping, system dynamics</td></tr>
<tr><td>Outputs: reports, stakeholder-informed research questions</td></tr>
<tr><td rowspan="3">Characterising circularity & decarbonisation options (WP3)</td><td>Inputs: academic and grey literature on circularity, decarbonisation, relevant modelling frameworks, and TRANSIENCE's case study regions</td></tr>
<tr><td>Processes: circularity frameworks, sociotechnical analysis, policy analysis, competitiveness analysis</td></tr>
<tr><td>Outputs: reports, database of circular economy measures</td></tr>
<tr><td rowspan="3">Development of modules & integration into the final model (WPs 4, 7 and Task 12.4)</td><td>Inputs: existing modelling code, stakeholder needs from WP2, academic and grey literature on products and services for circularity and decarbonisation</td></tr>
<tr><td>Processes: development of new modelling capacities, model soft-linking through automated routines</td></tr>
<tr><td>Outputs: new open modules, databases, full MIC3 model, simplified modelling tool, new industrial</td></tr>
</table>

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	transition scenarios for the EU, national and local levels	
Scenario co-creation and analysis; model validation by the stakeholders (WPs 8, 11)	**Inputs**: scenario definitions based on stakeholder engagement activities of the project	
	Processes: model scenarios using the new modules and the integrated MIC3 model	
	Outputs: modelling results in terms of GHG emissions, material needs, costs, industrial energy consumption mix, investment needs at the EU. National and local level (for case studies) etc.	

9.3 Ontology for open science modelling

In TRANSIENCE, ontologies are being developed to support structured, transparent, and interoperable data sharing across the project's modelling activities. Ontologies provide a shared vocabulary that defines the key concepts, parameters, and relationships within a research domain, ensuring that all partners interpret and use data in a consistent way. They enable knowledge to be represented formally and exchanged between researchers, models, and systems without loss of meaning.

Deliverable D3.8 "Open Science Protocols"[13] introduced the first steps toward building a common ontology for TRANSIENCE. The work focuses on identifying and defining the main variables, parameters, assumptions, and concepts used in the project's models, ensuring alignment with existing standards such as the IAMC nomenclature. These ontologies are being designed to link datasets and models within the MIC3 framework, enhancing transparency, interoperability, and reuse of information.

The implementation of the ontologies follows established standards such as the Web Ontology Language (OWL) and the Resource Description Framework (RDF), supported by tools like Protégé and Python-based libraries (Figure 5). Once validated, the ontologies will be published with full documentation and made openly available following open science principles. By formalising how knowledge is represented and shared, this work strengthens collaboration across modelling teams, improves reproducibility, and contributes to building an open and interoperable foundation for integrated assessment and industrial decarbonisation research.

[13] TRANSIENCE: D3.8 – Open science protocols

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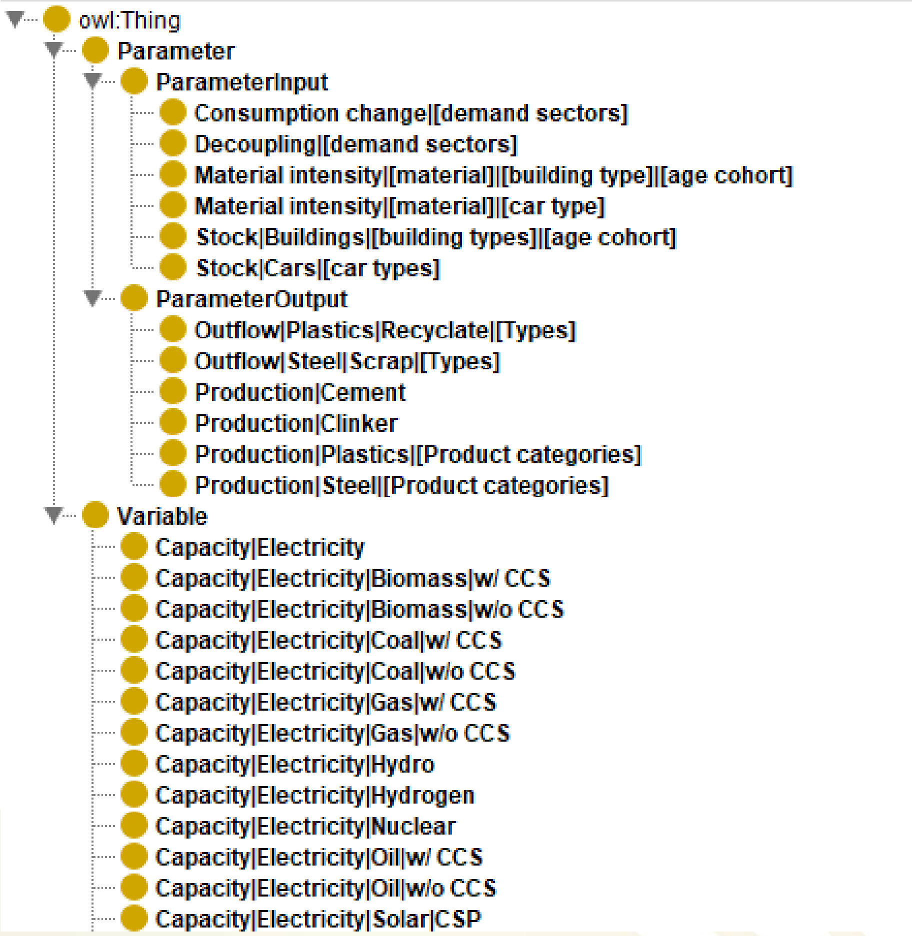

Figure 5. The OWL file tree of the TRANSIENCE project's nomenclature example visualised using the Protégé software. (Xexakis & Alexandrou, 2025)

10 TRANSIENCE Data Hub: An Overview

The following subsections present the modules of the MIC3 framework that were developed under WP4 and the open database of policies and technologies created in WP3, which together form the foundation of the TRANSIENCE modelling ecosystem. These module descriptions correspond to the first phase of model development and integration, linking material, industrial, energy, and socioeconomic systems to support the analysis of circular and decarbonisation pathways. Input data is made as open as possible in the modules following FAIR data protocols (Section 3). In the limited case of restrictive property rights for some input data, meta-information on the sources is provided. In the next update of the DMP (D11.2), input data will be populated with the finalisation of the development process of these modules, ensuring full documentation and interoperability within the MIC3 framework.

10.1 Open database of policies & technologies for industrial circularity and decarbonisation

10.1.1 Overview

This dataset, developed under WP3 Task 3.3 "Characterising circularity and decarbonisation technologies, opportunities, and policies" and linked to Milestone MS10 "Initial policy & technology database", compiles key interventions supporting industrial circularity and decarbonisation. It identifies the main technological measures, their estimated costs, and the parameters required for integration into the MIC3 modelling framework. The dataset is thoroughly documented in Deliverable D3.5.

Circular Economy interventions are categorised according to two complementary frameworks: the "narrow, slow, substitute, and close" resource-use strategies and the "9Rs" hierarchy, which includes refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, and recycle. Decarbonisation measures are included as either complementary circular actions or cross-cutting strategies spanning across these categories.

The dataset provides a structured matrix that links each type of intervention with its respective industrial sector, focusing on the three key sectors addressed in TRANSIENCE: cement and concrete, steel, and plastics. It also includes information on how these interventions can be translated into quantitative modelling inputs and parameters.

Complementary to this, the dataset integrates technology-specific data such as cost estimations for both primary and secondary production routes, a technology cost database, and technology trajectories describing potential impacts on greenhouse gas emissions according to established roadmaps.

Overall, the dataset serves as a foundational resource for analysing the combined effects of circularity and decarbonisation pathways. Its structure and documentation ensure transparency and traceability, with references included both in the accompanying report and within the dataset itself.

Table 8. Policies and Technologies Database components (Domenech Aparisi et al., 2025)

Component	Description
Policy Matrix	Dataset with interventions organised by the 9Rs framework and the 'narrow, slow, and close' framework. Provides examples of intervention types and specific applications across the three core sectors. Includes ideas on how to parameterise interventions in MIC3 models and links to relevant policies.

Matrix_Plastics	Detailed dataset for plastics, covering all aspects as in the Policy Matrix.
Matrix_Cement	Detailed dataset for cement, covering all aspects as in the Policy Matrix.
Matrix_Steel	Detailed dataset for steel, covering all aspects as in the Policy Matrix.
Technologies and Cost	Detailed list of technologies by sector, with qualitative assessment of costs.
Technologies_Plastics	Detailed dataset for plastics, covering all aspects as in the Technologies dataset.
Technologies_Cement	Detailed dataset for cement, covering all aspects as in the Technologies dataset.
Technologies_Steel	Detailed dataset for steel, covering all aspects as in the Technologies dataset.
GTAP-CE Cost	Key technologies across focus sectors estimated from the GTAP-CE dataset, with detailed costs of imported and domestic inputs.
GTAP-CE Cost Summary	Grouped summary of key technologies from the GTAP-CE dataset under a limited number of categories.
Prospective Modelling of Technology Trajectories	Summary of targets for key sectors based on roadmaps related to decarbonisation and circular production routes.

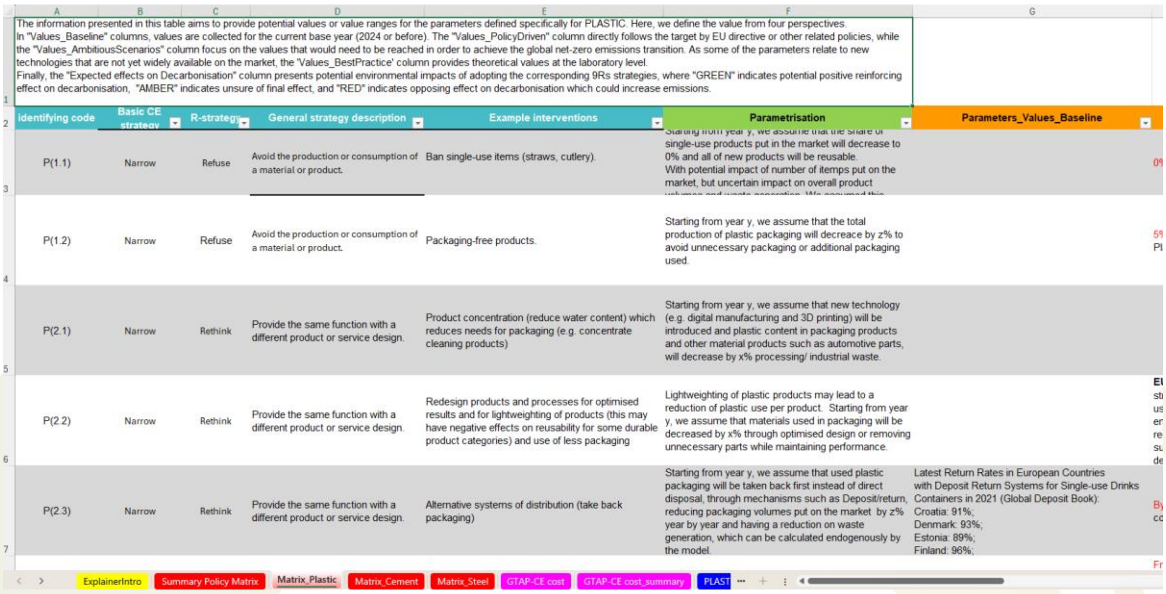

Figure 6. A snapshot of the dataset's spreadsheet file

10.1.2 Data inputs and sources

The policy and technologies database combines information from diverse sources to describe circular economy and decarbonisation interventions. It draws on policy documents, macroeconomic and technology datasets, and forward-looking roadmaps to provide a consistent base for modelling activities in TRANSIENCE. Table 9 summarises the main data inputs and their respective sources.

Table 9. Main data inputs and sources used to compile the Policy and Technologies database.

Type of Data Input	Main Sources / References	Description and Use
Policy dataset	• EU Circular Economy Action Plan and related strategies • Sectoral roadmaps for steel, cement,	Defines the policy context and identifies interventions for circularity and decarbonisation. Builds on Deliverable

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	and plastics • National and regional policies identified through keyword searches ("circular economy strategy", "low-carbon policies", "resource efficiency") • Eur-Lex • EEA Policy Database • OECD dataset • National portals • Reports from UNEP, OECD, and IEA	D3.3 and Task 3.3. Parametrisation informed by literature review and expert input from TRANSIENCE modellers to support MIC3 integration.
Technology dataset	• GTAP-CE database (version 11, 2017) • Peer-reviewed studies • IEA and EPRS technology catalogues. • Reports from Ellen MacArthur Foundation, OECD, WBCSD, and JRC	Provides macroeconomic and technology data on production routes, costs, and emissions across 140 regions and 65 sectors. Includes mature and emerging technologies with TRL, cost ranges, and circularity or decarbonisation potential, supporting model parameterisation in MIC3.
Technology trajectories	• EU and industry roadmaps (Plastics Europe, CEMBUREAU, EUROFER).	Targets for 2030 and 2050 were matched to corresponding technologies, such as mechanical recycling, hydrogen-based steelmaking, and clinker substitution. Baseline data from GTAP-CE (2017) were used to compare current production structures with future targets and to estimate costs and transition needs.
Impact estimations	• Sectoral roadmaps • IEA scenarios	Helps to identify how different technology routes contribute to circularity and decarbonisation goals and support the integration of technological pathways into MIC3 modelling.

10.1.3 Data harmonisation and access

The dataset was created in Excel and can be transferred to a relational database to support its integration with modelling workflows and shared templates across modelling tools. It complements the Policy Matrix developed in Deliverable D3.3 by introducing parameters that translate policy interventions into modelling inputs suitable for MIC3. It also includes key technologies and their associated costs for circularity and decarbonisation. Together, these elements support the quantification of costs for the circular and low-carbon transition, contributing to the model development in WP4 and the modelling exercises in WPs 7, 8, and 11.

Consistency was ensured in the organisation of interventions and technologies, and standard units were applied in the technology cost data. References and source links were included within the dataset to maintain transparency and traceability. The dataset is publicly available through the TRANSIENCE Zenodo community[14] and the IAM PARIS web platform[15], ensuring open access and facilitating its reuse within and beyond the project.

10.2 Socioeconomic module

10.2.1 Overview

The socioeconomic module of TRANSIENCE that was developed as the Deliverable D4.1, is based on the OPEN-GEM model, an open-source Computable General Equilibrium (CGE) model developed to assess the economic implications of energy, climate, and circular economy policies across the European Union. The model captures the interactions between EU Member States and the rest of the world, supporting the analysis of policy impacts on GDP, sectoral production, and industrial competitiveness.

OPEN-GEM represents the global economy through 28 countries or regions, including each EU Member State individually, while the remaining countries are grouped into a single "rest of the world" region. It is a multi-sectoral, recursive dynamic CGE model driven by capital accumulation and technical progress, providing detailed insights into the macroeconomy and its links to the environment and energy system. The model covers 44 activities, including detailed representations of industrial and energy sectors, as well as agriculture, transport, and services.

The module is designed to evaluate the complex interdependencies of the economic system that shape the transition towards a low-carbon, circular economy. CGE modelling offers the advantage of capturing economy-wide interactions, market feedback, and resource reallocations, allowing the identification of indirect effects, distributional impacts, and policy trade-offs. By soft-linking OPEN-GEM with industry-based models, TRANSIENCE extends its analytical capacity to cover key circular economy policies, integrating data on technologies, cost structures, and technology adoption rates by sector.

Overall, the socioeconomic module provides the foundation for assessing the macroeconomic and structural dynamics of Europe's decarbonisation and circular transition. Within the MIC3 framework, it forms a central component for linking industrial, energy, and material flow models, enabling a consistent analysis of economic and environmental outcomes across scenarios.

10.2.2 Data Inputs and Outputs

The OPEN-GEM model is calibrated using the GTAP Data Base (version 11), which provides comprehensive global data on economic, trade, energy, and environmental accounts for 160 countries and 65 activities. Calibration focuses on energy-intensive industrial sectors and uses the GTAP Circular Economy extension (v11, 2017), which distinguishes between primary, secondary, and recycling activities for metals, plastics, and non-metallic minerals. Elasticities for trade and production are also derived from the GTAP database, including Armington elasticities and CES-based substitution parameters.

Model outputs are expressed in monetary values (billion USD, base year 2017) and include key

[14] Open database on product-service specifications and characteristics
[15] Datastories · CE Intervention · IAM Paris

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macroeconomic aggregates such as GDP, household consumption, investment, government expenditure, imports, and exports. Sectoral results on production, imports, and exports by country and region are also included in model outputs.

10.3 Open database on product-service specifications and characteristics

The Product and Service (P&S) database was developed as Deliverable D4.2 of the TRANSIENCE project and published as an Excel dataset. The database supports a better understanding of the material composition of key technologies, service and product demand characteristics, and supply chain elements relevant to Europe's industrial energy transition. Its main goal is to improve transparency in material and circular economy assessments.

The P&S database addresses the need to connect socioeconomic service demand with the physical material requirements of the low-carbon transition, covering both bulk materials such as steel, copper, and aluminium, and critical raw materials such as iridium and neodymium. Material compositions are primarily derived from the premise life cycle assessment (LCA) framework, based on the ecoinvent 3.10 database[16] (Wernet et al., 2016), complemented by literature sources for sectors not sufficiently covered, such as buildings and vehicles.

As part of the Model for European Industry Circularity and Climate Change Mitigation (MIC3), the P&S database acts as a key module within WP4, linking the socioeconomic, energy-system, industrial, and material flow analysis (MFA) components. By translating service demand into product-level and material-specific needs, it enables consistent and coherent modelling across sectors.

Deliverable D4.2 provides open-access data that can be used by modellers, MFA researchers, policymakers, and industrial stakeholders to explore the material compositions of technologies relevant to a low-carbon economy. It also enhances interoperability between the MIC3 modules and contributes to the alignment of MFA, critical raw material assessments, and industrial decarbonisation pathways. The dataset is openly available through the TRANSIENCE Zenodo community[17] and will also be accessible through the IAM PARIS web platform, supporting FAIR access and reuse within and beyond the project.

Future updates will enhance the P&S database by improving methodologies and adding new links between service demand and product demand. The database is designed as a living resource that will continue to evolve throughout the project. Overall, it plays a central role in analysing material flows and integrating the various TRANSIENCE modules within the MIC3 framework.

[16] Database - ecoinvent
[17] Open database on product-service specifications and characteristics

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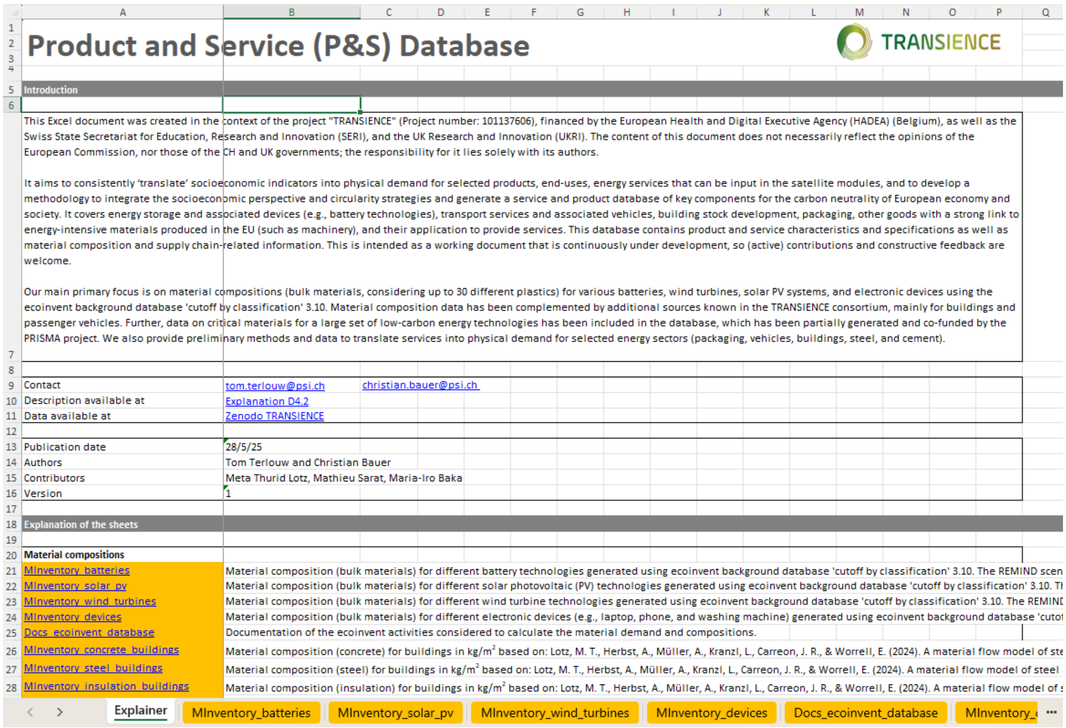

Figure 7. Product and service database Excel file screenshot.

10.4 EU material and sectoral flow pilot modules

10.4.1 Description

The EU MFA model represents a sequence of processes connected through material flows of steel, plastics, and cement. Each process and flow is determined by exogenous parameters such as consumption levels, product lifetimes, trade, and waste collection rates, defined according to the scenario specifications. The model is developed in Python using the flodym[18] (Flexible Open Dynamic Material Systems Model) library, created within the TRANSIENCE project under Task 4.5 (Deliverable D4.3). Building all EU MFA submodules with the flodym framework ensures a consistent code base across the module and with the Global MFA module of MIC3, which is developed using the same framework.

10.4.2 Data inputs and outputs

The EU MFA model relies on a wide range of input data, partly sourced from other MIC3 modules, complemented by external datasets for additional parameters. Table 10 provides an overview of the main exogenous inputs and their sources. The model produces a broad set of outputs, including key material flow variables that serve as inputs to the technoeconomic industry modules. Output data are provided in Table 11.

[18] https://github.com/pik-piam/flodym

Table 10. Exogenous parameters (Sourced from TRANSIENCE deliverable D4.3)

Parameter	Description	Source
Material intensity of buildings and vehicles	Determines the use of materials per unit	P&S database
Building in- and outflows	Determines the construction and demolition of buildings	P&S database
Vehicle registrations	Determines number of new vehicles	Open PROM
Consumption change	Indicates changes in the consumption changes in monetary units	OPEN-GEM
Translation	Indicates changes in the relationship between monetary and physical units	P&S database
Lifetimes	Indicates lifetime of products per use sector (mean and standard deviation)	Literature
Intra-EU trade	Determines exports and imports of basic materials, intermediaries, final products and waste	Various sources, harmonised with OpenGEM
Extra-EU trade		Global MFA
Production	Determines basic material production	Statistics
Process characteristics	Determines losses or input factors for specific processes	Literature
End use matrix	Allocates demand to end use sectors	Literature/ statistics

Table 11. Outputs to other modules (the data are preliminary and sourced from Deliverable D4.3)

Parameter	Description	Uptake
Production	Production of basic materials	Technoeconomic industry module
Waste/scrap	Availability of waste and scrap for secondary production	Technoeconomic industry module

10.5 EU industrial pilot modules

10.5.1 Overview

The EU industrial pilot modules deliverable (D4.4) brings together the two main industry models developed within TRANSIENCE: FORECAST-Sites and ITOM (Table 12). Those two models form the industrial analysis core of the MIC3 framework, and both are available as GitHub repositories[19,20] with documentation that will be further refined as the project progresses. The documentation report of the modules (D4.4) describes the concepts, data inputs and outputs, novelty of the developed models, planned integration into the MIC3 framework, as well as exemplary results.

Table 12. Comparison of the modelling approaches and resulting roles of the industry models FORECAST-Sites and ITOM (Neuwirth, 2025)

	FC-Sites	**ITOM**
Sectors	Iron & steel, Chemical & petrochemical, Non-ferrous metals, Non-metallic minerals (including cement), Food, beverages & tobacco, Paper, pulp & printing (Partly Phase 2) considered at once	Cement, Steel and Petrochemicals, each in separate sectoral implementations
Approach	It utilises a bottom-up modelling approach to deduce energy demand from various processes. In Phase 2, it will incorporate a top-down approach to align with the Eurostat energy balance and enable integration of processes within industrial sites, optimising from the perspective of each individual site. It considers infrastructure availability like the hydrogen backbone.	It utilises a bottom-up modelling approach to deduce energy and material demand considering process integration within and between sites through shared infrastructure. It performs model endogenous cost optimisation of production networks across production steps and sites. It finally depicts high granularity regarding processes, products, and intermediate products.
Role	To simulate the future energy demand of the entire European industry at site level.	To identify and analyse (cost-optimal) pathways to climate neutrality for sectoral production networks.

10.5.2 FORECAST-Sites data

This modelling approach relies heavily on detailed and accurate data. It requires comprehensive and reliable

[19] https://github.com/fraunhofer-isi/forecast-sites
[20] https://github.com/wupperinst/itom

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information on existing industrial sites, along with well-founded assumptions for economic factors such as energy prices and process-specific parameters, including investment costs and energy use.

10.5.2.1 Inputs

The FORECAST-Sites model depends on a wide range of input data, some of which are provided by other MIC3 modules. Table 13 summarises the main external parameters used in the model and their respective sources.

Table 13. Exogenous parameters (Neuwirth, 2025)

Parameter	Description	Type of Sources
Industry site information	Required for initialisation of industrial sites within the model	Industry databases (i.e., Industrial Site Database)
Techno-economic process data	Determines the calculations for economic competitiveness of various process alternatives and the investment decision algorithm	Literature
Production	Required for calibration of the site-specific production volumes	Literature / Public statistics / MFA Module
Energy price data	Driver for economic calculations	OPEN-PROM
CO_2 price development	CO_2-Certificate prices until 2050	Scenario data/OPEN-PROM
Infrastructure	Consideration of hydrogen infrastructure as determinant for process switch	European Hydrogen Backbone Initiative (EHB 2025)

10.5.2.2 Outputs

The model produces time series data on industrial energy demand, transition costs (including site-level investments, energy expenditures, and EU ETS CO_2 certificate), emission reductions, and process diffusion. Table 14 summarises the main output variables used as inputs to the energy system module, while provides selected examples of these results.

Table 14. Preliminary outputs to other modules (Neuwirth, 2025)

Parameter	Description	Uptake
Energy demand	Energy demand per energy carrier as time series to be covered by the supply sector	OPEN-PROM
Process shares	Shares per process and branch to assess process diffusion patterns in each energy-intensive sector	OPEN-PROM

Emissions	Emissions to estimate total reductions within the energy system	OPEN-PROM

10.5.3 ITOM data

10.5.3.1 Inputs

The ITOM framework operates with input data provided in a structured Excel format, as described in its technical documentation[21]. These files include information on products, technologies, their interconnections, transport options, costs, material demand, emissions, and other constraints. Each file represents a sectoral model, with dedicated documentation explaining how sector-specific concepts are translated into the framework's data structure. Scenario analyses are carried out by adjusting these sectoral input parameters.

Although the content varies by sector, the datasets generally include details on technologies and their parameters—such as energy and material inputs, production levels, emissions, and cost components (CAPEX, fixed and variable OPEX). They also include information on CO_2 and energy costs, import options, existing and planned capacities, and relevant constraints. The main parameters used for scenario design, along with their potential sources within MIC3, are summarised in Table 15.

Table 15. Overview of main input parameters of ITOM (Neuwirth, 2025)

Parameter	**Description**	**(Potential) source within MIC3**
Demand for basic materials	Differentiated by products, years and regions	EU-MFA module
Energy costs	Differentiated by year; for some energy carriers furthermore differentiated by country	OPEN-PROM
CO_2 certificate costs	Differentiated by year. Can be differentiated by region	Energy system module
Material costs	Typically differentiated by year. May include different sub-categories (e.g., different scrap qualities in ITOM-Steel)	ITOM database; scenario assumptions
CO_2 transport and storage costs	Differentiated by year. Moreover, differentiated by spatial zones in ITOM-Cement	Scenario assumptions
Installed plants	Capacity and age of plants at the beginning of the simulation period and announced (or expected) projects	ITOM database; scenario assumptions

[21] https://itom.readthedocs.io/en/latest/

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Other constraints	For example: limits to use of resources (e.g., biomass, waste), limits to installed capacity per year (e.g., to limit upscaling speed)	Scenario assumptions

10.5.3.2 Outputs

The ITOM framework produces 53 CSV files containing detailed information on capacity development, production by technology, costs, material and energy use, trade flows, transport, and emissions. Many of these outputs include location-specific data. To analyse the results, selected CSV files are usually imported into external tools such as spreadsheet applications.

The main content outputs of ITOM are summarised in Table 16, along with their potential use within the MIC3 framework.

Table 16. Main outputs of ITOM (Neuwirth, 2025)

Output	Description	Potential uptake in MIC3
Production volume by technology / mode of operation	Per product (final or intermediate), and per region / location and year.	Energy system module; LCA module
Material use, including use of secondary materials	Per region and year	CGE module
Installed capacity by technology	Per region / location and year. Can e.g., be used to examine intra-EU relocation.	CGE module
Energy use	Per technology, and per region / location and year	Energy system module
CO_2 emissions	Per technology, and per region / location and year	Energy system module
CO_2 captured and stored	Per region and year	Energy system module

10.6 Global Material flow and trade pilot module

10.6.1 Overview

The Global Material Flow and Trade Pilot Module (REMIND-MFA[22]) is a global-scale material flow analysis

[22] https://github.com/pik-piam/remind-mfa

(MFA) model developed within the TRANSIENCE project as Deliverable 4.5 and as a part of the integrated modelling framework MIC3. Its main purpose is to provide an international perspective for assessing decarbonisation pathways and circular economy strategies in basic material industries, particularly for globally traded commodities such as steel and plastics. By representing material production, trade, and demand flows worldwide, REMIND-MFA enables MIC3 to situate European industrial transitions within a consistent global context, accounting for interregional trade dynamics and competitiveness effects.

REMIND-MFA operates as a satellite module of the energy–economy–climate model REMIND, expanding its capabilities to include detailed material flow representation. Coupling these systems allows the simulation of global material cycles alongside energy system and technological transitions, providing scenarios for key world regions and harmonising European flows with those modelled in the EU MFA module. Inputs are derived from the TRANSIENCE Product and Service (P&S) database, while outputs such as global trade and production flows, are shared with other MIC3 modules to inform integrated scenario analysis.

Methodologically, REMIND-MFA applies material flow analysis (MFA) principles, a systematic approach to quantifying and tracking the flows and stocks of materials within defined systems. The model follows the concept of social metabolism, ensuring mass balance between material inputs, outputs, and in-use stocks through the conservation of mass principle. Dynamic stock modelling is incorporated to capture how materials accumulate in long-lived goods, while lifetime models describe how materials exit the stock over time.

The model is implemented using flodym (Flexible Open Dynamic Material Systems Model), a purpose-built Python library developed under TRANSIENCE to ensure flexible, transparent, and high-quality code for dynamic MFA applications. Together, REMIND-MFA and flodym provide a robust foundation for analysing global circular economy potentials and industrial decarbonisation strategies, linking European scenarios to global material and trade dynamics within the MIC3 framework.

10.6.2 Input and output data

The REMIND-MFA module uses a variety of input datasets, including historical production volumes, collection and loss rates, and projections for population and GDP. Data are stored in raw form and processed with R scripts based on the *madrat* package[23], ensuring transparent, reproducible, and harmonised input preparation. All data are managed in long-format CSV files for improved version control, with compatibility being developed for IAMC-format exchange to enable seamless integration with other MIC3 modules.

Given its global scope, REMIND-MFA primarily relies on harmonised rather than directly coupled data from other MIC3 modules, ensuring consistency across world regions and avoiding distortions in trade comparisons.

Model outputs include comprehensive material flow and stock data, exportable in both CSV and Excel formats, with IAMC-format support under development. A key output is the set of trade flows into and out of the EU, covering raw materials, final goods, and scrap materials, which are provided as inputs to the EU MFA module to ensure alignment across the MIC3 framework.

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[23] https://github.com/pik-piam/madrat

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10.7 Energy system pilot module

10.7.1 Overview

Achieving climate neutrality in European industry requires advanced modelling tools capable of capturing the interactions between circularity, decarbonisation, and wider sustainability objectives. Within this context, the TRANSIENCE project develops the Model for European Industry Circularity and Climate Change Mitigation (MIC3), an open-source modular framework designed to analyse industrial transformation pathways aligned with EU climate and industrial policies.

The Energy System Module (OPEN-PROM) [24] is developed as Deliverable 4.6 and forms a central part of this framework, linking energy dynamics with industrial and material system transformations. Originally developed under the DIAMOND project, OPEN-PROM ("Open PROMETHEUS") has been further refined in TRANSIENCE to enhance its industrial detail, improve representation of circular economy interactions, and integrate additional data sources for greater analytical robustness. These improvements allow the model to simulate the evolving role of industrial energy demand and supply under different decarbonisation and circularity scenarios.

OPEN-PROM is a global energy system model built upon the PROMETHEUS family of models and incorporating elements from the MENA-EDS ENERGY MODEL. It has been widely applied in energy and climate policy analysis for the EU and internationally, contributing scenarios to the IPCC AR6 database and European Commission studies. Within TRANSIENCE, the model provides a detailed representation of technology options, sectoral energy use, and carbon mitigation strategies across industries.

By integrating OPEN-PROM into MIC3, TRANSIENCE enables a consistent linkage between industrial modules and the wider energy system, ensuring that changes in industrial processes, technology uptake, and circular economy strategies are reflected in energy demand, emissions, and policy outcomes at both EU and global levels.

10.7.2 Input and output data

The OPEN-PROM model uses a wide range of input datasets to simulate the behaviour of the global energy system over time. Exogenous inputs include population and GDP projections, sectoral activity levels, technology and system characteristics, policy and regulatory assumptions, fiscal and financial parameters, behavioural factors, and renewable energy potentials. These inputs are drawn from trusted sources such as the IEA, Eurostat, ENERDATA, GTAP, and industry associations, with additional validation checks ensuring consistency across datasets.

Model outputs are generated endogenously in response to these assumptions, covering energy demand and consumption patterns, technology deployment, system costs, energy prices, and emissions. The results provide detailed insight into primary and final energy use, technology uptake, power generation capacity, and environmental indicators across sectors and regions.

OPEN-PROM's workflow is supported by two complementary data frameworks. The mrprom[25] framework

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[24] https://github.com/e3modelling/OPEN-PROM
[25] https://github.com/e3modelling/mrprom

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manages input preparation, providing a transparent, reproducible, and scalable R-based pipeline for harmonising and processing diverse datasets. It ensures data quality and consistency through automated checks and version control. The postprom[26] framework handles output processing, converting model results from GAMS into IAMC-compliant formats for analysis and visualisation. It enables the creation of aggregated indicators, mapping of variables, and automated generation of graphical summaries for scenario evaluation.

Together, these data frameworks ensure that OPEN-PROM delivers robust, transparent, and reproducible insights into the evolution of the energy system under different decarbonisation and circular economy scenarios.

10.8 Enviromental perspective LCA module

10.8.1 Overview

The environmental Life Cycle Assessment (LCA) module is a central component of the MIC3 framework developed within the TRANSIENCE project as Deliverable 4.7, to evaluate sectoral and circular transition pathways for a climate-neutral European industry. It enables the assessment of life cycle environmental impacts of products, industrial processes, and energy transition scenarios, complementing other MIC3 modules such as energy system (OPEN-PROM), industrial (FORECAST, ITOM), and material flow analysis (MFA).

Built upon the open-source Python packages premise[27], pathways[28], and brightway[29], the module integrates prospective LCA with data from energy and material system models to quantify environmental impacts beyond greenhouse gas emissions, including effects on human health and resource use. It also provides spatially explicit assessments and allows comparisons between EU-produced and imported goods to account for embodied emissions.

By linking scenario-specific energy and industrial data with dynamic life cycle modelling, the LCA module supports the evaluation of trade-offs and co-benefits of decarbonisation and circular economy strategies. It thus strengthens MIC3's ability to provide a holistic understanding of how mitigation pathways align with broader sustainability objectives.

10.8.2 Input and output data

The environmental LCA module integrates diverse data sources from both within and outside the MIC3 framework to assess life cycle impacts consistently across industrial and energy transitions. Its core input is the ecoinvent v3.10 database, complemented by scenario-based modifications from integrated assessment models such as IMAGE and REMIND to reflect global socioeconomic and technological developments. This coupling ensures that European transitions modelled in MIC3 are evaluated within a broader global context.

Within MIC3, the module draws on outputs from OPEN-PROM for energy system transformations, ITOM for steel, cement, and plastics industries, and FORECAST for country-level industrial data. These inputs allow

[26] https://github.com/e3modelling/postprom
[27] https://github.com/polca/premise
[28] https://github.com/polca/pathways
[29] https://github.com/brightway-lca

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the LCA module to modify background databases dynamically and calculate environmental burdens under alternative decarbonisation and circularity scenarios.

The framework also supports the integration of user-defined circular economy measures—such as process lifetime extensions, material efficiency improvements, or substitution of secondary materials—enabling flexible scenario design aligned with other MIC3 modules.

Model outputs include modified LCA databases consistent with scenario assumptions, quantifying environmental burdens across energy and industrial systems. These results can be visualised using tools like brightway or ActivityBrowser and exported for use in external LCA platforms such as SimaPro. The module produces detailed case studies, including analyses of hydrogen deployment and the EU Carbon Border Adjustment Mechanism (CBAM), demonstrating its capacity to link industrial pathways with broader environmental and policy insights.

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