TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 30/06/2025

D4.6 – Energy system pilot module

WP4 – Developing satellite modules

Disclaimer

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Health and Digital Executive Agency (HaDEA). Neither the European Union nor the granting authority can be held responsible for them.

Copyright Message

This report, if not confidential, is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0); a copy is available here: https://creativecommons.org/licenses/by/4.0/. You are free to share (copy and redistribute the material in any medium or format) and adapt (remix, transform, and build upon the material for any purpose, even commercially) under the following terms: (i) attribution (you must give appropriate credit, provide a link to the license, and indicate if changes were made; you may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use); (ii) no additional restrictions (you may not apply legal terms or technological measures that legally restrict others from doing anything the license permits).

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	D4.6 – Energy system pilot module			
Work Package	WP4 – Developing satellite modules			
Date of Delivery	**Contractual**	30/06/2025	**Actual**	30/06/2025
Nature	Demonstrator (DEM)	**Dissemination Level**	Public	
Lead Beneficiary	E3-MODELLING AE (E3M)			
Responsible Author	Maro Baka	**Email**	maro.baka@ricardo.com	
	E3M	**Phone**	+30 210 6775696	
Contributors	Anastasis Giannousakis, Panagiotis Fragkos, Fotis Sioutas, Michael Madianos (E3M)			
Reviewer(s)	Alexandros Nikas (ICCS); George Xexakis (HOL); Diego Garcia Gusano, Inigo Munos Mateos (TECNALIA); Georg Holtz (WI); Tobias Fleiter (Fraunhofer)			
Keywords	Energy system model, OPEN-PROM, satellite modules, MIC3, model development			

EC Summary Requirements

1. Changes with respect to the DoA

Although the DoA states that the energy system module will be based on PRIMES, OPEN-PROM (developed based on the PROMETHEUS model) will instead be used in the project. The rationale behind this choice lies in the fact that, while PROMETHEUS and PRIMES share a similar modelling logic, similar features and structural framework, with both offering detailed representations of energy demand, supply, and policy drivers as required for the TRANSIENCE energy system module, PROMETHEUS provides a more suitable foundation for open-source development due to its more modular and transparent structure, its global coverage (to capture the interlinkages between EU and non-EU countries) and its open data and modelling processes, facilitating collaboration and long-term maintainability. OPEN-PROM builds on this foundation and offers key advantages in terms of transparency and reproducibility, as it is fully open-source and accessible for independent review and adaptation. The project's primary focus is on the EU, and both models offer a detailed representation of the EU energy sector, including member state resolution. However, PROMETHEUS has a global scope (whereas PRIMES is EU-focused), which complements the analysis by enabling a coherent treatment of international energy markets and climate policy spillovers, which are important for understanding the EU's position in a globally interconnected energy system and the international impacts of EU's industry transition.

2. Dissemination and uptake

The Deliverables of WP4 (D4.1-D4.7) are intended for the broader stakeholder community of TRANSIENCE with a particular focus on supporting modellers and researchers. They provide a structured overview of the individual components/modules that will be integrated into the Model for European Industry Circularity and Climate Change Mitigation (MIC3). This deliverable focuses on the energy system module of MIC3, OPEN-PROM, which captures the complex link between industrial transformation and energy system transition towards net-zero. Modellers and researchers can use OPEN-PROM as a standalone tool or alongside other satellite modules of the MIC3 framework to assess diverse scenarios and support policymaking on decarbonisation, industrial transition, and circular economy strategies.

3. Short summary of results (<250 words)

OPEN-PROM is a global, open-source energy system simulation model that projects energy system developments under varying macroeconomic, technological, and policy scenarios. It uses a structured set of exogenous inputs, including economic drivers, technology parameters, resource constraints, and policy assumptions, to generate internally consistent outputs such as energy demand, fuel mix by sector, technology uptake, energy and electricity mix, emissions, investment needs, and energy prices. The model's workflow is supported by two data frameworks: mrprom, which automatises input data preparation and harmonisation, and postprom, which converts raw model output into analysis-ready formats compatible with Integrated Assessment Modelling (IAM) practices. These tools ensure data transparency, consistency, reproducibility, and traceability throughout the modelling process. OPEN-PROM plays a central role in the MIC3 modular framework, which additionally comprises macroeconomic (OPEN-GEM), industry (FORECAST, ITOM), material flow (EU-MFA, SIMSON), and life-cycle assessment (premise) models. OPEN-PROM translates macroeconomic trends into energy system projections and provides key outputs, such as energy prices and CO_2 emissions, to sector-specific industrial modules. These interactions enable detailed and coherent assessments of industrial decarbonisation pathways and circular economy strategies. Model enhancements

Funded by the European Union

PROCESSES4PLANET

are underway to improve its sectoral detail and realism. Key upgrades include the explicit modelling of industrial technologies, e-fuels, Direct Air Capture (DAC), energy storage, and endogenous fuel price formation. These developments will reinforce the model's ability to analyse complex energy-industry interactions in support of sustainable transition strategies in the EU and globally.

4. Evidence of accomplishment

This report and the GitHub repository.

Preface

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

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – 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

Funded by the European Union

Executive Summary

This report provides a comprehensive overview of the OPEN-PROM energy system model and its role within the MIC3 modelling framework. OPEN-PROM is an open, scenario-based, global energy system model that simulates energy supply and demand dynamics under varying technological, policy, and socio-economic assumptions. It uses a combination of exogenous inputs (e.g., macroeconomic trends, technology costs, policy constraints) and a simulation approach to ensure consistent projection of endogenous system variables such as energy demand, emissions, technology uptake, and energy prices up to 2050 and 2100.

The model's data pipeline is built around two dedicated tools: mrprom, which automates and standardises the preparation of input data using the MADRaT R package, and postprom (R-based), which facilitates structured post-processing and analysis of model results. These tools enhance transparency, reproducibility, and integration with broader IAM research frameworks.

OPEN-PROM serves as the core energy system simulation module in the modular MIC3 ecosystem, interfacing with models of macroeconomics (OPEN-GEM), industry (FORECAST, ITOM), and material flows (EU-MFA, SIMSON). Through tiered workflows and feedback loops, OPEN-PROM provides critical boundary conditions and price signals (e.g., for CO2 and energy prices) that enable detailed downstream assessments of industrial and material transitions.

Planned improvements include the integration of industrial process technologies, e-fuels, and DAC, as well as enhancements such as endogenous fuel price formation and the inclusion of energy storage. These extensions will strengthen the model's capacity to support robust, policy-relevant scenario analysis across the energy and industry domains.

Current Model metadata	
Link to code repository	https://github.com/e3modelling/OPEN-PROM
Legal Code License	GNU AGPLv3 (https://choosealicense.com/licenses/agpl-3.0/) with the "Commons Clause" to restrict commercial use: https://commonsclause.com/
Code versioning system used	git/Github
Software code language	GAMS[1]
Link to documentation / manual	https://e3modelling.github.io/OPEN-PROM/ OPEN-PROM/tutorials at main · e3modelling/OPEN-PROM

Disclaimer: OPEN-PROM is under continuous development. For the most up-to-date information and documentation, please refer to the official GitHub repository.

[1] Although OPEN-PROM is implemented in GAMS, a commercial software, its model logic and source code are fully open and publicly shared to ensure transparency and enable collaboration.

Funded by the European Union

PROCESSES4PLANET

Contents

Table of Figures

Table of Tables

1 Introduction

Achieving climate neutrality in industry requires advanced modelling tools that can capture the interdependencies between circularity performance, decarbonisation, and broader sustainability goals. TRANSIENCE addresses this challenge by developing the Model for European Industry Circularity and Climate Change Mitigation (MIC3), an open-source modelling ecosystem designed to support the systemic transformation of European industry.

The MIC3 framework integrates a series of interoperable modules, each representing a distinct but connected aspect of industrial transformation, from material flows and product systems to socioeconomic drivers and environmental outcomes. This modular structure enables a flexible and holistic assessment of industrial transition pathways aligned with EU climate and industrial policy objectives.

The first phase of TRANSIENCE focuses on the development of these satellite models under Work Package 4, with individual tasks dedicated to specific components/modules. OPEN-PROM was originally developed within the context of the DIAMOND project and has been further advanced in TRANSIENCE to enhance its industrial representation and account for circular economy policies and impacts, in line with the requirements as an interoperable energy system module within MIC3. In particular, TRANSIENCE contributes significant enhancements to OPEN-PROM, including improved technology detail, enhanced sectoral representation, refined demand modelling for industrial sectors with attention to circular economy dynamics, and the integration of additional data sources for an improved and more robust representation of industrial sectors and related activities.

This report outlines the structure, inputs, and outputs of OPEN-PROM, and discusses its role within the MIC3 framework as a key interface for linking energy dynamics with industrial and material system transformations.

1.1 Structure of the report

This report is organised as follows:

- Section 1 introduces the report and outlines its structure.
- Section 2 provides an overview of the model's concept and structure, including its main inputs and outputs, as well as the related frameworks.
- Section 3 discusses the integration of the energy system model within the MIC3 framework, highlighting planned linkages with other modules to be implemented in the 2nd phase of the project.
- Section 4 outlines the next steps for model development, validation, and full integration into the MIC3 ecosystem.

2 Module description

OPEN-PROM ("Open PROMETHEUS") is a global energy system model developed by integrating elements from the MENA-EDS ENERGY MODEL v4.0[2] and PROMETHEUS[3] Global energy system model that has been extensively used for energy and climate policy impact assessments in the EU and globally (Fragkos et al., 2024), (Mikropoulos et al., 2025), (Fragkos, 2020), (Fragkos et al., 2015), (Marcucci et al., 2019) and provided scenarios to the IPCC AR6 database and the European Commission. The following subsections provide an overview of the model's structure, as well as its key inputs and outputs.

2.1 Model structure

OPEN-PROM is a recursive dynamic energy system simulation model. Within this framework, variables are calculated based on their values from previous years, adjusted for the evolution of explanatory variables ("drivers") and other exogenous inputs and parameters. This structure enables the model to simulate year-by-year developments in the energy system while accounting for path dependencies capturing both short- and long-term transition dynamics. The model has global coverage, with a regional breakdown as illustrated in Figure 1 and detailed in Table 4 of the Annex. The regional split of OPEN-PROM is based on both technical and contextual considerations. EU member states are modelled individually to enable detailed analysis of the EU's industrial transformation in the context of net-zero analysis. Major global economies are also represented individually, while regions with similar geographical and socioeconomic characteristics are grouped together. This regional aggregation is compatible with established global models (e.g., MAgPIE), facilitating both the linking of the models and comparison of results.

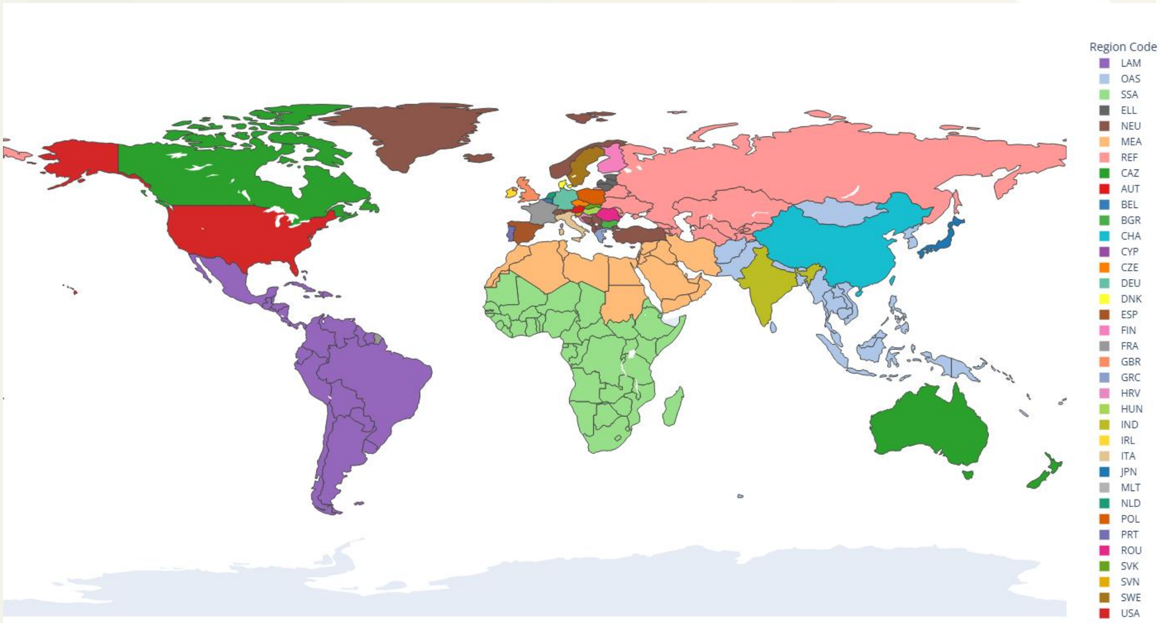

Figure 1. Regional coverage of OPEN-PROM

[2] https://www.i2am-paris.eu/detailed_model_doc/mena-eds
[3] https://www.i2am-paris.eu/detailed_model_doc/prometheus

As a comprehensive energy demand and supply simulation tool, OPEN-PROM supports a wide range of applications, including energy system analysis, energy price projections, power generation planning, industrial transformations, and the assessment of climate change mitigation policies. The following subsections provide a detailed overview of the model's energy demand and energy supply components.

2.1.1 Energy Demand

Energy demand is modelled in terms of useful energy services, such as heating, mobility, industrial production of materials (i.e. steel or cement), and appliance use, and their corresponding final energy carriers. The model ensures consistent energy balance by linking useful and final energy through technology-specific efficiencies (Figure 2). In the context of TRANSIENCE, we have gathered new, recent data on technology-specific energy efficiencies for all industrial subsectors and countries/regions and thoroughly integrated them in OPEN-PROM to allow for a more credible and consistent projection of industrial energy demand, fuel mix, and emissions.

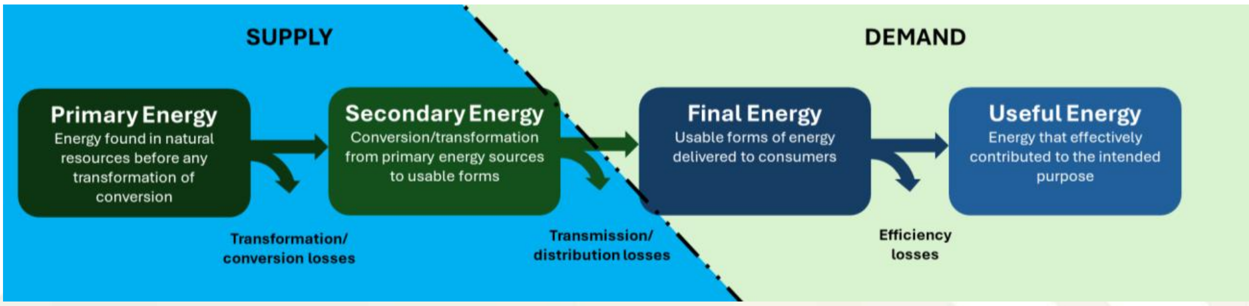

Figure 2. Energy flow from supply to end use: from primary energy to useful energy

Energy demand is divided into three main demand sectors: industry, domestic, and transport. These are further divided into subsectors (Table 1).

Table 1. Sectors and subsectors of energy demand in OPEN-PROM

Sector	Subsector	Sector	Subsector
Industry	Iron and Steel	**Transport**	Passenger Transport – Cars
	Non-Ferrous Metals		Passenger Transport – Busses
	Chemicals		Passenger Transport – Rail
	Non-Metallic Minerals		Passenger Transport – Inland Navigation
	Pulp and Paper		Passenger Transport – Aviation
	Food Drink and Tobacco		Goods Transport – Trucks (GU)

Sector	Subsector	Sector	Subsector
	Engineering		Goods Transport – Rail (GT)
	Textiles		Goods Transport – Inland Navigation (GN)
	Other Industrial sectors	**Non-Energy**	Petrochemicals Industry
Domestic	Services and Trade		Other Non-Energy Uses
	Agriculture, Fishing, Forestry etc.	**Bunkers**	Bunkers
	Households		

Demand for useful energy services (useful energy demand) is determined at the subsector level with an econometric top-down approach, where demand for useful energy services is driven by appropriate macroeconomic factors (e.g., GDP, population, household income, industrial activity) and the average cost of providing these services based on econometrically derived elasticities differentiated by sector and country/region. In the context of TRANSIENCE, new data have been used (about industrial production, industrial energy demand, and energy prices) and new econometric estimations have been implemented to estimate updated values for the elasticities used in the relevant model equations. Table 2 provides an overview of useful energy services across demand sectors, distinguishing between services subject to fuel substitution (where different fuels can compete to meet the service demand, i.e., for space heating) and those relying exclusively on electricity, and non-energy uses of fuels.

Table 2. Useful Energy Services and Non-Energy Uses by Sector

Sector	Useful Energy Services (subject to fuel substitution)	Useful Energy Services (electricity only)	Non-Energy Uses
Industry	Heat (e.g. process heat, steam generation)	Electricity (e.g., lighting, ICT systems, automation)	Feedstocks (e.g., for materials, chemicals)
Domestic	Heat (e.g. space heating, water heating, cooking)	Electricity (e.g., lighting, appliances, electronics, cooling)	—
Transport*	Mobility (passenger-km, tonne-km) for road, rail aviation, marine	—	—

***Note**: *In transport, electricity (e.g., via EVs) is treated as one of several possible energy carriers for providing the useful service of mobility, rather than being a distinct useful energy service in itself.*

A typical useful energy demand equation is used to estimate the evolution of total demand for useful energy services[4] for each subsector in OPEN-PROM, and has the following form:

$$\ln(DEM_{i,t}/DEM_{i,t-1}) = \alpha + \beta \ln(ACT_{i,t}/ACT_{i,t-1}) + \sum_{l=0}^{p} \gamma_l \left[\ln\left(\frac{AVCOST_{i,t-l}}{AVCOST_{i,t-l-1}}\right)\right]$$

where:

DEM: useful energy demand
ACT : activity indicator (e.g., industrial production value for industrial subsectors, disposable household income for the residential subsector) that drives changes in energy demand
$AVCOST$: weighted sum of the costs of different options/average cost of meeting energy services[5]
α: trend parameter capturing exogenous growth or decline in demand not explained by activity or costs
β: elasticity with respect to the activity indicator
γ_l: lagged weighted elasticities with respect to changes in the average energy cost
i: subsector
t: year
This formulation captures how the future development of energy demand by sector depends not only on changes in economic/activity levels ("drivers"), but also on the evolution of average energy-related costs over time. The inclusion of lagged elasticities, which are weighted to reflect the relative importance of cost changes at different time lags, allows the model to represent delayed responses of energy demand to cost changes, reflecting short- and medium-term adjustment processes. Even when the activity indicator (e.g., industrial production) increases, the rising costs of meeting energy services can dampen or even reverse the growth in energy demand. This occurs through mechanisms such as improved energy efficiency, substitution to less energy-intensive processes or technologies, and behavioural or structural shifts in production. As a result, the model reflects the dynamic interplay between economic growth and cost-induced efficiency or demand adjustments.

Useful energy requirements at the subsector level must be met through the consumption of final energy commodities, accounting for the efficiency of the technologies and the fuels used. In the context of TRANSIENCE, the technoeconomic features of energy-related technologies and equipment have been updated based on recent literature, while the derived energy demand has been cross-validated with recent data from the IEA (for non-EU countries) and Eurostat (for EU Member States). In addition, a stock-flow consistent representation has been integrated in OPEN-PROM (esp. in industry, alongside the other sectors) to allow for a more credible and nuanced representation of the industrial transition dynamics. In the model, a representative agent acts as an aggregate, rational decision-maker within each subsector, reflecting the collective behaviour of firms or consumers in this sub-sector. This agent is assumed to make cost-effective and technically feasible choices among fuels, technologies, and energy-saving measures, while considering existing infrastructure, policies, and equipment. More information regarding substitution between

[4] As activities in the transport sector are endogenous to the model, the demand equation differs.
[5] For useful energy services restricted to electricity, $AVCOST$ represents electricity prices.

technologies/energy forms is provided in Section 2.1.3. Final energy demand is then derived from useful energy requirements and the efficiency of the selected options (technology/fuels) (Figure 2).

$$FE_{i,k,t} = \frac{UseDemRemEquip_{i,k,t} + sh_{i,k.t} * GAP_{i,t}}{eff_{i,k,t}}$$

where:

$FE_{i,k}$: Final Energy of technology/fuel k in subsector i
$UseDemRemEquip_{i,k}$: Useful demand covered by installed equipment[6] of technology/fuel k available in year t (see scrapping mechanism in Section 2.1.3.1)
$GAP_{i,t}$: The gap in useful energy demand in subsector i (see Section 2.1.3.1)
$sh_{i,k.}$: The share of technology/fuel k in new equipment in subsector i
$eff_{i,k}$: The efficiency of technology/fuel k in subsector i

2.1.1.1 Industry

The industrial sector is divided into ten subsectors, as shown in Table 1. While this representation does not follow the full granularity of the NACE classification, in the context of TRANSIENCE, we have developed a full mapping of all manufacturing activities under NACE to one of the defined subsectors. This approach ensures comprehensive coverage of EU manufacturing activities while focusing on the most energy- and emissions-intensive industries/sectors that are the focus of TRANSIENCE (iron and steel, cement, chemicals).

As described above, OPEN-PROM models industrial electricity demand separately from substitutable energy demand, with both disaggregated by subsector and model region. The evolution of industrial electricity demand is driven by two main factors: the growth rate of the industrial subsector's production level value[7] (activity indicator) and changes in industrial electricity prices (which are endogenous in OPEN-PROM). Similarly, the evolution of substitutable energy demand, covering demand for steam and heat, is determined by the growth rate of industrial production[3] and by the evolution of the "steam price," defined as the weighted average of fuel prices for industrial consumers, using the base year's shares in substitutable industrial energy demand as weights.

Multiple energy forms compete for gaining shares in the demand-supply gap for industrial substitutable energy, created by retirement of equipment and/or increase of demand (see section 2.1.3). In the context of TRANSIENCE, in addition to the "conventional", already-in-market energy forms (fossil fuels, electricity, various forms of bioenergy), hydrogen has been integrated as an option to meet industrial demand, with specific features by industrial sub-sector and process. This integration is based on a comprehensive mapping conducted within TRANSIENCE to analyse those industrial processes/subsectors that can use hydrogen either with current or advanced

[6] Equipment that is installed before year t
[7] Exogenous to the model

technologies. Energy efficiency improvements are driven by rising energy prices and by technology or fuel choices at the end-use level, while they can also be achieved through direct investments in energy-saving measures.

Total industrial electricity demand is determined by the summation of demand for non-substitutable electricity and the portion of electricity used within substitutable industrial energy demand. This demand is met through the electricity grid or combined heat and power (CHP) facilities. CHPs are included among the competing technologies for meeting substitutable energy demand and are primarily used to supply industrial heat. Their operation results in the co-production of electricity, which is accounted for in the power generation requirements within the power supply sector (see section 2.1.2.1).

In OPEN-PROM, non-energy uses in the industrial sector refer to the consumption of energy carriers as feedstocks rather than as fuels. These include inputs such as oil products and natural gas used in the production of chemicals, plastics, and other materials. While these feedstocks are not used for energy purposes, their processing can still release emissions through industrial chemical reactions. Non-energy uses are treated separately from energy demand and are linked directly to industrial activity levels in relevant subsectors, such as chemicals and refining. They are excluded from final energy consumption but remain important for tracking overall resource use and associated emissions from industrial processes.

2.1.1.2 Domestic

The domestic sector in OPEN-PROM comprises three subsectors: residential/households, services, and agriculture. It follows the same modelling structure as the industrial sector for electricity and substitutable energy demand but differs in the choice of activity indicators. In the services and agricultural subsectors, energy demand evolves in line with their respective production level value, while in the household subsector, demand is driven by total household consumption expenditure. Across all domestic subsectors, changes in fuel and electricity prices influence both the level and composition of energy demand, through substitution effects and dynamics and energy efficiency responses.

2.1.1.3 Transport

The transport sector is considered one of the most significant sources of energy-related GHG emissions and is represented in detail in OPEN-PROM. The model includes eight transport modes, excluding bunkers, five for passenger transport and three for freight (Table 1), and incorporates a technology layer that links energy demand for transport with specific energy forms and fuels (Table 8 in the Annex).

OPEN-PROM features an endogenous representation of transport activity, energy use, and emissions by subsector and region. The passenger car segment is modelled in detail, projecting vehicle stock evolution based on socio-economic drivers, population and GDP growth, and transport costs influenced by fuel prices. The model captures shifts in consumption patterns, including income-driven growth in developing regions and saturation effects in developed ones. Since transport activity is modelled endogenously, OPEN-PROM can capture mode shifts between different transport modes, such as from private cars to public transport or rail, in response to cost, policy, or behavioural changes.

Technology uptake is not predetermined but emerges from economic competition between vehicle technologies (e.g., EV, Plug-In Hybrid, ICE), whose market shares depend on total cost per kilometre, including capital, operation, maintenance, and fuel costs, and maturity factors that reflect infrastructure and network effects. In the TRANSIENCE project, a new feature is added based on stock-flow dynamics for passenger car stock, which evolves through scrapping and new additions of vehicles, with additions influenced by income, energy prices, vehicle costs, and a non-income term, and constrained by saturation levels that implicitly reflect societal norms and infrastructure. Fuel consumption is calculated from vehicle stock, efficiencies and average mileages. New data from various sources (including IEA, Enerdata, EDGAR, etc.) have been used to derive real-world data on the efficiencies and mileages of different private car technologies in each OPEN-PROM region.

Other transport subsectors, including aviation, buses, rail, and inland navigation, are modelled in OPEN-PROM in a more aggregated way compared to road passenger transport. Final energy consumption in these subsectors is primarily driven by GDP growth and average fuel prices, among other influencing factors (e.g., population growth).

2.1.2 Energy Supply

The OPEN-PROM model incorporates a detailed representation of energy supply, covering the conversion of primary energy carriers into secondary forms (that can be used by consumers) and the distribution of final energy forms to meet energy demand in all sectors (Figure 2). It features a comprehensive power generation sector and a detailed representation of hydrogen supply, including multiple production pathways and their competition based on cost, efficiency, and availability. Electricity and hydrogen demand from the end-use sectors (industry, domestic, transport) are the primary drivers of the power generation and hydrogen supply sectors, respectively.

2.1.2.1 Power generation

In each model region, total electricity generation ($PROD_t$) is calculated as the sum of final electricity consumption from end-use sectors ($ElCons_{i,t}$) (2.1.1), power plant self-consumption ($PPSCons_t$), transmission and distribution losses ($Losses_t$), minus net electricity imports[8] ($NetImp_t$).

$$PROD_t = \sum_{i=0}^{n} ElCons_{i,t} + PPSCons_t + Losses_t - NetImp_t$$

OPEN-PROM features an enhanced portfolio of power generation technologies (see Annex Table 5), which compete to satisfy electricity requirements in two levels: first, the model decides on the investments in new capacity for power technologies (capacity expansion) in order to meet the projected electricity demand considering premature decommissioning and planned investments. Once capacities are decided, the model simulates the operational dispatch of power capacities to meet power demand in each time segment of the Load Duration Curve. The model includes two realisations of dispatch mechanisms: a detailed variant using a segmented load duration curve to

[8] Electricity trade between regions is exogenous to the model.

approximate intra-annual variability with 9-time segments, and a simplified variant using a single annual segment for computationally lighter scenarios. The additional generation capacity required in each region is driven by evolving electricity demand across sectors, projected plant retirements, including firmly planned decommissioning of old and inefficient units, committed investments (particularly for nuclear and RES)[9], and the required security of supply margin. Decisions for new capacity installations follow the substitution mechanism described in section 2.1.3.2 and are mostly driven by the Levelised Cost of Electricity (LCOE) of competing technological options.

Dispatch decisions (multiple time segments)

The utilisation of the capacity of power plants in different time segments, called the "dispatching" of power plants, is endogenous in OPEN-PROM and is determined by the annual load duration curve in combination with variable Operation & Maintenance (O&M) and fuel costs (including potential carbon emission costs) and the installed capacities of the different technologies. The year is divided into nine segments ($h_0, h_1 \dots h_8$), which provides a practical balance between capturing the main features of the load duration curve and keeping the computational complexity of the model manageable, ensuring an adequate resolution of demand variation without excessive model detail. The annual load duration curve is approximated by a constant base load combined with an exponential component that captures higher demand over shorter durations (Figure 3). The exponential parameter λ_t is calculated implicitly from the equation:

$$\frac{1 - e^{8.76 * \lambda_t}}{\lambda_t} = \frac{PROD_t - 8.76 * B_t}{M_t - B_t}$$

and total electricity production ($TOTPROD_t$) is approximated using the formula:

$$TOTPROD_t = \sum_{i=0}^{8} \left[(M_t - B_t) * e^{-\lambda_t * (0.25 + i)} \right] + 9 * B_t$$

where M_t is the peak load demand and B_t is the base load demand, representing the level of demand that persists continuously throughout the year (8760 hours).

[9] These are exogenously given in the model based on a wide literature review.

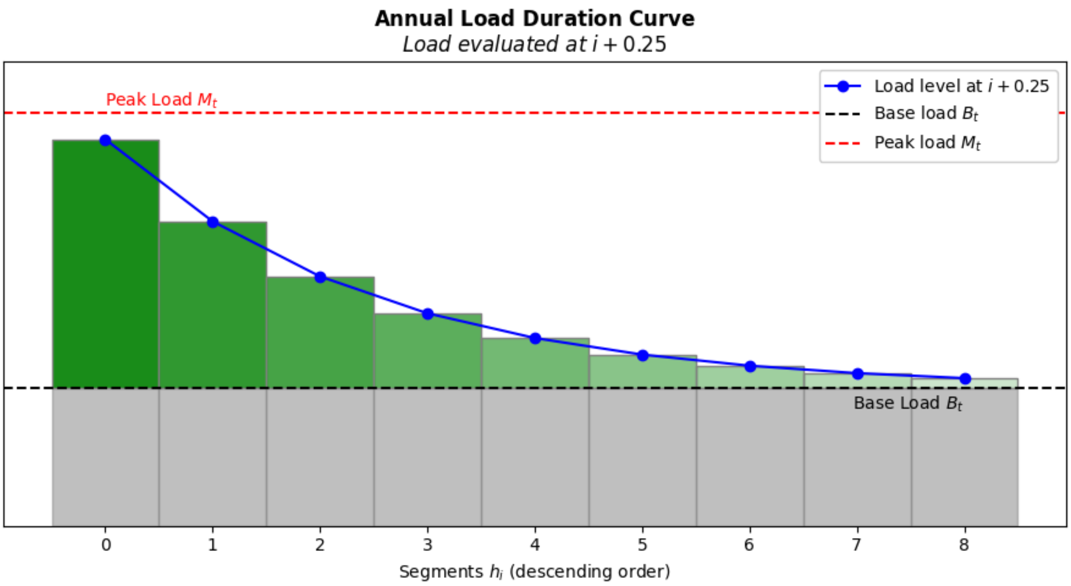

Figure 3. Annual Load Duration Curve (9 segments)

The extent to which power plant technologies k are utilised within each time segment ($h_0, h_1 \ldots h_8$) is determined by the following relationship, which is solved implicitly for $a_{i,t}$ for each time segment i.

$$\sum_k CAP_{k,t} * e^{\frac{a_{i,t}}{disp_{k,t}}} = \left[(M_t - B_t) * e^{-\lambda_t * (0.25+i)}\right] + B_t$$

In this specification, $CAP_{k,t}$ is the effective capacity of technology k in year t, and $disp_{k,t}$ represents the share of technology k allocated to meet power generation requirements in year t, derived from its short-term marginal cost, including variable O&M and fuel expenses. The parameter $a_{i,t}$ is an implicit balancing factor that governs the distribution of capacity deployment across technologies within each time segment i in year t. It ensures that the weighted sum of technology capacities, adjusted for their dispatch shares, equals the electricity demand in that segment. The values reflect a simplified dispatch pattern that is applied uniformly across all time segments within the year.

While this approach provides a reasonable approximation for dispatchable technologies, it does not explicitly capture the temporal variability and intermittency of variable renewable energy sources (VRES), such as wind and solar PV. In the absence of storage in the current version of OPEN-PROM, VRES availability is instead reflected through technology-specific capacity factors that are influenced by renewable energy potentials (i.e. simulating a reduction in capacity factors as PV or wind production reaches the relevant potential by region as capacity should then be installed in less efficient sites with lower capacity factors and higher costs) and effective capacity estimates, which limit their contribution in each time segment.

Dispatch decisions (single time segment)

A different realisation of dispatch decisions in OPEN-PROM is applied when only a single time segment is considered. In this case, the generation from each electricity technology is allocated in proportion to its installed capacity relative to the total system capacity. Specifically, generation is computed by scaling the installed capacity of each technology by the ratio of total electricity demand to total available capacity. This simplified representation, developed in the context of TRANSIENCE[10], assumes equal utilisation rates across time (but different by technology) and does not incorporate marginal cost-based dispatch. While computationally efficient, this approach does not capture merit-order effects or operational constraints, making it more suitable for stylised analyses or long-term scenarios where detailed temporal dynamics are less critical.

2.1.2.2 Hydrogen supply

In OPEN-PROM, hydrogen supply is modelled through five centralised production technologies, (see Table 6 in the Annex), each competing to meet demand based on their levelised costs. Within TRANSIENCE, the representation of hydrogen is enhanced through data and modelling improvements in the different hydrogen production routes/technologies, the addition of more production pathways, and the integration of hydrogen demand from industrial sectors[11]. The model determines annual investment requirements by considering hydrogen demand growth (arising from various sectors and processes) and technology lifetimes. The distribution of investments among technologies follows the substitution mechanism outlined in Section 2.1.3.2 based on the development of the Levelised Cost of Hydrogen (LCH) of the different options competing for hydrogen demand. Levelised production costs account for capital and operating expenditures, feedstock costs, and, where applicable, electricity prices for electrolysis (and the potential CO_2 costs). Total hydrogen supply is constrained by installed capacity and technology-specific capacity factors, ensuring realistic representation of operational limits and resource availability.

In addition to production, the model incorporates hydrogen storage and distribution infrastructure (see Table 7. H in the Annex), which plays a crucial role in ensuring reliable delivery of hydrogen to end-users across different sectors. This infrastructure includes various pipeline types, storage options, and service stations, all represented in detail within the model to capture the spatial and technical aspects of hydrogen logistics, including the capacity limitations and operational costs associated with each infrastructure element. This integrated approach allows OPEN-PROM to capture the full supply chain dynamics from hydrogen production through to end-use delivery.

2.1.2.3 Heat generation

Centralised heat generation technologies compete to meet substitutable energy demand in both industrial and domestic sectors. Combined heat and power (CHP) plants are included in the industrial and domestic subsectors, reflecting their role in co-producing electricity and heat. Heat-only plants supplying district heating networks are modelled within the domestic subsector,

---

[10] Dedicated github branch for Simple dispatch mechanism: https://github.com/e3modelling/OPEN-PROM/tree/SimplifyPGMod
[11] Dedicated github branch for Hydrogen demand: https://github.com/e3modelling/OPEN-PROM/tree/HydrogenDemand

capturing their contribution to centralised heat supply.

2.1.3 Gap and Substitution mechanism

The energy-related equipment (i.e. power plants, passenger cars, or heating boilers) available in each period, on both the energy supply and the demand side, represents the installed technologies that can actively produce and consume energy, respectively. This includes power plants, heating systems, industrial machinery, vehicles, and end-use appliances that remain operational based on their technical lifetimes and usage patterns. As the energy system transitions towards net-zero, this equipment is gradually retired, either through normal scrapping at the end of its lifetime or through pre-mature scrapping when changes in variable and fuel costs render the continued operation of energy equipment economically unviable (see Section 2.1.3.1). This process reduces the share of demand and supply that can be met by existing assets and creates a "gap" that must be filled by new equipment. For useful energy services that can be provided by multiple technology options (subject to fuel and technology substitution) and for supply sectors such as power generation and hydrogen production, this gap is addressed by selecting among competing alternatives[12]. In OPEN-PROM, this selection is governed by the model's substitution mechanism.

Without loss of generality, both the gap and the substitution mechanism discussed in the following sections will be analysed from the demand perspective. A similar approach is applicable for the energy supply sectors.

2.1.3.1 Gap and scrapping mechanism

The gap is defined in terms of useful energy and is determined by the difference between useful energy demand ($DEM_{i,t}$ - useful energy demand equation) and the amount of energy that can be satisfied using existing equipment.

$$GAP_{i,t} = DEM_{i,t} - CAP_{i,t}$$

In the above equation, $CAP_{i,t}$ represents the useful energy satisfied by the capacity of the equipment of subsector i, which has been installed by year $t-1$ and is not scrapped in year t, and is defined by the following:

$$CAP_{i,t} = \sum_{k} (1 - SCR_{i,k,t}) * DEM_{i,k,t-1}$$

where the summation includes all competing technologies k, $DEM_{i,k,t-1}$ stands for the demand satisfied by technology k in year $t-1$ and $\mathrm{SCR}_{i,k,t}$ is the overall scrapping rate of technology k in year t, which includes both normal scrapping ($norscr_{i,k,t}$) and premature scrapping[13] ($prescr_{i,k,t}$). The inclusion of the latter, pre-mature scrapping, is important for capturing rapid technological transformation, particularly under scenarios involving strong climate action or sharply rising fossil fuel prices, where the renewal of equipment stock accelerates. The general algebraic

[12] Services using only electricity will have electric equipment.
[13] Premature scrapping is currently applied only in the power supply sector

formulations[14] for the scrapping rates are the following:

Normal scrapping: $norscr_{k,t} = \frac{1}{lft_k}$

Pre-mature scrapping: $prescr_{k,t} = 1 - \frac{vom_{k,t}^{-\gamma_t}}{h_{k,t} * \sum_{j \neq k}\left(totcost_{j,t}^{-\gamma_t}\right) + vom_{k,t}^{-\gamma_t}}$

where $norscr_{k,t}$ is the normal scrapping rate of technology k, lft_k is the economic lifetime of technology k and $prescr_{k,t}$ is the pre-mature replacement rate of technology k, $vom_{k,t}$ is the variable (including fuel) cost of technology k and $totcost_{j,t}$ is the total cost of using technology j including capital and variable costs (index j represents all competing technologies in a sector i excluding technology k). Factor $h_{k,t}$ is stochastic and used for scaling purposes and γ_t (also stochastic) is a measure of sensitivity of investment decisions to cost considerations. Premature scrapping is included to capture technology turnover and enable the model to respond to sudden changes in carbon or fuel prices, avoiding lock-in and encouraging continuous improvement. It is modelled by comparing the operating costs (OPEX) of existing technologies with the total Levelised Cost of Electricity (LCOE) of new investments and if the new option becomes more cost-effective, early replacement is enabled.

In most cases, demand for useful energy services increases or does not decline faster than total scrapping, resulting in a positive "gap". However, in cases where demand for useful energy services is lower than the amount that can be met by existing equipment, the gap is assumed to be zero, and no competition between technologies occurs.

2.1.3.2 Substitution mechanism

Competition between technologies occurs in terms of market shares within the gap. The allocation of new investments is modelled as a quasi-cost-minimising function and is driven by the total cost of the competing options. The total cost of technology k at time t is expressed as:

$$totcost_{k,t} = \frac{\left(\frac{dr_t * e^{dr_t * lft_k}}{e^{dr_t * lft_k} - 1}\right) * cc_{k,t} + fc_{k,t}}{ur_{k,t}} + vom_{k,t} + \frac{fuelprice_{k,t}}{eff_{k,t}}$$

where $cc_{k,t}$ is the capital cost, $fc_{k,t}$ is the fixed cost for operation and maintenance (O&M), $vom_{k,t}$ refers to the variable costs of O&M, $eff_{k,t}$ is the efficiency factor, $ur_{k,t}$ is the utilisation rate, $fuelprice_{k,t}$ is the price of the energy source used by technology k, dr_t is the discount rate, which is a function of long term interest rates derived, and lft_k is the economic lifetime of technology k.

The shares of each option k in the gap for the year t are calculated as follows:

$$sh_{k,t} = \frac{w_{k,t} * totcost_{k,t}^{-\gamma_t}}{\sum_k w_{k,t} * totcost_{k,t}^{-\gamma_t}}$$

[14] The subscript of the subsector i is omitted for legibility

The above equation (Weibull specification) determines the market share in the gap of technology k based on its total cost $totcost_{k,t}$. In this specification, the parameters γ_t represent the sensitivity of the share in the gap with respect to the total cost of each technology, while the weights $w_{k,t}$ can be interpreted as reflecting the relative "maturity" factor of each technology in terms of readiness of consumers to adopt them. These factors play an important role in modelling the process of technology diffusion. In the context of the TRANSIENCE project, we used recent energy and cost data to conduct new econometric estimations that are of particular interest and relevance to the MIC3 ecosystem and industry transition analysis.

The use of the term quasi-cost minimising highlights that investment decisions are not strictly determined by selecting only the lowest-cost technology. Instead, the chosen mechanism favours cheaper options but still allocates some share to more expensive of less mature technologies, preventing the "winner takes it all" assumption prevalent in linear optimisation models. This approach better reflects real-world behaviour, where decisions are influenced by inertia, preferences, uncertainty, and imperfect information, allowing for smoother, more realistic technology adoption pathways.

2.2 Data (inputs and outputs)

OPEN-PROM uses exogenous inputs, such as population and GDP, sectoral activity levels, technology data, energy resources (both for fossil fuels and renewable energy) and policy assumptions, to project the behaviour of the energy system over time. The model applies an iterative estimation process to reconcile interdependent variables like energy prices, demand, and technology deployment. Through this approach, OPEN-PROM ensures internal consistency between inputs and model responses for endogenous variables across time steps. The outputs, which are endogenous variables, represent the system's response to the external assumptions and include energy consumption, fuel mix by sector, technology utilisation, energy costs, emissions, and other key performance indicators.

2.2.1 Inputs

OPEN-PROM relies on a comprehensive set of exogenous inputs, including:

- **Macroeconomic and Demographic Drivers**: Population, GDP, and sectoral activity (activity indicators) projections
- **Technology and System Characteristics**: Capital and operating costs, efficiencies, lifetimes, useful energy conversion factor
- **Policy and Regulatory Assumptions**: Emissions constraints, climate, energy, and industrial policies, CO2 prices/taxation
- **Fiscal and Financial Parameters**: International fuel prices, energy taxes and subsidies, discount rates
- **Behavioural and Structural Factors:** Energy consumption habits and comfort levels
- **Energy Resource Potentials:** Technical and economic potential of renewables per region for renewables and region-specific constraints

Overview of input data sources: The required input data originate from various reputable

sources (e.g., IEA, ENERDATA, Eurostat, EDGAR emissions database). In the context of the TRANSIENCE project, we have gathered data from additional sources (i.e., IEA, Eurostat, GTAP, Steel Association) to ensure that our database (feeding into OPEN-PROM) includes the most up-to-date and comprehensive data, while a series of validation checks have been performed to ensure that data gathered from multiple sources are consistent and can be used in the model.
A complete and regularly updated list of the data sources used in OPEN-PROM is available in the GitHub repository[15].

2.2.2 Outputs

The outputs of OPEN-PROM are endogenous model results, generated in response to the specified inputs usually in the form of alternative scenarios. These include:

- **Energy Demand and Consumption:** Primary energy, primary fuel mix, fuel input for power generation, final energy demand, fuel mix by sector, electricity generation, shares in electricity production, vehicle stock of passenger cars
- **Technology Uptake and Utilisation:** Power generation capacity by technology, capacity additions, investments in power system
- **Energy Prices and System Costs:** Electricity prices, CO_2 prices
- **Emissions and Environmental Indicators:** Sectoral CO_2 emissions and CO_2 captured
- **System-Level Indicators:** Indicators of energy efficiency and intensity for each sub-sector of the energy system

2.2.3 Data-related Frameworks

To ensure high-quality, transparent, and reproducible modelling, OPEN-PROM is supported by dedicated data handling frameworks for both input preparation and output processing. These tools enhance consistency and reproducibility across scenarios and streamline the modelling workflow.

2.2.3.1 Input preparation - mrprom

The mrprom framework[16] provides a robust and scalable data preparation pipeline for the OPEN-PROM modelling framework. It addresses common shortcomings associated with manual data processing in Excel, such as lack of transparency, reproducibility issues, and limited scalability, by offering a flexible, open-source environment based on the MADRaT (Model and Data Retrieval and Transformation) package. This R-based toolchain automates and standardises the preprocessing of large and diverse input datasets. The mrprom framework has been developed in the context of the DIAMOND project and has been significantly enhanced and expanded in the TRANSIENCE project, especially with regard to additional data for industrial sub-sectors and technologies as well as hydrogen production and consumption variables.

[15] https://github.com/e3modelling/OPEN-PROM/blob/main/tutorials/InputDataOverview.csv
[16] https://github.com/e3modelling/mrprom

The workflow consists of clearly separated steps: ***readSource*** ingests raw data, either as-is or with basic format conversion; ***convert*** optionally harmonises data to a standard ISO country level; and ***calcOutput*** blends multiple datasets into a unified model input, aggregated to the regional and sectoral definitions used by OPEN-PROM. Tools such as ***toolCountryFill*** and ***toolAggregate*** allow for infilling missing values and mapping data across different regional resolutions (e.g., 249 countries to model regions), while caching mechanisms reduce redundancy by storing intermediate results for reuse.

Key advantages of mrprom include:

1. Reproducibility and Version Control: All transformation steps are scripted and documented, enabling full traceability and easier collaboration.
2. Efficiency via Caching: Repeated computations are avoided by automatically retrieving results from cache when available.
3. Data Quality Assurance: Built-in checks, tests, and metadata handling improve data consistency and reduce the risk of silent errors, e.g., checks units to prevent mismatched aggregations, ensures completeness across regions and time steps.
4. Modular Design: The framework separates tasks into modular components, making it easier to update or extend the workflow with new data sources.

We use mrprom as a standard part of our data preparation workflow. It ensures high-quality, harmonised, and reproducible inputs to the model, which is essential for transparent and policy-relevant scenario analysis.

2.2.3.2 Output processing - postprom

The postprom framework[17] is a publicly available repository that provides a suite of tools for the post-processing of model outputs generated by the OPEN-PROM framework. The main input is the gdx output file produced by the GAMS-based model, and it facilitates the transformation of this raw data into a structured, analysis-ready format. The postprom framework has been developed in the context of the DIAMOND project and has been significantly expanded and enhanced in the TRANSIENCE project, allowing a more comprehensive and nuanced post-processing and visualisation of industry-related data and modelling projections.

The R-based package processes model outputs for all regions, years, and variables, generating a mif (Model Intercomparison Format) file that follows the IAMC (Integrated Assessment Modelling Consortium) data template/format, allowing integration with standard tools used for scenario analysis and intercomparison.

Key features of postprom include:

1. **Flexible Variable Naming via Mapping Files:** Users can define custom naming conventions for model variables using Excel-based mapping.
2. **Consistent Global Aggregation**: The tool supports global aggregation of variables (e.g., summing across regions or scaling by population, GDP, or other metrics) to ensure

[17] https://github.com/e3modelling/postprom

consistency in whole-world reporting.

3. **Integrated Plotting Capabilities**: The mif file can be fed into a built-in plotting function, which generates a consolidated PDF report. This report visualises key indicators, such as electricity demand and supply, making it easier to evaluate the physical coherence and predictive behaviour of the model.

We use postprom in our modelling workflow for every scenario run. It helps us quickly assess model behaviour, identify inconsistencies, and interpret the physical meaning of results (e.g., whether electricity supply balances demand), which is critical for model validation and iterative refinement.

3 Integration in MIC3/ Module linkages

The MIC3 model will comprise a set of modules, including OPEN-PROM as the energy system module. Table 3 provides an overview of these modules, including their software implementations and associated modelling paradigms.

Table 3. Overview of MIC3 modules and corresponding software implementations & model paradigms

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

3.1 Placement within MIC3

The planned interfaces within the MIC3 modelling framework are illustrated in Figure 4[18]. OPEN-PROM, as an energy system model, captures the complex links between the industrial transformation and energy transition at the system-wide level.

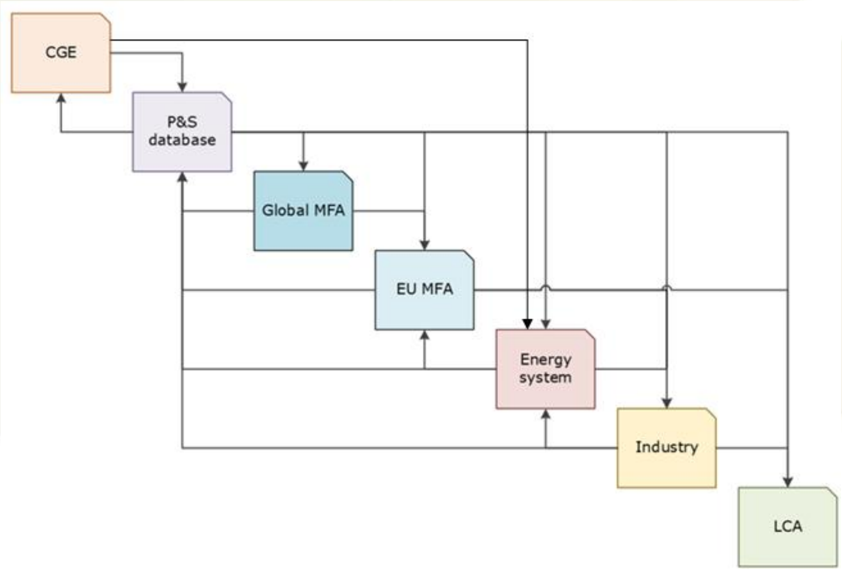

Figure 4. Planned interfaces in the MIC3 framework

The set of displayed connections illustrates the potential pathways for module communication. The specific interfaces used, and the order in which they are employed, will depend on the

[18] Adapted from Deliverable D3.4 – Framework for industrial transition modelling

research questions being addressed.

The baseline workflow is structured around a tiered modelling approach, in which models covering broader system-level dynamics are run first to establish key boundary conditions. OPEN-GEM initiates the process by translating scenario narratives into macroeconomic and demographic developments (e.g. GDP growth, sectoral value added, industrial production). These socioeconomic drivers are then passed to OPEN-PROM, which simulates the evolution of the energy system under given policy, technology, socioeconomic development assumptions (provided by OPEN-GEM) and resource constraints.

OPEN-PROM provides key outputs, such as projections for electricity and CO_2 prices, energy demand and fuel mix by sector, and sectoral energy use, that serve as inputs to more detailed modules. For example, FORECAST (the techno-economic industry model) will use OPEN-PROM's price signals (both for CO2 and electricity prices that are determined by systemic interactions) and sectoral energy trends to analyse process-level energy demand and technology uptake in specific industrial subsectors. Similarly, the EU-MFA module receives sectoral activity data (e.g. car registrations) to calculate material demand and potential reductions aligned with Circular Economy (CE) strategies.

While OPEN-PROM provides a consistent baseline for energy system developments, detailed industrial and material flow models produce refined insights that may, in turn, influence the broader system understanding. To enable this, feedback loops will be established, particularly between industrial modules and OPEN-PROM or OPEN-GEM. For example, projected industrial energy consumption and/or fuel/technology mix derived from detailed sectoral modelling (industrial modules) together with the required industrial investment can be fed-back into OPEN-PROM, which will then be re-run to assess the resulting impacts on power generation, energy prices, and system-wide energy balances. This ensures coherence across the MIC3 framework and supports iterative refinement where sectoral insights significantly affect macro-level assumptions.

The definition of data interfaces and workflows remains a dynamic process, to be further refined as the project progresses, particularly during the second phase of the project. Additional workflows are being designed to accommodate alternative entry points and perspectives, such as material flow questions or policy-driven technology assessments, ensuring the flexibility and interoperability of the MIC3 open modelling ecosystem.

4 Model novelty & planned model improvements

The core novelty of OPEN-PROM lies in its integrated yet flexible and modular structure, which captures the dynamic interactions across energy demand, supply, technology competition, and macroeconomic drivers. It combines detailed representations of end-use sectors with energy system transformation pathways, enabling scenario analysis that reflects feedbacks between consumption patterns, technology uptake, and policy interventions.

Within TRANSIENCE, the modelling framework has been enhanced with data sources focused on industrial sectors and technologies and improved representations of their energy demand, technoeconomic features, and their respective fuel consumption according to fuel prices. The methodology for the supply and the associated fuel prices has been enhanced, so that prices of secondary carriers, electricity and hydrogen, are now endogenously determined in the OPEN-PROM model influenced by the dynamics of energy demand and supply and the costs to produce and provide electricity and hydrogen supply to final consumers in each sector (industry, transport, buildings). This enhancement allows for reflecting the impact of cost and penetration of different technologies in the electricity and hydrogen generation mix, as electricity and hydrogen are essential carriers for the decarbonisation of hard-to-abate emissions in Energy-Intensive Industries (EIIs). This feature will be used in the MIC3 modelling framework with OPEN-PROM providing the electricity and CO_2 prices for the other modules, especially for FORECAST-Industry. Furthermore, industrial emissions in each of the ten industrial subsectors have been disaggregated to energy-related (fuel combustion) and emissions from industrial processes to improve the impact assessment of adopting different technology pathways. In the context of TRANSIENCE, in addition to the “conventional”, already-in-market energy forms (fossil fuels, electricity, various forms of bioenergy), hydrogen has been integrated as an option to meet industrial demand, with specific features by industrial sub-sector and process. This integration is based on a comprehensive mapping conducted within TRANSIENCE to analyse those industrial processes/subsectors that can use hydrogen either with current or advanced technologies. Finally, the integration of stock-flow consistent representation for the electricity, transport, and industrial sectors allows for a more nuanced and credible projection for the transformation dynamics by subsector and country/region represented in OPEN-PROM.

Another important improvement in the context of TRANSIENCE is the addition of new data sources specifically focusing on industrial energy demand, industrial technologies used in each sector and their technoeconomic features, and other energy- and emissions-related data. This allowed us to further improve the mrprom and postprom data processing tools, but also to perform additional validation and checking tests to ensure the appropriate data quality and self-consistency. In addition, the new data gathered in the TRANSIENCE context (about industrial activity, industrial energy demand, fuel mix, and energy prices) have been used to perform new econometric estimations using various techniques to estimate updated values for the income and price elasticities used in the relevant model equations.

OPEN-PROM is under continuous development to ensure it remains a robust and policy-relevant tool for assessing energy transitions in the context of broader industrial transformation. Several key modelling improvements are ongoing to expand the model’s capabilities and improve its representation of emerging technologies and system interactions. In the scope of TRANSIENCE, the following enhancements are developed:

- **Integration of industrial processes and a detailed technology layer[19]:** The industrial sectors are being expanded to include process-level detail and specific technology options across key sectors, mainly energy-intensive industries like iron and steel, cement and chemicals. This will enable a more accurate simulation of fuel and technology switching potentials, electrification, and decarbonisation pathways in industry. This is focused on EIIs, and specifically on Iron & Steel, Chemicals, and Non-metallic minerals (e.g., Cement). In Figure 5 the technology routes and the decarbonisation options of the Iron & Steel sector are depicted.

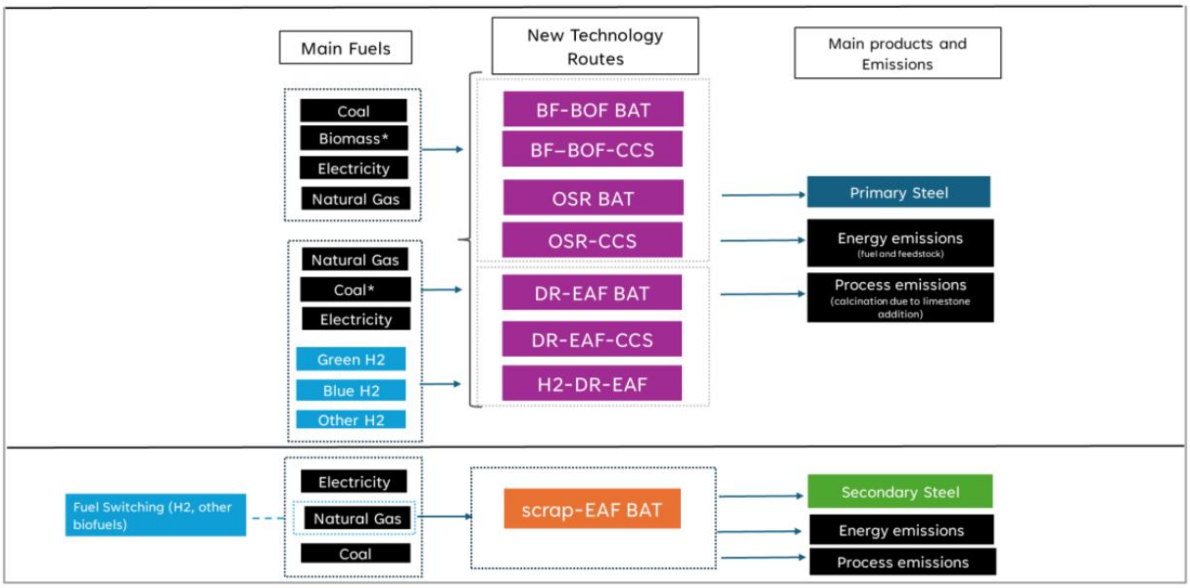

Figure 5. Decarbonisation options and technology routes in the Iron & Steel sector

- **Integration of circular economy considerations across sectors:** Ongoing developments in OPEN-PROM aim to incorporate circular economy impacts by adjusting energy demand, efficiency, production costs, and technology uptake in multiple sectors relevant for circular economy strategies. This enables the model to better reflect how circularity-driven changes in production, consumption, and resource use influence energy system dynamics and decarbonisation pathways. This particular enhancement is essential to implement the soft-linking within the MIC3 modelling framework for scenarios with different CE measures and policies in the context of TRANSIENCE.

In addition to TRANSIENCE-funded developments, other ongoing enhancements to the model further strengthen its capabilities and add value to its application within TRANSIENCE (especially in the 2nd and 3rd reporting period).

- **Inclusion of e-fuels and Direct Air Capture (DAC):** To better represent future decarbonisation options especially in hard-to-abate industrial and transport sectors, the

[19] Dedicated github branch for the enhancement of Iron and Steel subsector https://github.com/e3modelling/OPEN-PROM/tree/Iron-and-Steel-Industry-development

model is planned to incorporate the production and distribution of synthetic clean fuels produced from renewable electricity and carbon dioxide, as well as Direct Air Capture (DAC) technologies to directly remove CO2 from the atmosphere. This will allow for the evaluation of negative emissions strategies and the role of carbon dioxide removal in climate change mitigation strategies at the national and EU levels. The integration of clean synthetic fuels in the OPEN-PROM model is essential to allow assessing net-zero trans**formation** pathways in specific countries and sectors, where the conventional decarbonisation options would not suffice for net-zero (i..e heavy industry, shipping, aviation, etc)

- **Modelling trade of primary energy carriers and biomass**: the future development of OPEN-PROM is planned to enhance the representation of international trade in fossil fuels (coal, oil and gas) and biomass. This will allow for a better representation of the (currently exogenous) imports and exports in model regions, improving the realism of global market dynamics. The "global pool" approach to modelling trade of energy carriers will be used as a first approximation. This will allow the assessment of the interplay between ambitious climate policies, energy trade and international energy prices with differentiating impacts in energy exporters and importers.
- **Inclusion of energy storage technologies:** The addition of energy storage systems is intended to improve the model's ability to capture the flexibility needs of increasingly variable renewable-based power systems and improve the quantification of transition costs and investment requirements in the electricity sector. This includes both short-term storage (e.g. batteries) and long-duration options (e.g. hydrogen or pumped hydro), which are critical for balancing supply and demand across time scales.

These enhancements aim to strengthen OPEN-PROM's analytical depth and modelling capabilities and its integration within broader modelling frameworks (including MIC3), eventually supporting comprehensive assessments of low-carbon transitions and industrial transformations.

ANNEX

Disclaimer: OPEN-PROM is under continuous development. For the most up-to-date information and documentation, please refer to the official GitHub repository.

Table 4. Regional coverage of OPEN-PROM

OPEN-PROM Region Code	Name	OPEN-PROM Region Code	Name
AUT	Austria	**PRT**	Portugal
BEL	Belgium	**ROU**	Romania
BGR	Bulgaria	**SVK**	Slovakia
CYP	Cyprus	**SVN**	Slovenia
CZE	Czech Republic	**SWE**	Sweden
DEU	Germany	**ELL**	Other EU27 Countries
DNK	Denmark	**NEU**	Non-EU Europe, including Norway, Switzerland, Turkey
ESP	Spain	**CAZ**	Canada, New Zealand, Australia
FIN	Finland	**CHA**	China, Taiwan and near area
FRA	France	**GBR**	United Kingdom
GRC	Greece	**IND**	India
HRV	Croatia	**JPN**	Japan
HUN	Hungary	**LAM**	Latin America and the Caribbean
IRL	Ireland	**MEA**	Middle East, North Africa, Central Asia
ITA	Italy	**OAS**	Other Asia
MLT	Malta	**REF**	Reforming Economies of Former Soviet Union, including Russia
NLD	Netherlands	**SSA**	Sub-Saharan Africa

POL	Poland	**USA**	United States

Table 5. Power generation technologies in OPEN-PROM

Power generation technologies			
1	Conventional Thermal Monovalent Biomass and Waste	**18**	Large Hydro Plants
2	Advanced Thermal Monovalent Lignite	**19**	Small Hydro Plants
3	Advanced Thermal Monovalent Hard Coal	**20**	Advanced Small Hydro Plants
4	Advanced Thermal Monovalent Fuel Oil	**21**	Wind Plants
5	Advanced Thermal Monovalent Natural Gas	**22**	Advanced Wind Plants
6	Advanced Thermal Monovalent Biomass and Waste	**23**	Wind Offshore
7	Supercritical Lignite	**24**	Solar Photovoltaic Plants
8	Supercritical Coal	**25**	Advanced Solar Thermal Plants
9	Fluidised Bed Lignite	**26**	Advanced Building Integrated PV Plants
10	Fluidised Bed Hard Coal	**27**	Advanced Geothermal Plants
11	Integrated Gasification Combined Cycle Lignite	**28**	New Nuclear Designs
12	Integrated Gasification Combined Cycle Hard Coal	**29**	Supercritical Coal with CCS
13	Integrated Gasification Combined Cycle Biomass	**30**	Supercritical Lignite with CCS
14	Conventional Combined Cycle Gas Turbine	**31**	Integrated Lignite Gasification with CCS
15	Advanced Combined Cycle Gas Turbine	**32**	Integrated Coal Gasification with CCS
16	Advanced Gas Turbine (peak devices) Diesel Oil	**33**	Gas Turbine Combined Cycle with CCS
17	Advanced Gas Turbine (peak devices) Natural Gas	**34**	Advanced Thermal Monovalent Biomass with CCS

Funded by the European Union

Table 6. Hydrogen production technologies in OPEN-PROM

Hydrogen Production Technologies	
1	Gas steam reforming
2	Gas steam reforming with Carbon Capture & Storage (CCS)
3	Water electrolysis from grid power
4	Biomass gasification large scale
5	Biomass gasification large scale with CCS

Table 7. Hydrogen storage and distribution technologies in OPEN-PROM

Hydrogen Storage and Distribution Technologies	
1	Turnpike pipeline used also as a storage medium
2	High pressure for industry
3	High pressure for urban
4	Medium pressure for urban
5	Low pressure for urban
6	Medium pressure for service stations of length of 2km
7	Service stations gaseous H2

Table 8. Transport technologies and corresponding energy forms/fuels

Technology	Energy Form/Fuel
Internal Combustion Engine – Gasoline	Gasoline
Internal Combustion Engine – Liquified Petroleum Gas	Liquified Petroleum Gas
Internal Combustion Engine – Diesel Oil	Diesel Oil
Internal Combustion Engine – Natural Gas	Natural Gas
Internal Combustion Engine – Ethanol	Ethanol
Internal Combustion Engine – Biodiesel	Biodiesel
Internal Combustion Engine – Methanol	Methanol

Electric Vehicle/Pure Electric Engine	Electricity
Plug in Hybrid – Gasoline	Gasoline
	Electricity
Plug in Hybrid – Diesel Oil	Diesel Oil
	Electricity
Conventional Hybrid – Gasoline	Gasoline
Conventional Hybrid – Diesel Oil	Diesel Oil
Fuel Cells: Hydrogen	Hydrogen
Gas Turbine – Kerosene (for aircrafts)	Kerosene

Funded by the European Union
PROCESSES4PLANET

Bibliography

Fragkos, P. (2020). Global Energy System Transformations to 1.5 °C: The Impact of Revised Intergovernmental Panel on Climate Change Carbon Budgets. *Energy Technology*, *8*(9), 2000395. https://doi.org/10.1002/ente.202000395

Fragkos, P., Kouvaritakis, N., & Capros, P. (2015). Incorporating Uncertainty into World Energy Modelling: The PROMETHEUS Model. *Environmental Modeling & Assessment*, *20*(5), 549–569. https://doi.org/10.1007/s10666-015-9442-x

Fragkos, P., Van De Ven, D.-J., Horowitz, R., & Zisarou, E. (2024). Analysing the Transformative Changes of Nationally Determined Contributions and Long-Term Targets. *Climate*, *12*(6), 87. https://doi.org/10.3390/cli12060087

Marcucci, A., Panos, E., Kypreos, S., & Fragkos, P. (2019). Probabilistic assessment of realizing the 1.5 °C climate target. *Applied Energy*, *239*, 239–251. https://doi.org/10.1016/j.apenergy.2019.01.190

Mikropoulos, E., Roelfsema, M., Chen, H.-H., Staffell, I., Oreggioni, G., Hdidouan, D., Thellufsen, J. Z., Chang, M. A., Fragkos, P., Giannousakis, A., Chatterjee, S., Ürge-Vorsatz, D., Pfenninger, S., Pickering, B., Victoria, M., Brown, T., & Van Vuuren, D. P. (2025). Examining pathways for a climate neutral Europe by 2050; A model comparison analysis including integrated assessment models and energy system models. *Energy*, *319*, 134809. https://doi.org/10.1016/j.energy.2025.134809

Funded by the European Union