



D2.2 Report discussing lessons learnt from PoC for further development

Public report 'Testing the AMIGDALA framework for the EU plastic value chain in scenarios without and with global cooperation and circularity'

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AMIGDALA project summary

Achieving climate neutrality by 2050, as envisioned in the European Green Deal, poses a multi-faceted challenge. Europe must foster a sustainable process industry that is not only climate-neutral but also globally competitive and resilient. This transformation requires strategic foresight to navigate the complex interplay of demand, global trade, and industrial production.

Decision-makers face critical choices, from crafting policies and regulations to investing in advanced technologies for public infrastructure and industrial assets. Supporting these decisions with actionable insights is essential to steering the evolution of the basic industry within the European Union.

The EU-funded project AMIGDALA – short for Alliance for Modelling Industries towards the Green Deal's objectives And circuLArity – aims to provide public and private decision-makers with insights from scenario analysis. The analysis is augmented by computer models to project transformation pathways towards climate neutral destinations.

AMIGDALA is building a powerful set of tools that can project pathways of transformation for Europe's industrial sector. These tools connect different types of models from global, EU and local scale - covering the economy, energy use, materials, and climate - with real-world scenarios and input from stakeholders. The goal is to turn data and models into practical advice for the people making key decisions on various pathways toward a climate neutral process industry.

Summary of this document

This report details the proof-of-concept (PoC) of the AMIGDALA framework, which has been designed and developed in WP1 and WP2 of the AMIGDALA project. This deliverable, D2.2, covers the lessons learnt from developing the PoC, in terms of methodology but also in terms of intermediary results, meant for stakeholders to further think along with the development and improvement of the AMIGDALA framework in the next phases of the project. Modelling **results contained in this report are therefore preliminary and should not be cited.**

To support the European Union's 2050 climate neutrality goals, the AMIGDALA project is developing an integrated framework that aims to produce pathways of industrial transformation towards climate neutral, circular, and competitive futures.

The AMIGDALA concept combines four key elements:

1. Decision analysis, facilitate and support the interaction of public and private decisionmakers with the modelling results;
2. Scenario building, focused on economic indicators and the decision options employed by decision-makers;
3. Integrated modelling, with models from different domains to reduce the number of endogenous parameters;
4. Data management, to harmonize input data for the different models.

At the heart of AMIGDALA framework lies the integrated model suite (IMS) of nine soft-linked models. Linking the models facilitates integration of the domains of Economy, Energy, Environment, and Materials (incl. circularity) across a wide geographical scope, from the global level, to a focus on the EU and its member states, down to the local level of a single industrial cluster.

In WP2, the AMIGDALA framework designed in WP1 was progressed into an actionable state through the PoC. For this purpose, the plastics value chain was selected as test case and a set of four scenarios was designed along the dimensions of climate ambition (in the rest of the world) and EU circularity.

To develop the IMS to the stage required for the PoC, model updates and extensions were performed to represent the plastics value chain in

sufficient detail for the domains in scope, on the required geographical scale (model dependent) as well as on a process level.

The goal of the current PoC study was to test the AMIGDALA framework and in particular the developed IMS. Important aspects of the framework, which have been tested in the PoC include:

- implementation of harmonised scenarios in the models,
- the IMS soft-linking scheme,
- data-exchange tables,
- analysis of scenario results,
- conversion of model outputs to Key Performance Indicators,
- trial integration of model outputs into the prototype Decision dashboard,
- setting-up the data-explorer with historical data.

From the process and the preliminary outcomes, the following insights were derived:

- The IMS soft-linking scheme and data-exchange ran without major technical problems.
- IMS soft-linking and harmonization of scenarios across all models, all geographical levels and domains, enables consistent modelling, limiting the need for exogenous assumptions.
- Scenario projections of energy commodity prices worldwide are an asset of our integrated approach as these impact the energy transition at the EU and local level.
- The dimensions of circularity and demand side strategies included in the IMS strongly impacts sectoral (plastics for the PoC) development in terms of production requirement, energy consumption and process selection.
- Integration of a limited number of feedback loops will improve model outcomes. In particular, feeding back the impact of recycling on production requirements, which is modelled on EU level only, to global level is expected to impact virgin production beyond the EU.
- Harmonization of techno-economic parameters is essential; this will be arranged sector by sector in WP3.
- Aligning, running, analysing and validating IMS is labour-intensive; partial automation using a multi-model platform may improve this.

In summary, the PoC of the AMIGDALA framework has proven to be an essential step towards WP3 of the project where the framework will be technically refined and completed. This includes finalising and operationalising scenarios, the IMS, data repository, and stakeholder dashboard. In this process, the PoC approach and the lessons learnt will be rolled out to realise full industrial sector coverage.

Acronyms and abbreviations

AMIGDALA	Horizon Europe project Alliance for Modelling Industries towards the Green Deal's objectives And circuLArity
API	Application Programming Interface
CALLIOPE	Multi-scale energy system modelling framework
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Use
CIMS	Chemelot Integrated Model System
CITS	Circular Industrial Transformation System
DAC	Direct Air Capture
DD	Decision Dashboard, module of the AMIGDALA framework
DE	Data Explorer, module of the AMIGDALA framework
ELDEST	Energy poLicy DEcision Support Toolbox
ETS	Emission Trading System
EU	European Union
EXIOMOD	EXtended Input-Output MODel
GDP	Gross Domestic Product
GLOBIOM	GLOBAL BIOSphere Management model
HVO	High-value olefins
IMS	Integrated Model Suite of AMIGDALA
KPI	Key Performance Indicator
MCDA	Multi Criteria Decision Analysis
MS	Member States
MTO	Methanol to Olefin production process
PoC	Proof of Concept
PRISM	Plastic Recycling Impact Scenario Model
ROW	Rest of World
SSP	Shared Socio-economic Pathway
TIAM-ECN	Times Integrated Assessment Model-Energy Centre of the Netherlands
TIMES-EUROPE	TIMES (The Integrated MARKAL-EFOM System) for Europe
WP	Work Package

1 Introduction

This chapter introduces the AMIGDALA project, its objectives, and the structure of this report.

1.1 The AMIGDALA project

The European Green Deal sets ambitious climate goals, including a 55% reduction in greenhouse gas (GHG) emissions by 2030, compared to 1990 levels, and climate neutrality by 2050. In 2022, industrial emissions accounted for 20.3% of total EU GHG emissions, underscoring the sector's critical role in meeting these targets (European Parliament 2024). Nevertheless, decarbonizing industry poses a significant challenge, for it must strike a delicate balance between environmental ambition and economic profitability and competitiveness.

Decarbonizing industry requires both technological solutions and policy intervention. Technological solutions include both supply-side and demand-side approaches. Examples of supply-side solutions are energy efficiency improvements, electrification, and the deployment of low-carbon hydrogen as both a heat source and a chemical feedstock. Demand-side approaches, includes reducing material waste, substituting high-carbon inputs by low-carbon alternatives, and embracing circular economy (Rissman et al. 2020).

But technology alone is insufficient. A supportive policy framework is essential to drive technological adoption, promote circular practices, and ensure economic viability. Key interventions include carbon pricing mechanisms, with border adjustments to prevent carbon leakage, and strong governmental support for research, development, and deployment (Meckling, Sterner, and Wagner 2017).

Despite political willingness and the maturity of decarbonization technologies, the pathways to industrial decarbonization are clouded by uncertainty. The Alliance for Modelling Industries towards the Green Deal's objectives And CircuLArity (AMIGDALA) sets out to pierce through the fog of uncertainty surrounding industrial decarbonization by equipping decision-makers, in government and industry, with the tools to define and evaluate viable pathways toward circular, climate-neutral, and competitive industries.

In AMIGDALA, we acknowledge that the complex interplay of technical, economic, social, and behavioural phenomena taking place in the European industrial transformation cannot be captured by one single model. Therefore, to achieve our goal, we develop an integrated model

suite, encompassing multiple established models, each addressing a crucial dimension of the transition.

In addition, to ensure practical relevance, we align modelled projections with real-world decision-making practices by identifying key control levers and performance indicators for business and government. We call this alignment the decision-framework. Designed scenarios provide input parameters for the models and serves as a bridge between internal model parameters with control levers and performance indicators that matter to users. Finally, to enhance the real-world impact of model outputs, we deploy an interactive online dashboard that allows users to explore projections from multiple perspectives and create personalized views.

Taken together, these methodological innovations enable decision-makers to navigate complex decarbonization pathways with clarity by leveraging key control levers, to net-zero actionable strategies for industrial transformation.

1.2 Objectives of this report

A critical step in developing our integrated modelling approach lies in establishing a framework for models, databases, scenarios, and dashboard - a key milestone in achieving AMIGDALA's goals.

In the first year of the project, the AMIGDALA framework has been designed, and a first version has been implemented. Next, we selected a value chain, introduced in Chapter 3 to further develop, demonstrate and test the framework in a proof-of-concept (PoC).

This report covers the lessons learnt from the PoC, in terms of methodology but also in terms of preliminary results, in general and in particular for the selected value chain. **Results are preliminary and should not be cited.** This report only includes intermediary results, meant for stakeholders to further think along with development of the AMIGDALA framework, as a basis for further improvement in the next phases of the AMIGDALA project.

1.3 Structure of this report

Chapter 2 describes the approach taken, starting with the AMIGDALA framework, the Integrated Model Suite (IMS), Key Performance Indicators (KPI) and decision analysis.

Chapter 3 introduces the PoC in terms of selected value chain, research questions and scenarios.

Chapter 4 presents the draft results for the PoC from the point of view of historic data, model results and decision making.

Chapter 5 draws conclusions of the PoC preliminary results, on the approach and how to improve these.

Chapter 6 finalizes the report with an outlook on the next phases of the AMIGDALA project in terms of framework, models and scenario analysis.

The annexes give background information on the AMIGDALA sector coverage, models and model improvements realised for the PoC and foreseen for next phase of the project.

2 Approach

This chapter gives a short overview of the approach developed for AMIGDALA by presenting the AMIGDALA concept and framework as a whole and the Integrated Model Suite, the Key Performance Indicators and the decision analysis.

2.1 AMIGDALA framework

The AMIGDALA concept combines four key elements. For each element we have a separate expertise group to apply the state of the art:

1. Decision analysis, facilitate and support the interaction of public and private decisionmakers with the modelling results;
2. Scenario building, focused on economic indicators and the decision options employed by decision-makers;
3. Integrated modelling, with models from different domains to reduce the number of endogenous parameters;
4. Data management, to harmonize input data for the different models.

The AMIGDALA framework is made up by nine modules, as visualised in Figure 1. The modules each have a well-defined function within the framework and are built by one of the four expertise groups, shown in distinct colours.

Knowledge and skills in the AMIGDALA project are concentrated in the four specialized expertise groups mentioned above. Each group consists of one lead-partner and has members of the other partners to include their expertise on the topic and liaise with the other expertise groups that develop other modules. The nine modules are produced by the four expertise groups. The exchange of information between the modules needs to be coordinated. The coordination is managed by the liaisons in the expertise groups that develop the modules.

Some modules are directly involved in making projections (background & foreground scenarios and modelling). Other modules can be seen as providing a service towards the model (data repository) or the users (historic data & data explorer, decision-logic & decision-dashboard).

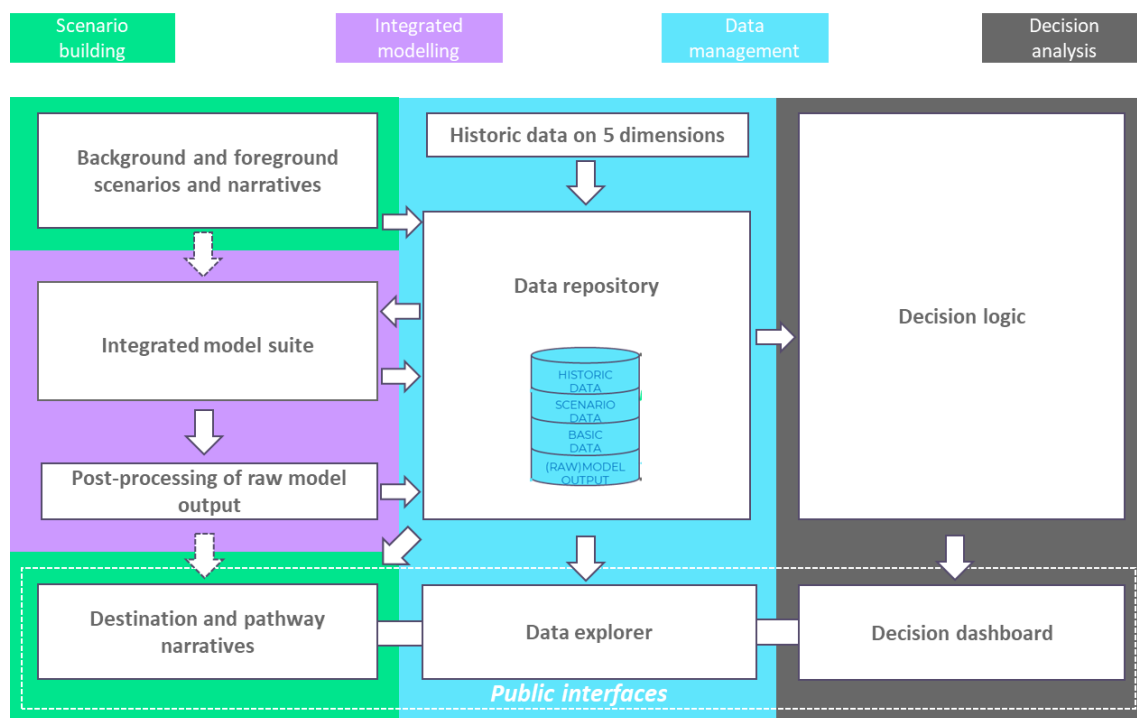


Figure 1. Modules in the AMIGDALA framework, with arrows indicating the flow of information. The Data-explorer, Narratives of destination and pathways and the Decision dashboard are interfaces with the public.

2.2 Integrated Model Suite

The aim of the AMIGDALA integrated model suite is to project transformative pathways which lead the European process industry to a climate-neutral, more circular, and yet competitive future. It consists of nine individual models that are soft-linked to allow coordinated operation. This setup enables the integration of the Economy, Energy, Environment, and Materials domains across a wide geographical scope, from the global level, with a focus on the EU and its member states, down to the local level of a single industrial cluster. In addition, this integrated approach offers the opportunity to combine different modelling time-resolutions providing more detail to the local level.

Different technological CO₂ mitigation solution routes exist to make a transformation to a CO₂ neutral industry. These relate to different domains such as energy, circularity and CO₂ capture, storage and use. These types of options can be related to distinct parts of the value chain. Hence, these types of solution routes can be related to the five dimensions of climate neutrality (see Deliverable 2.1) and are listed accordingly in Table 1.

Table 1. Overview of types of CO₂ mitigation solution routes to cover, related to the five dimensions.

Dimension	#	Solution route	Relevant model
(1) energy demand and use and energy efficiency	1	energy efficiency	TIAM-ECN, TIMES-Europe, CALLIOPE, CIMS
	2	heat electrification (low CO ₂)	
	3	process electrification (low CO ₂)	
	4	(green) hydrogen	
(2) emissions including process emissions	5	CCS (and all other options in this table)	GLOBIOM
(5) possibility of replacing fossil carbon in materials by more sustainable streams (e.g., recycled carbon from industrial emissions, from waste, sourced from sustainable biomass or directly from the atmosphere)	6	CCU (incl. DAC)	
	7	biomass	PRISM
(3) use of raw materials, chemicals, and water (e.g., via increasing the use of circular approaches and material substitution, also in view of ensuring affordability of industrial products)	8	recycling (close the loop)	
(4) production of consumer goods / equipment / construction products (e.g., looking at sustainability of products and embedded carbon – a preliminary approach only)	9	refuse and reduce (narrow the loop)	Process industry TIMES-Europe (raw minerals not implemented), TIAM-ECN, (GLOBIOM bio), Recycling & chemicals / water CITS, PRISM, CALLIOPE, CIMS
	10	material substitution	
	11	lifetime extension (slow the loop)	EXIOMOD, CITS

It is the aim of AMIGDALA to cover all these types of solution routes in the integrated model suite. For that reason, different types of models are needed, e.g. macro-economic, energy system, land-use, dynamic mass flow and stock and techno-economic models. These are indicated in the right column of Table 1.

In the AMIGDALA framework, the integrated model suite is receiving input on data and scenarios to produce pathways for decision analysis, see Figure 2. In the AMIGDALA soft-linking approach the global models – EXIOMOD, TIAM-ECN and GLOBIOM – provide the global context for the developments in Europe. These are projected by the models TIMES-Europe, CITS and PRISM. Similarly, the European-level models make sure that the projections on local level (provided by Calliope, CIMS and ELDEST models) are embedded in a coherent European context.

The arrows indicate the linkages made between the different models (dashed arrows are not yet established in the Proof of Concept). The original idea was to run simulation models (left part of scheme) to provide input on constraints for which optimization models could identify cost-effective techno-economic pathways (models on the right part of the scheme). However, the global macro-economic model EXIOMOD needs ‘economic shocks’ as input for the economy to respond to. These inputs need to be at world region level but also at EU Member State level (since this version of EXIOMOD also details EU MS). For this reason, both the global energy system model TIAM-ECN and the EU MS energy system model TIMES-Europe precede EXIOMOD to provide it with the energy transition input to ‘shock’ the economy. After that, the global picture can be completed with GLOBIOM, followed by the EU level model train starting with the stock-flow simulation model CITS, the plastic recycling optimization model PRISM and the energy system optimization model TIMES-Europe. Within TIMES-Europe, global information on biomass, fossil and renewable energy availability and prices and EU MS data on product and material circularity and demand as well as recycling potentials are integrated and optimized with respect to climate policy goals.

At local level, TIMES-Europe energy availability and pricing is used in Calliope to assess optimal power infrastructure and in CIMS to calculate cost-optimal CO₂ strategies for the Chemelot site. Calliope provides pathways to ELDEST to make agent-based analysis of the electricity market. At a later stage, outputs from ELDEST and Calliope can be used to refine CIMS optimization (indicated by the dashed arrows in Figure 2).

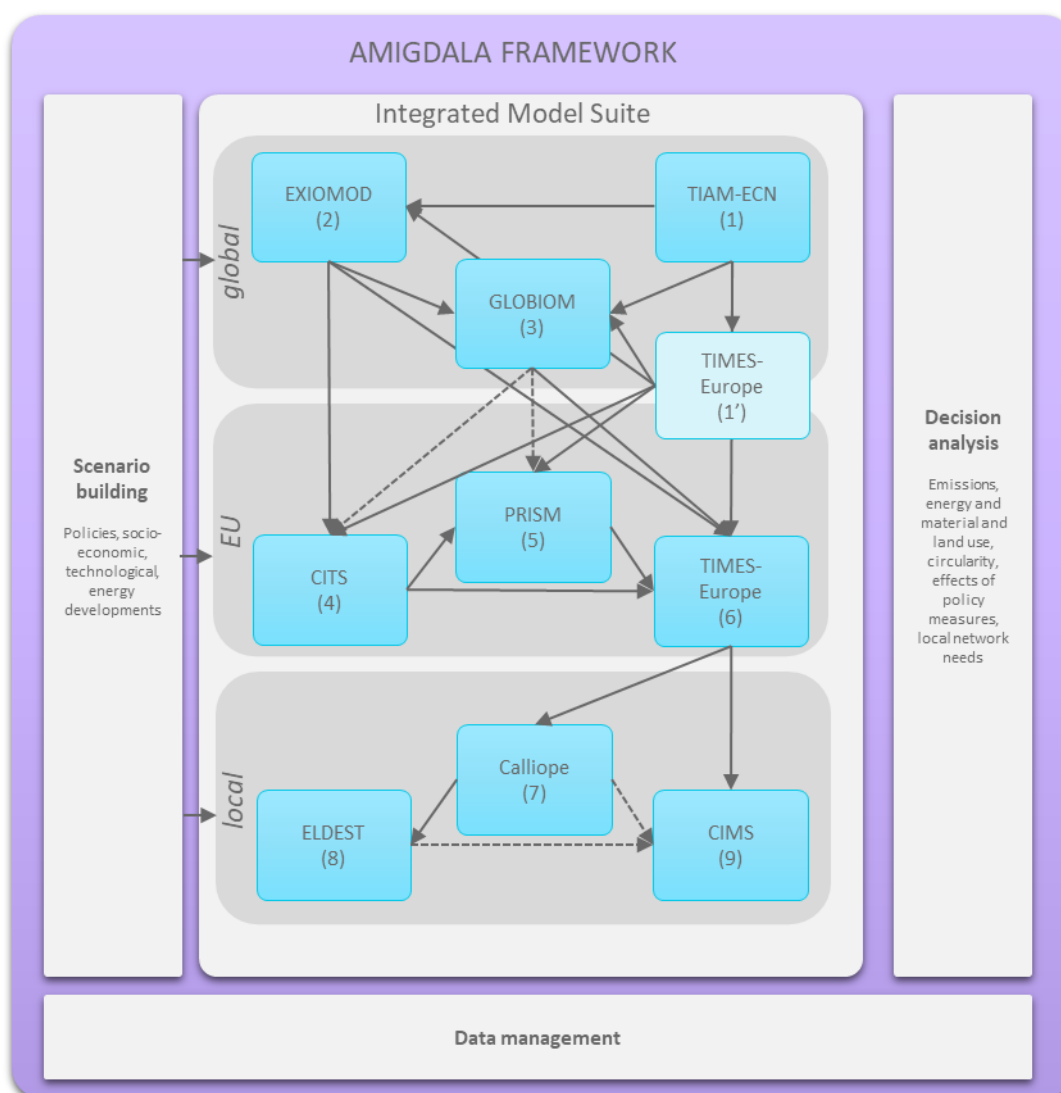


Figure 2. Overview of soft-linked models within the integrated model suite within the framework of AMIGDALA, where the numbers indicate the order of model running (dotted arrows are not implemented in the PoC).

For the PoC, we have chosen to limit the number of model iterations/feedback loops to the most relevant ones. Connecting and aligning the models as described above will reach the AMIGDALA goals on inclusion of materials and circularity, detailing all process industry sectors, alignment of scenarios and different types of models and combining global, EU, MS and local level (see D1.1 Decision framework & integrated model architecture design). Furthermore, soft-linking has been chosen for practical reasons since the 9 models have different owners and run on different servers with different software. For the PoC, serial runs of 4 scenarios of the integrated model suite of 9 models took 2 working weeks (on average about 1 day per model).

As described before, we followed largely a linear linking chain which starts at global level, continues to European level to finalize at local level. The only exception is TIMES-Europe which performs an extra run at the start of the sequence (step 1') to provide a necessary input to EXIOMOD (more details below).

Next to scenario alignment of models, this serial linking and running of models leads to highly interdependent models at each geographical scale but also between scales, herewith aiming for more complete and consistent results.

Details on model development have been documented in AMIGDALA D1.1 and D2.1. A short overview of the models can be found in Annex 9 of this report. A description of the model improvements made in AMIGDALA, as well as a short conclusion on these in the PoC and recommendations for the next phase can be found in Annex 10.

2.3 KPI's

The transition towards climate neutrality will involve many choices - critically by decision-makers in government and industry. To maximize the impact of AMIGDALA project results, potential end-users have been interviewed to understand the transformation from their perspectives and responsibilities. We have interviewed key decision makers split across two different populations: policy decision-makers (both at European and sub-European administrative levels) and industrial decision-makers (executives from companies in sectors covered by the AMIGDALA project operational perimeter). These interviews aimed to assess how decision-makers perceive the world. We analysed the interviews to identify the data required to take decisions furthering (or impeding) Green Deal objectives. From these, we selected and prioritized the most significant indicators to establish them as Key Performance Indicators (KPIs), see Table 2. These KPIs form the foundation for developing scenarios and analysing decisions throughout the project. These KPIs are allocated to the most relevant stakeholder group, either Industry or Policy makers, but may still be relevant for both groups.

Each KPI indicator is associated both to dimensions of climate neutrality and assessment dimensions. While the five dimensions of climate neutrality are focused on a specific topic, assessment dimensions are broader concepts such as Competitiveness (e.g. KPI 1 to 5), Resilience (KPI 3 to 5) and Climate neutrality (KPI 5 to 6) but also Sustainability (KPI 5 to 10).

These KPIs will serve to characterize scenarios and thereafter sort them based upon user preferences. As the filter through which users will be able to select and visualize scenario results, they require numeric and/or graphic interpretations.

Table 2. Selection of 10 aggregated KPIs according to two different user populations.

	#	KEY PERFORMANCE INDICATOR (KPI)	
INDUSTRY	1	Energy mix evolution and price	
	2	Availability & cost of technology	
	3	Raw material and feedstock availability and cost	
	4	Demand evolution in Europe and globally	
POLICY	5	Carbon price trajectory	
	6	Industry emission reduction	
	7	Job creation	
	8	Tax revenue + cost to public sector	
	9	Competitive position vs <u>RoW</u> + Trade balance	
	10	Wider environmental impact	

2.4 Decision analysis

The decision analysis approach implemented in the prototype Decision dashboard Excel for the PoC is a simplified version of the methodology presented in D2.1, which will be applied in the final web-based software implementation. For full details on the methodology we refer the reader to D2.1.

The Decision analysis methodology's primary purpose is to model and visualize the interplay of various factors within industrial processes, with a specific focus on the plastics sector across the European Union. The methodology allows for the analysis of different scenarios, examining how chosen control levers and user preferences influence Key Performance Indicators (KPIs), different operational dimensions, and critical assessment dimensions over a projected timeline, typically from 2020 to 2070.

The entire structure of the analysis is built to facilitate strategic decision-making and impact assessment, particularly concerning environmental sustainability, energy consumption, and emissions within the industrial landscape. It integrates diverse data points and establishes relationships between them to offer a holistic and predictive view of system behaviour under varying conditions.

The analysis takes into account Scenarios, Control levers, Preferences, Dimensions of climate neutrality, assessment dimensions, selected KPIs as well as models' inputs and outputs.

Scenarios selection implies specific control levers states which the user can then modify. Control levers are then bound to the various KPIs, dimensions, preferences, and assessment dimensions they influence. Control levers are also related to the precise inputs and outputs of the underlying model acting as filters selecting which models' runs are to be presented in the results.

Results of the decision logic application are the selection of suitable runs and their prioritization. Model output is integrated into meaningful KPIs representing broader concepts. Filtered runs are then prioritized according to their decisional score, which is obtained by integrating KPIs and user preferences. Finally, the ranked runs are displayed to the user through charts reporting KPI values as well as Dimensions of climate neutrality scores and assessment dimensions scores.

3 The Proof of Concept

Although the scope of the AMIGDALA project is much broader, encompassing various energy-intensive industrial sectors for a large variety of scenarios and cases, the PoC focuses on one value chain and a limited number of selected scenarios for the sake of simplicity.

This chapter presents the three main parts of the PoC, viz. the selected value chain, being the plastics value chain, the research questions to be addressed in the PoC and the scenarios designed for the PoC.

3.1 The plastics value chain

Plastics are a wide range of (semi)synthetic materials composed primarily of polymers. Their main characteristics such as low weight, durability, flexibility and low-cost production allows them to be used in many applications. Plastics have become an integral part of the global economy, being used in almost all economic sectors, such as packaging, construction, automotive, electronics, textiles etc. Hence, plastic demand has grown to 460 million tons of plastic worldwide in 2019 (OECD 2022).

The vast majority of current plastic production starts with extraction of crude oil, after which it is distilled in an oil refinery. One of the produced petroleum products, naphtha, is the crucial compound to make plastic (although other means are possible, such as natural gas). After cracking of naphtha into monomers such as ethylene and propylene, these are linked together in a polymerization process. The resulting polymers are compounded, using different blends of materials, into plastic materials with different properties, making them applicable for various uses.

Plastic production comes with an amount of plastic waste of 353 million ton per year, which is half landfilled, and for the other half mismanaged, incinerated or recycled (OECD 2022). The plastic life cycle results in all kinds of environmental impacts, among which CO₂ emissions which are a multitude of the plastic weight, being 1.8 Gt CO₂-eq. in 2019 (OECD 2022).

The plastics value chain has been selected as test case for the PoC for a number of reasons. These include: 1) most models incorporate plastics, 2) high relevance across all modelling domains of energy, materials, economy and environment, and 3) sectoral development includes many options and pathways, including both evolutionary and revolutionary changes. Significance of the sector in terms of CO₂ and

other environmental impact is certainly also required, but this is the case for almost all industrial process sectors.

Plastics Europe's roadmap indicates relevance of the full spectrum of economy, material and energy related measures such as reuse, recycling, biobased feedstocks, energy saving, fuel switch, renewable electricity and CCS, as illustrated in Figure 3 (Plastics Europe roadmap, Deloitte analysis 2023). This means that all models in the IMS play a significant role.

For all the above reasons, the plastic value chain was considered a good demonstration and learning case to refine the IMS and AMIGDALA framework, as a basis for extension to other sectors in subsequent work packages (see Annex 8).

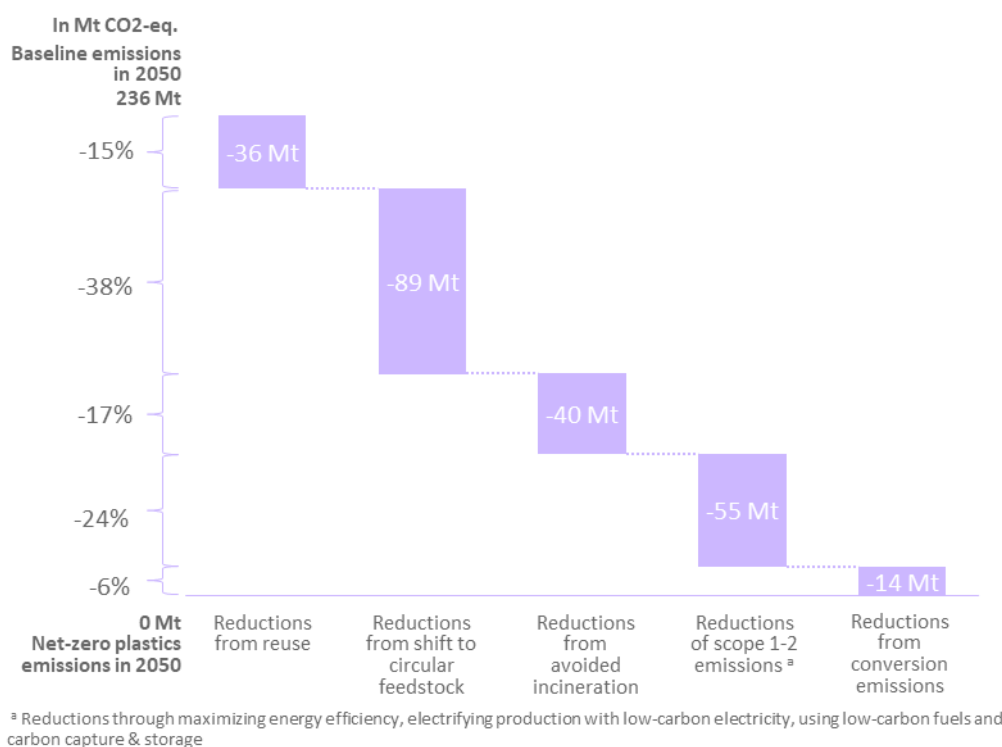


Figure 3. Reductions needed to reach net-zero greenhouse gas emissions in the plastics industry in Europe in 2050 in Mton CO₂-eq. according to the roadmap of Plastics Europe (after source Deloitte analysis, 2023).

The coverage of the plastic value chain in the IMS stretches from cradle to grave, being the main cut-off points for AMIGDALA. The energy models start at resource extraction, in this case particularly of oil, but also alternative carbon sources such as natural gas, CO₂ or biomass are included. For biomass, a special model GLOBIOM is available. The

conversion processes and their innovative alternatives to produce intermediates and plastics are present in the energy system models at global, EU and local level (TIAM-ECN, TIMES Europe and CIMS). The demand for plastic products by different sectors and applications is covered in economic (EXIOMOD) and material terms (CITS), where the last model also includes the plastics material stocks and end-of-life (waste phase) for the different sectors. The plastic waste can be landfilled, incinerated (with energy recovery and with or without carbon capture and storage) or recycled.

Hence, each of these stages in the life cycle are specified at global, EU and local level in terms of materials, energy and CO₂-equivalent emissions, as well as in techno-economic processes including costs. The broader environmental impacts (LCA impacts such as air quality, toxicity, acidification, etc.) are only available for EU material life cycles. On a global level, GLOBIOM can provide land-use and biodiversity impacts. Infrastructure is partially dealt with in relation to energy (electricity and different types of gas) at EU level, but not in terms of environmental impacts.

3.2 Research questions

In recent years, the global political situation has changed drastically. It can be characterized in short as global political and economic fragmentation after a few decades of integration. In this new setting, the EU maintains its strategy to become CO₂ neutral in 2050. It is, however, unclear to what extent the climate policies in the ROW will influence the EU, e.g. in terms of economic growth, industrial production or renewable energy resources.

In addition to CO₂ neutrality, the EU strives to reach a Circular Economy in 2050 as well. This goal has been set in a slightly different light due to the recent global developments, emphasizing the need for circularity not only as a means to reach sustainability but also to become more independent in terms of resources. EU scenarios and modelling are historically strongly oriented to energy and climate and less so to the topic of materials and circularity. AMIGDALA has the objective to fill this lacune.

Hence, this very actual situation inspired us to formulate two important research questions for the PoC to test and demonstrate the AMIGDALA

framework, one on differences in CO₂ mitigation efforts and one on materials and circularity:

1. What is in general the impact of (a lack of) climate policy in the ROW and in particular on the competitiveness and mitigation strategies of the EU, notably the process industry?
2. How can EU Circular Economy contribute to reaching EU climate neutrality?

3.3 PoC scenarios

For the PoC, a limited number of scenarios were developed that sketch very different and relevant developments that allow to test and demonstrate the AMIGDALA framework. Furthermore, the selected scenarios chosen should provide answers to our previously presented research questions posed in the previous section.

Four scenarios were selected. Two background scenarios which describe global developments and two foreground scenarios framing EU policy developments. The background scenarios have been inspired by the SSP scenarios, which combine economic and political developments with climate change policy ambitions and related average global temperatures. From this, we selected as most important differentiator the climate change policies and combined it with the middle of the road economic and politics scenario SSP2. This resulted in 2 background scenarios: one scenario for a world heading for 2.4°C (“Current policies”, in the scenario abbreviation indicated as W2.4) and another for a world meeting global net-zero emissions resulting in a world with 1.5°C (“Global net-zero”, in the scenario abbreviation indicated as W1.5). This is relevant for the EU reaching their targets.

The EU foreground scenario is in all cases meeting a net zero-EU as this is EU policy (characterised as current policies, in the scenario abbreviation indicated as EU net0). The differentiator here is excluding or including EU Circular Economy policies and targets (in the scenario abbreviation indicated as EU net0 CE). This differentiator is chosen for analytical reasons since it enables to show the impact of Circular Economy policy measures on reaching climate change targets.

These 4 scenarios are presented schematically in Table 3 and are designed to answer the research questions in the previous section.

Table 3. Schematic overview of the 4 scenarios for the Proof of Concept, resulting from 2 global background and 2 EU foreground scenarios.

		EU FOREGROUND	
		EU climate neutrality	EU climate neutrality without fossil carbon as a feedstock as from 2050
GLOBAL BACKGROUND	Current policies (2.4°C)	Current Policies (1. W2.4-EU net0)	EU Circular (2. W2.4-EU net0 CE)
	Global Net-Zero (1.5°C)	Global Net-Zero (3. W1.5-EU net0)	Global Net-Zero EU Circular (4. W1.5-EU net0 CE)

4 Draft results

This chapter presents preliminary results on the plastic value chain to demonstrate the Proof of Concept of the AMIGDALA framework as designed and developed the past one and a half year. It starts with a section on historical data, followed by results of the Integrated Model Suite on global, EU, interregional and local level and ends with an impression of the Decision Dashboard.

4.1 Historical developments for the EU27

To put the models' results of the PoC into perspective and connect the past evolutions with the future projections, a set of historical data regarding climate neutrality in the European plastic industry has been collected. The selection of data has been done according to the 5 dimensions of climate neutrality (cf. Deliverable 2.1):

1. **Energy consumption,**
2. **Emissions,**
3. **Use of raw materials,**
4. **Production of end products,** and
5. **Fossil carbon replacement in materials.**

The data collection focused on the EU and its member states, as well as some other European countries when available. Regarding the sector, focus was on the plastic, petrochemical, chemical or industry sectors, depending on the availability of the information. The data has been harmonized and uploaded to the Data Explorer. The following 5 sections show the historical developments for the EU27 along the 5 dimensions. They can be related to the modelling results at the EU level summarized in the section 4.3 EU modelling results.

4.1.1 Energy Consumption

To represent the 1st dimension, as no specific data on the final energy consumption in the production of plastics are publicly available, we used the final energy consumption in the chemical industry (Figure 4) and the final non-energy consumption in the industry (Figure 5), both from Eurostat.

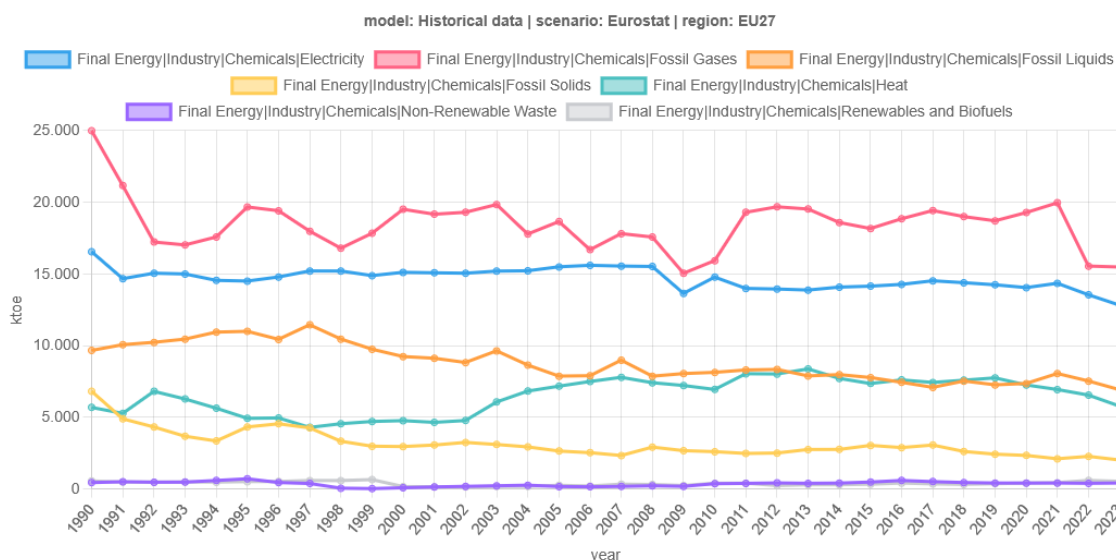


Figure 4. Final energy consumption in the chemical sector for the EU27.

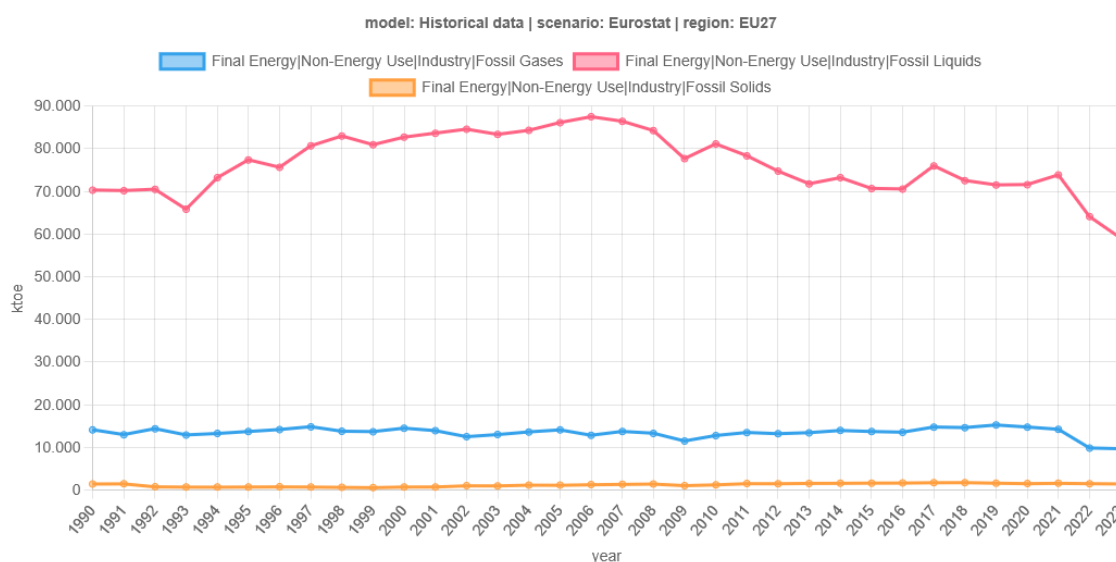


Figure 5. Final non-energy consumption of fossil fuels in the industry sector for the EU27. The fossil liquids are mostly used in the petrochemical industry.

Eurostat also makes available an indicator called “renewables share” that is calculated based on the overall final energy consumption and according to the Renewable Energy Directive¹ (Figure 6). This indicator is used to monitor the overall progress towards the renewable targets stated in the directive. According to its definition some multipliers are applied in the mobility sector.

¹ Details on the renewables share indicator can be found in the metadata: https://ec.europa.eu/eurostat/cache/metadata/en/nrg_ind_share_esmsip2.htm

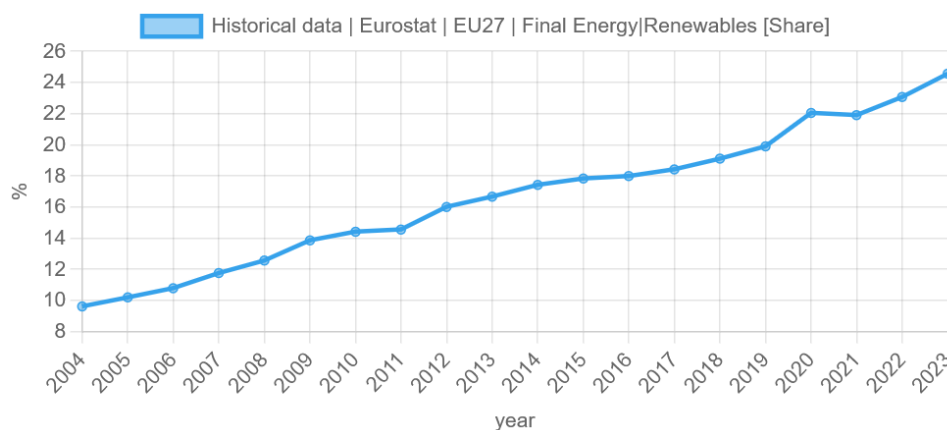


Figure 6. Overall renewables share in final energy, as calculated according to the Renewable Energy Directive.

4.1.2 Emissions

For the 2nd dimension, the greenhouse gas emissions of the chemical industry, including the petrochemical industry, were obtained from Eurostat (Figure 7). Since it is a driver to reduce emissions, the CO₂ price resulting from the Emission Trading System (ETS) has also been collected (from the World Bank, Figure 8).

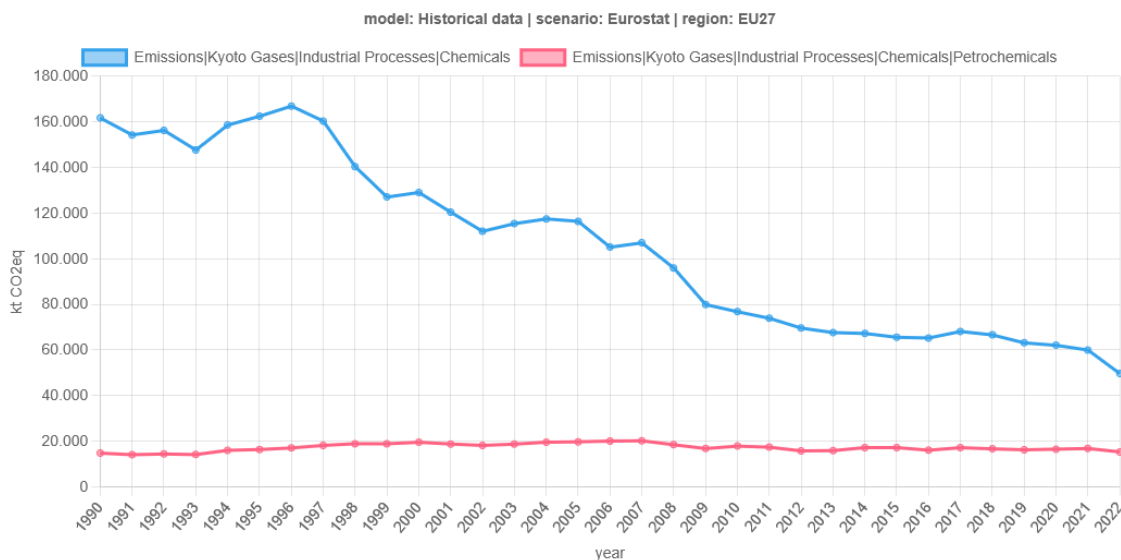


Figure 7. GHG emissions from the chemical sector, including the petrochemical sector for the EU27.

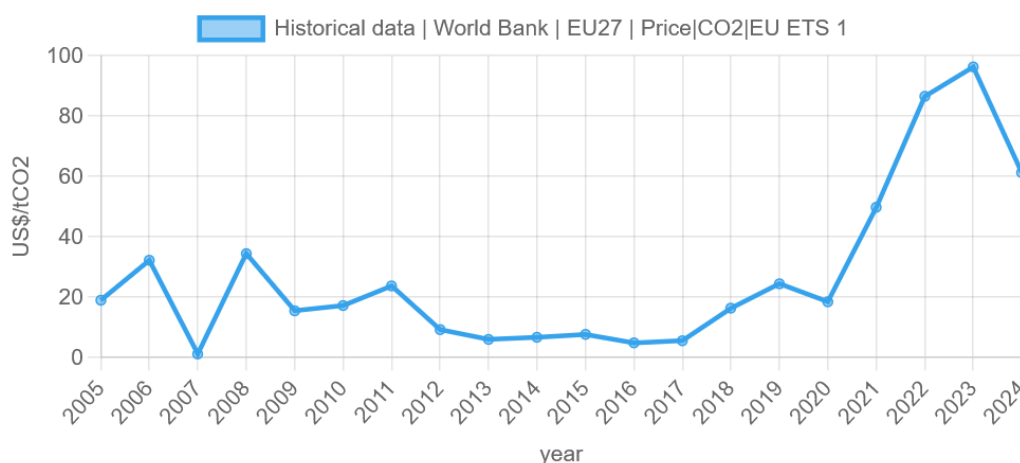


Figure 8. CO₂ price resulting from the European Emission Trading System.

4.1.3 Use of Raw Materials

For the 3rd dimension, we looked at the use of fossil materials, including recycled fossil materials, both from Eurostat (Figure 9).

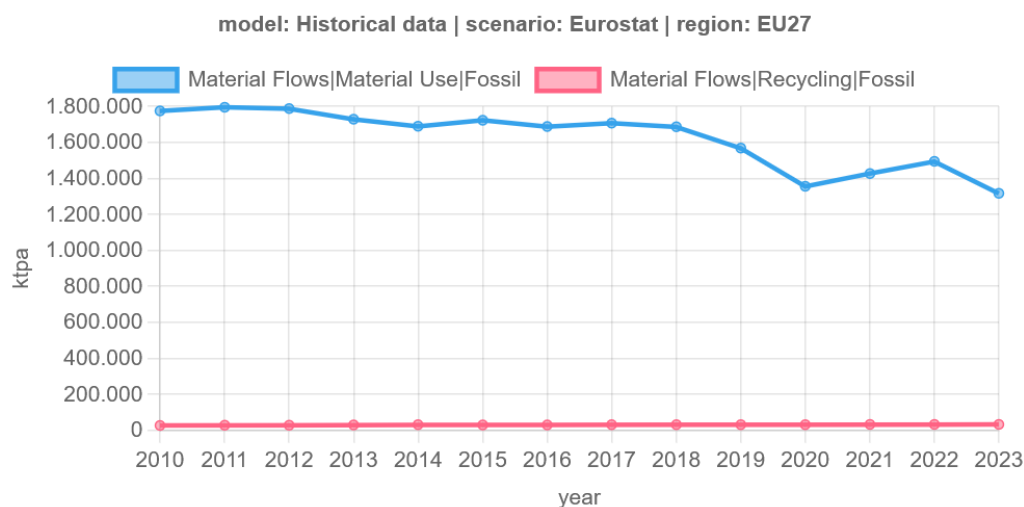


Figure 9. Use of fossil materials, including recycled fossil materials for the EU27.

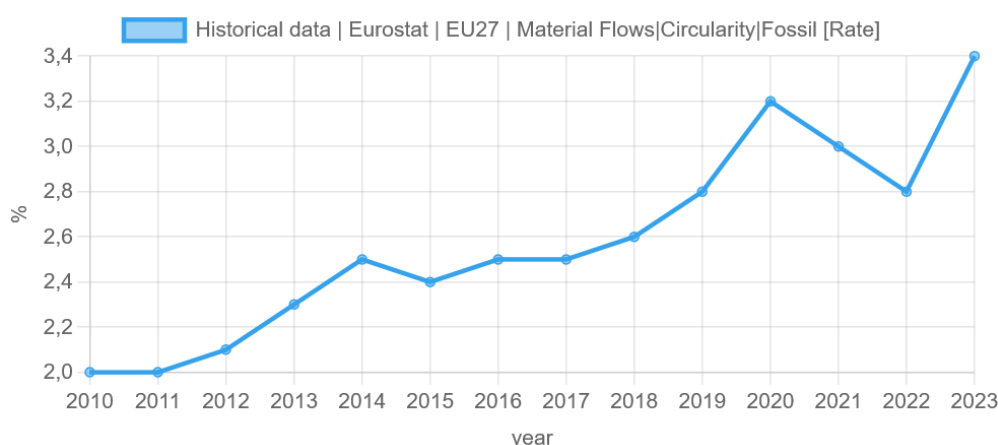


Figure 10. Circularity rate of fossil materials (i.e. share of recycled fossil materials) for the EU27.

Steam cracking is the main upstream process for the whole petrochemical industry, including the production of plastics. The feedstock consumption for steam cracking is available from Petrochemicals Europe, albeit only for Western Europe and the exact regional scope is changing over the years. Therefore, it has not been uploaded yet to the DE.

4.1.4 Production of End Products

For the 4th dimension, the production value of plastic and rubber products is selected (Figure 11). The data was taken from Eurostat. The data regarding the production volumes was not collected since it is incomplete.

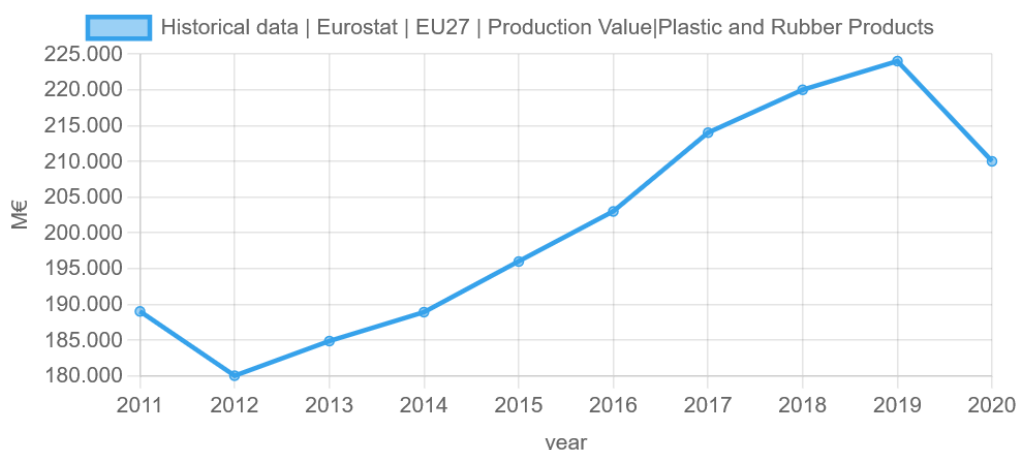


Figure 11. Production value in M€ of plastic and rubber products within the EU27.

4.1.5 Fossil Carbon Replacement in Materials

For the 5th dimension, the shares of biobased and recycled plastics in the plastic production have been used, since they are the only

substitutes for fossil carbon in plastics so far. The data was published by Plastics Europe aggregated over the EU27, United Kingdom, Switzerland, and Norway (EU27+3).

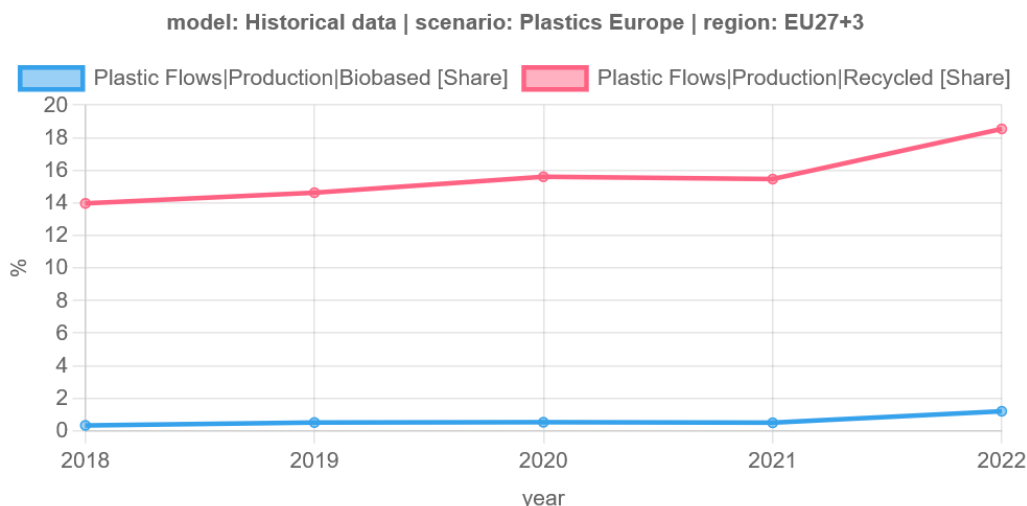


Figure 12. Shares of biobased and recycled plastics in the plastic production for the EU27+3 (EU27, United Kingdom, Switzerland and Norway).

This historical data can be compared with the corresponding model projections that are presented in the following sections.

4.2 Global modelling results

4.2.1 Overall developments energy, economy and emissions

At global level, the W2.4 and W1.5 are the major differentiating scenarios, while the Circular Economy aspect is not in scope for the global models. Exception is the specification of the EU in the global macroeconomic model EXIOMOD. It could include CE input, which should in that case be provided from models at the EU level (CITS and PRISM). This would require a feedback loop from EU to global models, which is beyond the current PoC. This will be included in the next phase when we refine our modelling with feedback iterations. Hence, for the current global analysis, we focus on the two W2.4 and W1.5 scenarios with very different global climate change policies.

The rate at which the rest of the world decarbonises, differs greatly between the W1.5 and W2.4 scenarios. In a W1.5 world, global emissions decline at a linear rate of about 280 Mt per year from 2030 onwards, while in a W2.4 world, net carbon reductions only take place after 2050, see Figure 13.

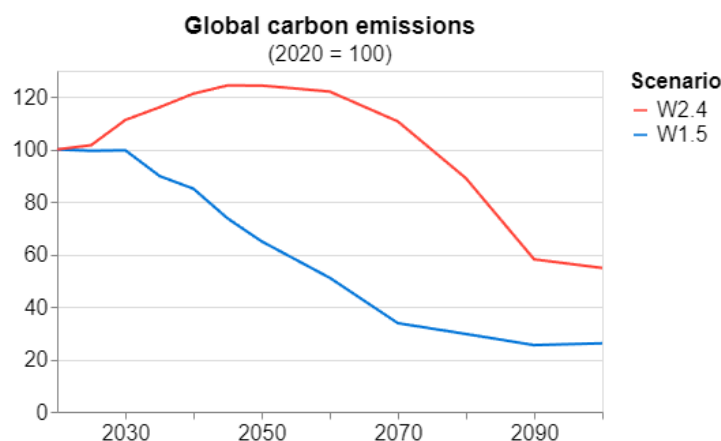


Figure 13. Global carbon emissions (index 2020) for the scenarios W2.4 and W2.1 (source: TIAM-ECN).

In the W2.4 scenarios, the incongruity in abatement targets between the EU and the ROW results in different carbon prices, with the EU facing higher prices than other regions, while this incongruity disappears in the W1.5 scenarios, see Figure 14. Despite this, the European carbon price in the W2.4 scenarios is still low compared to the European carbon price in the W1.5 scenarios. This difference may be attributed to heightened abatement costs in a world where all countries have ambitious targets and as such are competing more strongly for abatement options. One such option is the heavy use of biomass, for example for the purpose of negative emissions (BECCS). The difference between the scenarios is clear here: in a W1.5 world, the use of primary solid biomass is 20% higher in 2040 compared to a W2.4 world, with the average biomass price in the period 2020 – 2050 being more than twice as high. This biomass demand is used as input for the GLOBIOM global land use model. Please note that in 2045, a spike in the carbon price arises, which is due to relatively limited abatement potential compared to the strict CO₂ abatement targets. It needs further research to identify whether this is a realistic model result or a model artefact.

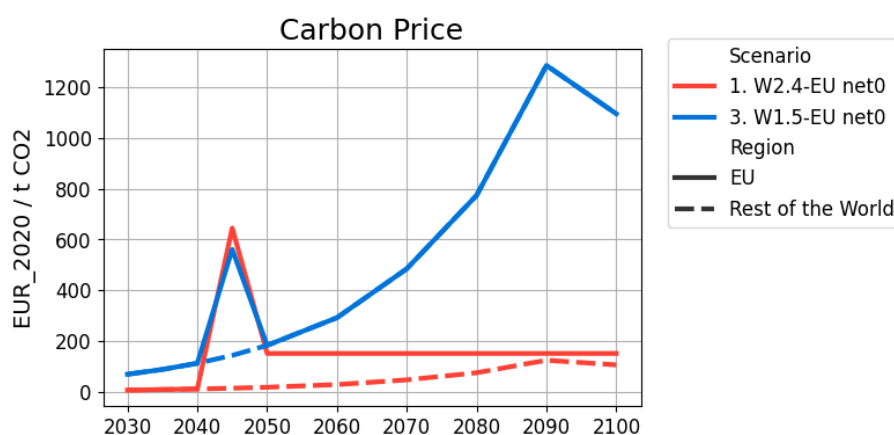


Figure 14. Carbon price of EU and ROW in a W2.4 and W1.5 scenario (source: TIAM-ECN).

The total primary energy from biomass deployed in the TIAM-ECN model increases from 61 EJ/year in 2020 to 105 EJ/year by 2100 for the W2.4 scenarios and to 127 EJ/year for W1.5 scenarios, see Figure 15.

The primary energy demand from biomass was matched by the GLOBIOM model, primarily by utilizing agricultural crop residues, corresponding to 30 and 35 % of the total demand by 2050 for W2.4 and W1.5 scenarios, respectively (24 and 32 EJ/year). Besides the increase in crop residues, we observed a substantial increase in the share of dedicated bioenergy crops, especially in the second half of the century, with a concurrent saturation in the potential of crop residues for bioenergy use. This was particularly evident for the high decarbonisation scenarios (W1.5), where energy crops use increased from 6.4 to 28.2 EJ/year in the period 2050-2100. The same patterns were also observed for the forest industry residues (sawdust, wood chips, black liquor), doubling from 4 EJ/year in 2020 to 8 EJ/year by 2050 and 13 EJ/year by 2100.

Similar to the results on the primary energy biomass deployment, the corresponding AFOLU (agriculture, forestry and land use) GHG emissions varied with the decarbonisation scenarios, where higher carbon price for W1.5 led to a faster uptake of AFOLU mitigation options (e.g. larger afforestation area) (not shown here). The development of AFOLU emissions reflected the land use patterns across the scenarios. We observed an increase in forest area, driven by afforestation (575 and 646 million ha for W 2.4 and W 1.5, respectively). and cropland area expanded around 130 to 140 million ha by the end of the century (excluding energy crops). The expansion of cropland and forest area observed in the scenarios, however, partly replaced other natural lands.

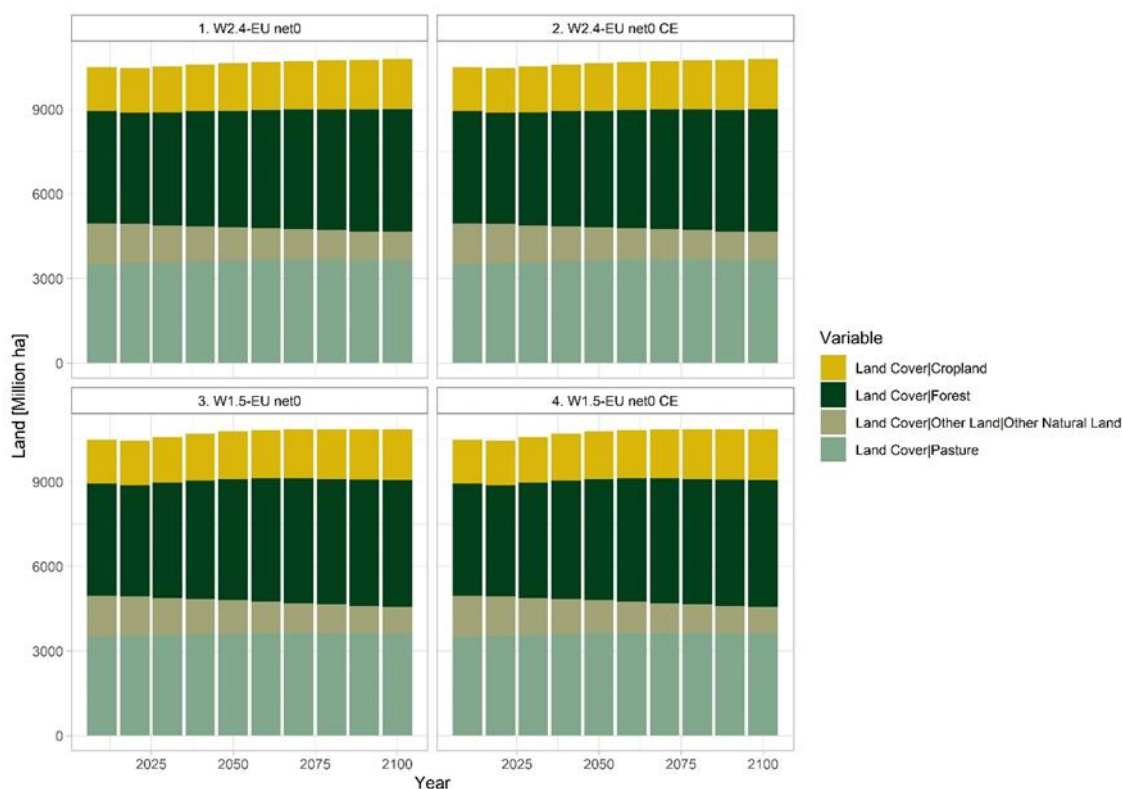


Figure X. Land cover development for the scenarios tested.

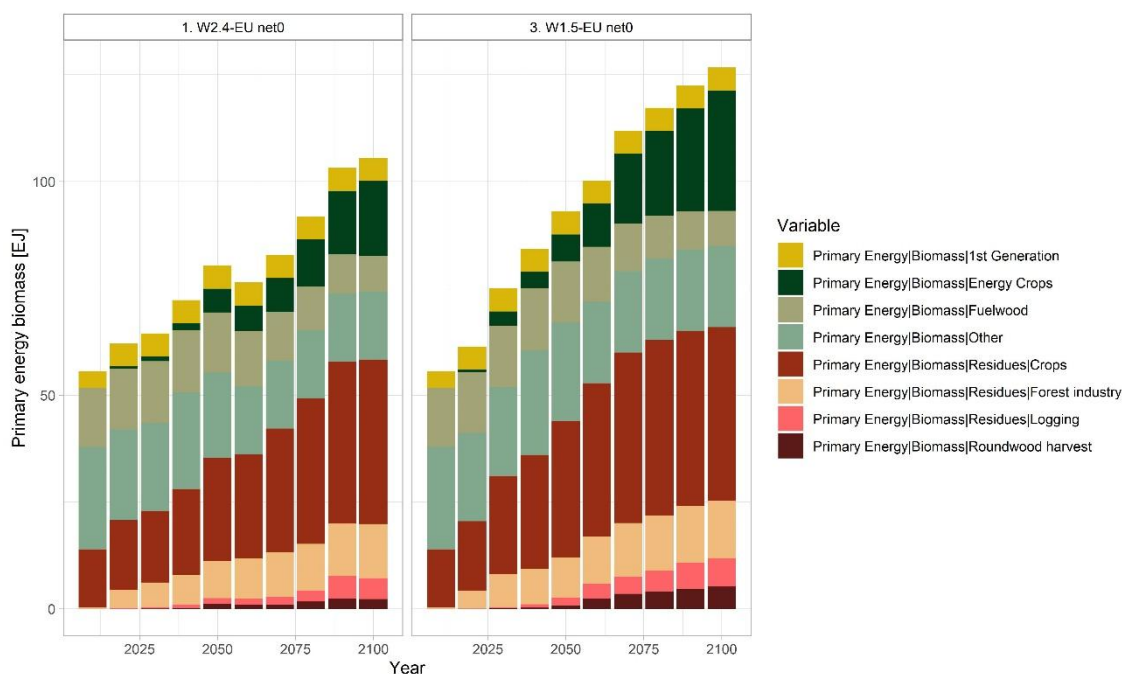


Figure 15. Primary energy biomass for the W2.4 and W1.5 scenario (source GLOBIOM).

GDP in EU is lower in the W2.4 scenarios compared to the W1.5 scenarios where the ROW joins in the energy transition measures.

This implies that the competitive advantage of the EU is worse in the W2.4 scenarios. For the ROW regions, it is the other way around. Compared to the W1.5 scenario, in the W2.4 scenario the ROW regions are not restricted as much by climate policy / energy transition measures. Figure 16 shows the expected GDP in million euro for the EU countries and the ROW countries in 2055 and the percentage change between 2019 and 2055 resulting from energy transition measures. In the ROW W2.4 scenario, the energy transition measures have very little impact on ROW GDP.

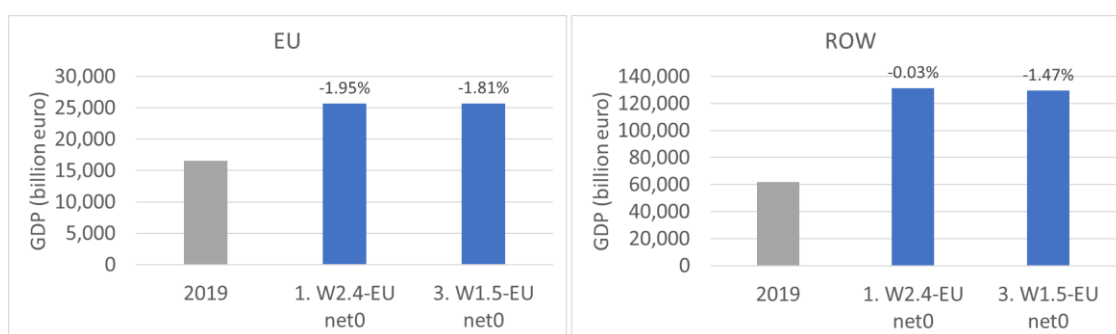


Figure 16. GDP in million euro for EU countries and ROW countries in 2055 (mln euro). The percentages indicate the percentage change in GDP resulting from the energy transition measures between 2019 and 2055 (capital and labor improvements neglected) (source EXIOMOD).

Capital and labour productivity have the biggest impact on GDP of the six scenario measures included in EXIOMOD. This input measure implies that with the same amount of capital and labour more economic value can be created. Table 4 shows the impact of the six separate measures on EU GDP (2055 vs. 2019). Since the capital and labour productivity is exactly the same for all four scenarios, this will not have any impact on the *differences* between the scenarios. Also, electricity mix and energy demand in households have little impact on GDP. Changes there rather result in an energy mix shift (e.g. more electricity, less demand for fossil fuels). We identified two measures that have a negative impact on GDP. The transition comes at higher capital costs and CO₂ prices, which make the competitive position in the EU slightly worse. Capital costs have been approximated based on the extent to which energy shares in a sector have been modified by the transition.

Table 4. Impact on EU GDP (2055 v 2019) of separate measures in the scenarios (source EXIOMOD).

2055 v 2019	Capital and labour improvements	Electricity mix	Energy demand industries ³	Energy demand households	CO2 prices	Higher capital costs
Impact of measure on EU GDP	57.76%	0.01%	-0.09% to -0.15%	0.00%	-0.47% to -0.58%	-1.27% to -1.21%

Regarding the sectoral structure of the EU economy, there are sectors that make changes in their production structure (e.g. the chemical sector and metal sector) and there are sectors that are affected indirectly by changes in demand in other sectors (e.g. the mining, coke ovens, refined petroleum or electricity sector). Manufacturing or service sectors that use energy in their production process will experience changes due to expensive changes in capital use, via the increased CO₂ price or via higher or lower energy costs.

A critical assessment of the current state of the macroeconomic model EXIOMOD is that despite inclusion of energy mix, demand and capital costs and CO₂ prices, the competitiveness of the EU is mainly affected in terms of relative industrial sector growth of energy intensive sectors. The overall economic competitiveness of the EU is determined mainly by historic differences², which are being extended in the future, and not so much by differences in (timing and extent of) energy and climate transition. This will be further addressed in the next phase of the project.

4.2.2 The plastic value chain

The difference in economic growth indices between W1.5 and W2.4 of two plastic related sectors are largest in the Rest of World. The differences in EU are smaller, see Figure 17 which presents the economic growth indices of two plastic related sectors in EXIOMOD, being basic plastic and rubber and plastic manufacturing. The basic plastic sector (this is part of the chemical industry) produces the raw input required by the rubber and plastic manufacturing sector. The relatively large growth in the ROW regions can be explained by capital and labour productivity improvement potential in developing regions outside the EU. Countries in the EU are in general more developed,

² The capital supply in the model is currently still exogenous, which implies that regions will continue to grow at the similar pace as we might have seen in the past. Ideally, a (dynamic) recursive capital supply function is implemented which reflects the willingness of investors to invest in the market.

corresponding to a lower economic growth. However, both plastic related sectors grow slower than the average growth in the GDP in the EU (55% GDP growth between 2019 and 2055).

The carbon price (input from TIMES-Europe) **and higher capital costs have a negative effect on the competitive position of the rubber and plastic manufacturing sector in the EU**³. For the ROW regions, EXIOMOD receives sectoral energy demand from TIAM-ECN. These inputs show improved energy efficiency for the rubber and plastic sector. Hence, this sector grows even faster than the average GDP in the ROW (GDP growth is equal to 112% in W2.4-EU net0 and 109% in W1.5-EU net0.)

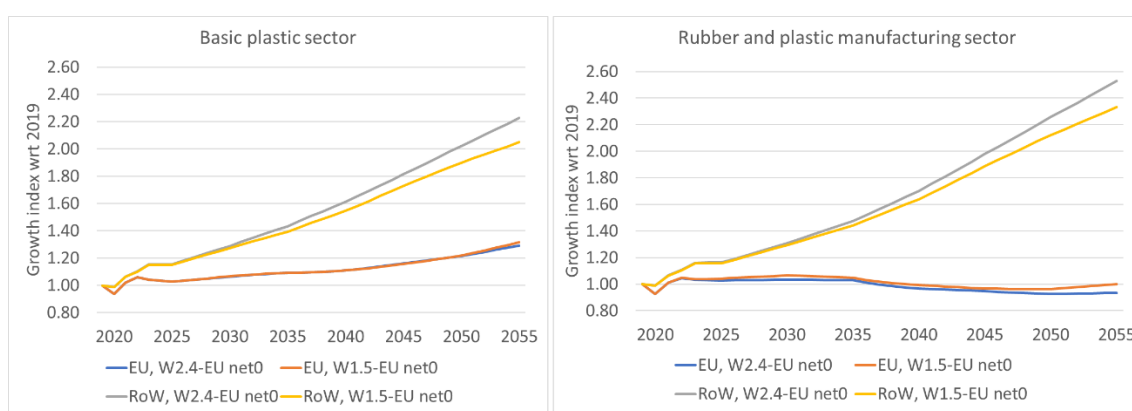


Figure 17. Growth trajectories of two plastic related sectors in the EU and in the aggregated ROW region (source EXIOMOD).

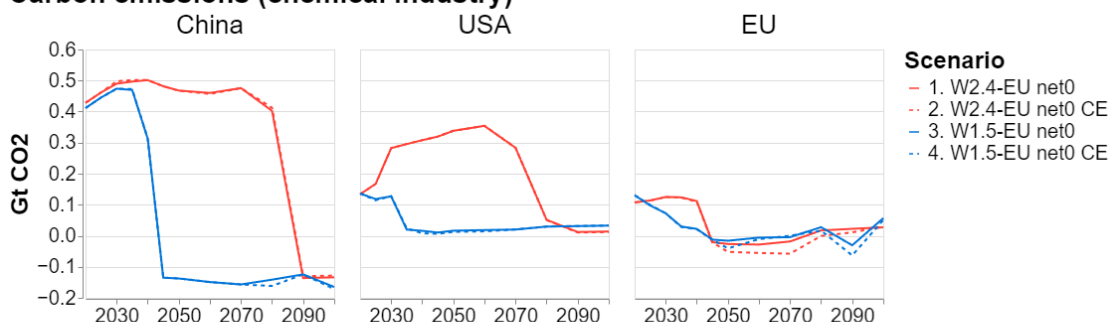
In the EU, the growth rate of the basic plastic industry is slowed down mostly by the higher carbon price in 2055 (the basic plastic industry is part of the chemical industry, and also an energy intensive sector). However, also higher capital costs influence the sector's competitive position. Outside the EU, the higher CO₂ price under the W1.5 scenario and the higher capital costs in this industry explain the difference in growth rates between the two scenarios.

In 2020, CO₂ emissions from China's chemical sector accounted for 32% of chemical sector emissions worldwide, making China the

³ In review of this document, it was found that the calculation of energy efficiency within the model EXIOMOD was not correct. In the current results, the rubber and plastic manufacturing sector seems to decline partly due to the implemented energy in-efficiency. However, instead, an improved energy efficiency should have been implemented. After correction of these results, it is likely that the rubber and plastic sector in the EU will (rather than decline) slightly grow due to the achieved energy efficiency. Similarly, the projected growth in the basic plastics sector is likely to be underestimated due to this.

country with the largest chemical sector CO₂ emissions. The emission reduction pathways differ by region (upper part of Figure 18). In the W2.4 climate scenarios, China continues to emit at a constant level up to 2080, operating on an energy mix consisting mostly of coal (>60%) and electricity (30%) (lower part of Figure 18). After 2080, a sudden switch is made where coal is fully substituted with gas, resulting in major emission savings. Conversely, in the W1.5 scenarios, this switch occurs already in 2045.

Carbon emissions (chemical industry)



Energy mix by region (chemical industry)

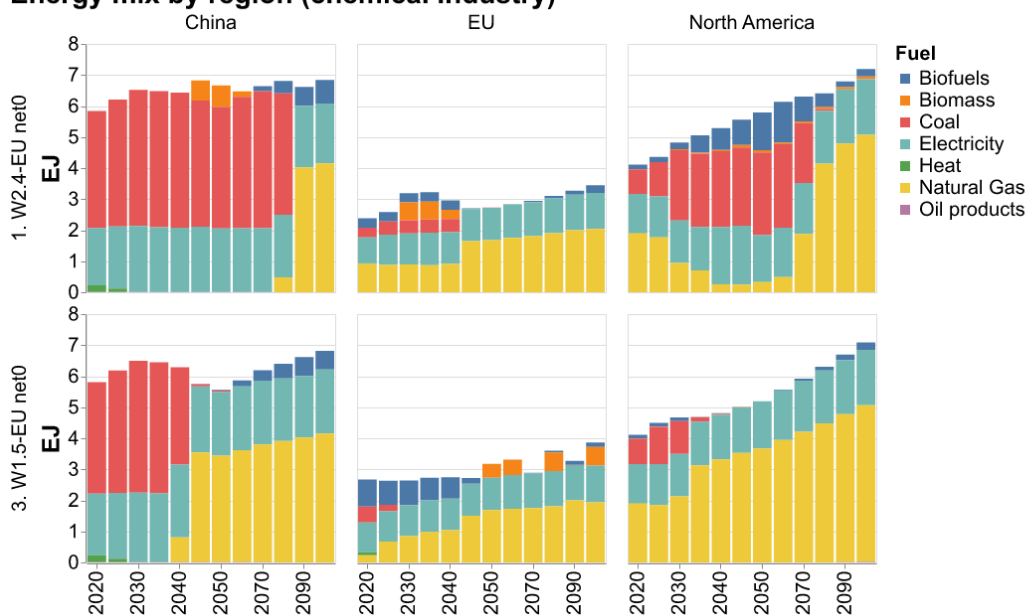


Figure 18. Carbon emissions and energy mix of the chemical industry of 3 selected regions in W2.4 and W1.5 scenarios (source TIAM-ECN).

In North America, coal is effectively phased out in 2035 in the W1.5 scenario and 2070 in the W2.4 scenario. The chemical industry's energy mix in North America already starts with a significant amount of gas (about 45% of total energy demand), with the rest of energy demand being filled with electricity and coal. Despite the large share of gas, North American emissions continue to rise in the W2.4 scenarios. This rise corresponds with a phase-in of coal, which peaks around 2050.

Only from 2070 coal products are phased out, resulting in lower emissions. In the W1.5 scenarios, the North American energy mix simply continues to operate on mostly gas and electricity, with coal effectively phased out by 2035, allowing a near net-zero chemical industry.

Similar to North America, the EU chemical industry currently operates mostly on a mix of gas and electricity, which together fulfil about 70% of energy demand. In the W1.5 scenarios, the remaining 30% is filled mostly with biofuels, which continue to play a role until 2045, until gas use has scaled up sufficiently. In a W2.4 world, coal forms a minor fuel source up until 2040, after which it is phased out. In all four scenarios, the European chemical industry reaches net-zero by 2045. Interestingly, the role of electricity in industry remains relatively stable, even in the W1.5 scenarios, at around 25% of energy demand.

4.3 EU modelling results

At European Union level and lower, the W2.4-EU net0 and W1.5-EU net0 scenarios have two variants for the EU, i.e., without and with Circular Economy strategies for the plastics sector. These result in additional EU scenarios 2. W2.4-EU net0 CE and 4. W1.5-EU net0 CE. This will allow for the analysis of the contribution of Circular Economy policies to the energy and climate transition of the EU industry.

4.3.1 Climate & energy

The implemented EU Climate policy targets drive down the CO₂ emissions effectively. Figure 19 displays the evolution of the projected EU27 sectoral CO₂ emissions over time. Clearly, the CO₂ reduction pathways of all four scenarios show a great resemblance. This is a consequence of the fact that the overall EU emission level is determined by the EU targets which are equal in all scenarios. From 2040 negative emissions occur; these are related to the deployment of Bio-Energy CCS (BECCS) in power and heat. In general, the CO₂ (shadow) prices projected by TIMES-Europe peak in 2040 at 170-200 €/2015/ton (data not shown) with slightly higher prices in the W1.5 scenarios. From 2050 prices in the circular scenarios exceed CO₂ prices in the non-CE scenarios.

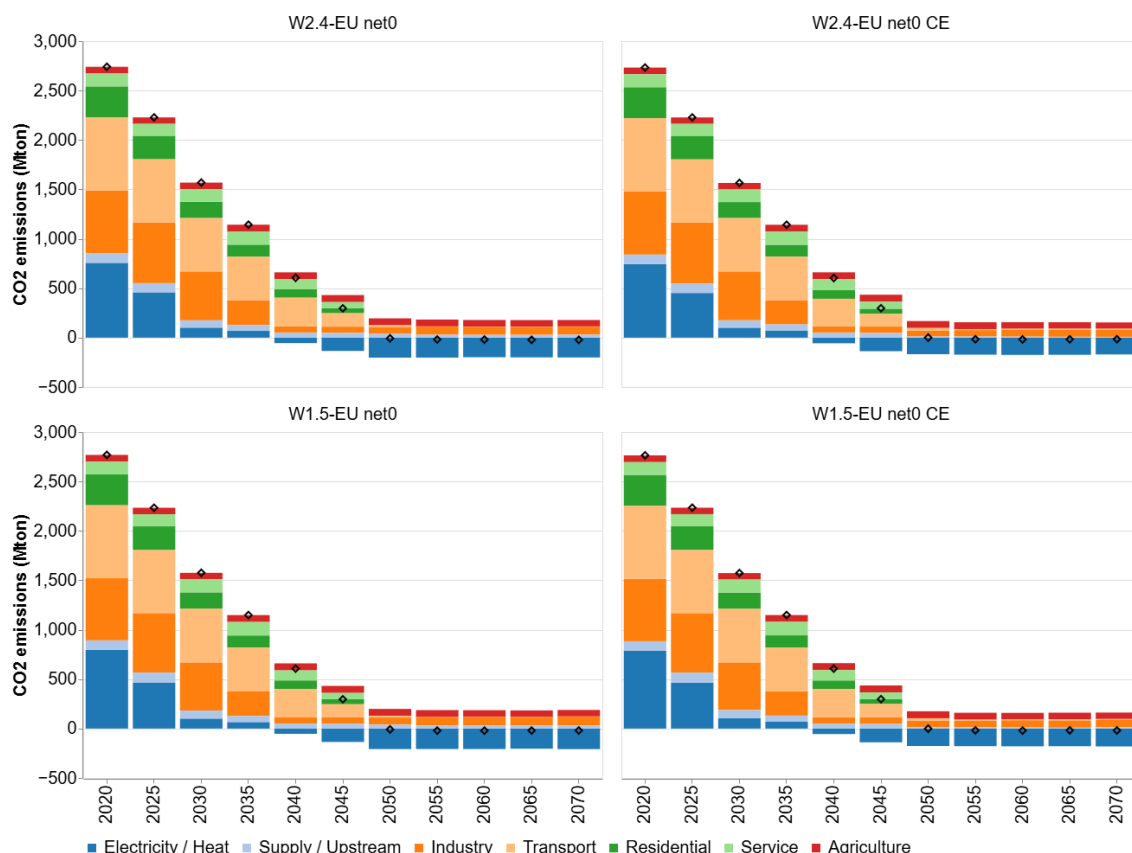


Figure 19. The EU27 CO₂ emissions for the four scenarios (source TIMES-Europe).

The EU27 + UK final energy demand reduces by 22-25% in the 2020-2050 period with slightly higher reduction for the W2.4 scenarios (see Figure 20). Overall the 2050 final energy demand is lower in W2.4 by 0.6 EJ and 0.9 EJ for the circular and non-circular scenarios respectively. This is almost entirely due to a lower final energy demand in industry for the W2.4 vs. W1.5 scenarios (data not shown), which is assigned to the worse competitive position of the EU when climate measures stay behind in the ROW. Similarly, in 2020, the Industry sector contributes roughly 25% to the final energy demand, this increases to 33 – 37% in 2050, where the higher part of the range corresponds to the W1.5 scenarios. In 2030 final energy saving in the EU is ~10% (w.r.t. 2020) amounting to ~36 EJ, which is approx. 4 EJ above the EED target, which was not implemented in the current model runs.

The share of oil & coal in final energy reduces from around 40% in 2020 to 11-14% by 2050. In all scenarios, there is an increase in electricity demand due to increasing electrification by at least 50%. (see Figure 20) Bio-energy for energy use reduces in all scenarios, in particular in the circular scenarios, where there is a stronger

competition with biomass for feedstock use. In 2050 hydrogen demand for energy purposes has increased to 1 – 1.2 EJ, the largest part of it is used in steel making, next to 200-300 PJ in road transport. Consumption of Hydrogen derived synthetic fuels (HDSF) rises to significant levels in 2040, and subsequently increases to more than 2 EJ in the second part of the century in all scenarios. These concern mainly synthetic fuels for road transport and aviation.

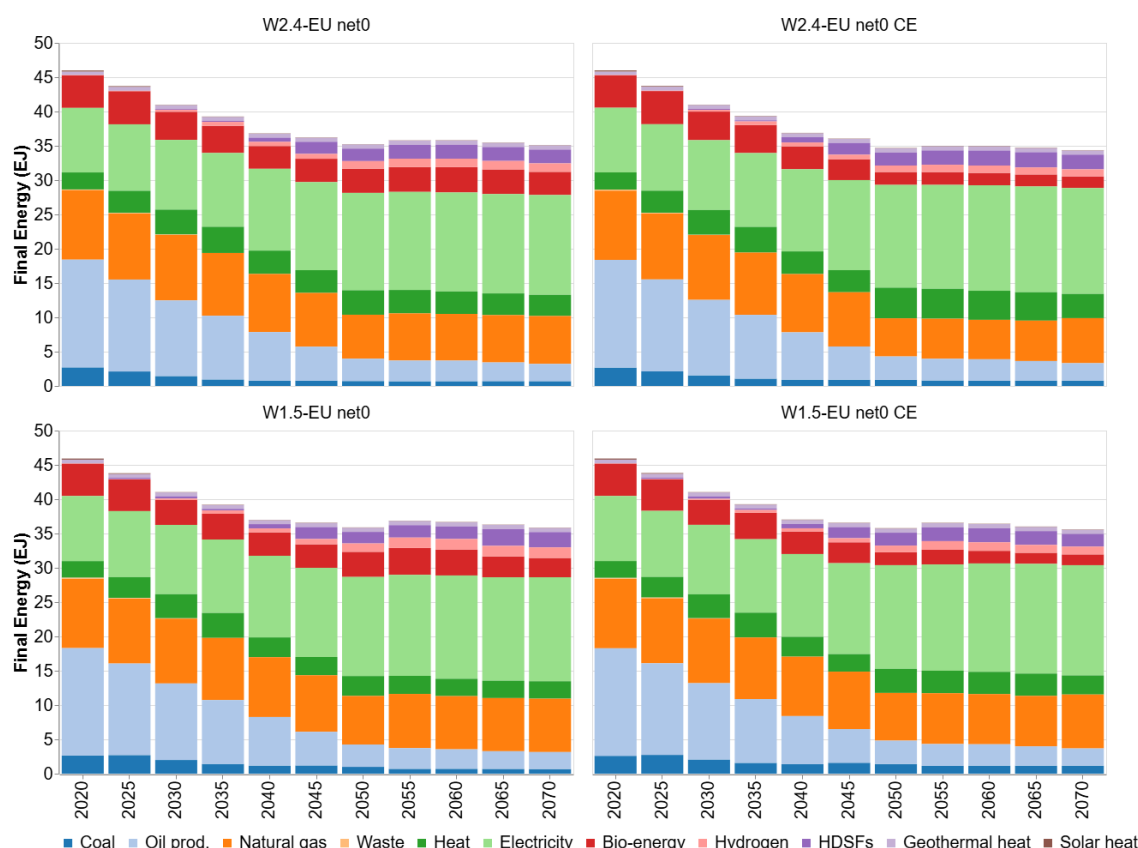


Figure 20: Final energy demand in EU27+UK excluding international marine bunkers and non-energy use (source TIMES-Europe).

Electricity production (nearly) doubles between 2020 and 2050 in the CE scenarios. In the non-CE scenarios growth is ~ 70% (see Figure 21). In addition to electrification of end-use demand, part of this growth can be attributed to the production of HDSFs, including (e-)fuels and (e-)feedstocks. Fossil based electricity production reduces strongly. Nuclear, wind and PV become increasingly dominant in the electricity mix. Remaining fossil fuel generated electricity is combined with CC(U)S. The share of electricity from renewables is significantly larger in the W1.5 scenarios. This is in particular true for the share of wind energy; this increase goes at the expense of electricity from natural gas. Most likely this is related to the higher gas price in the W1.5 scenarios.

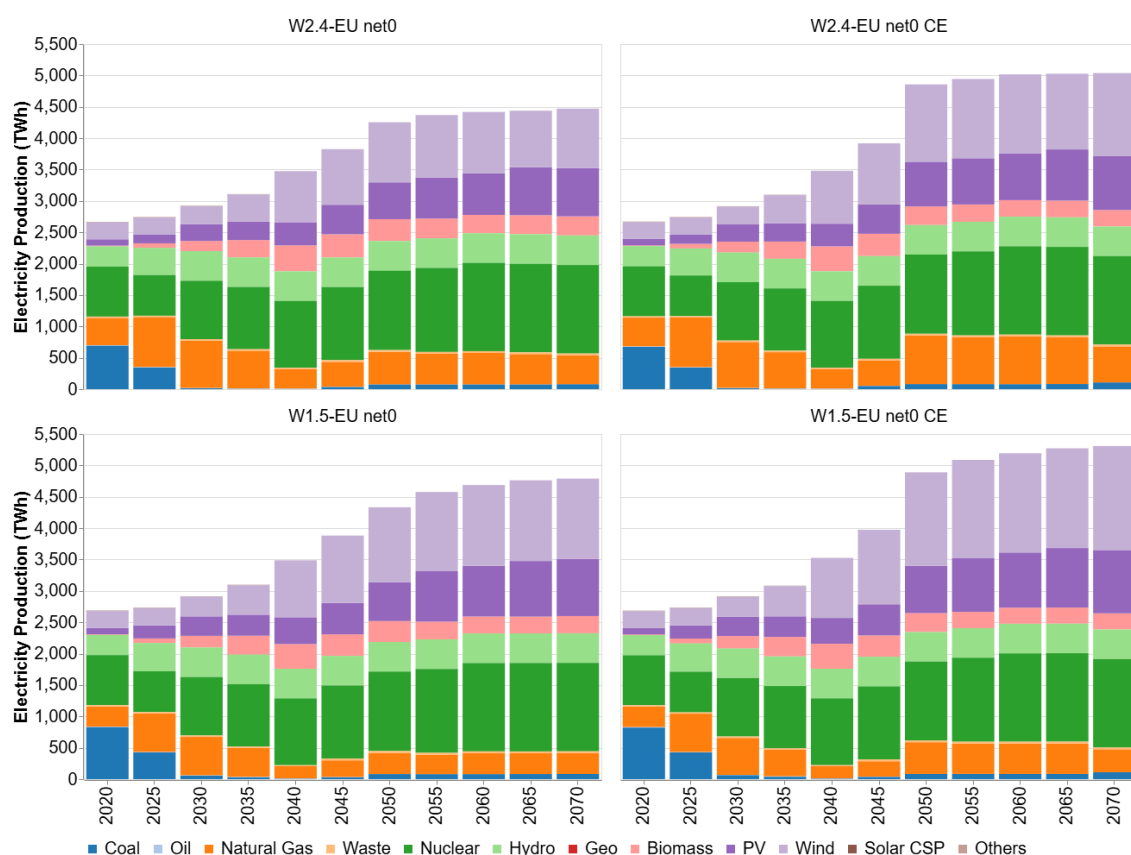


Figure 21. Electricity production in EU27+UK (source TIMES-Europe).

4.3.2 The plastic sector

Without circular strategies, plastic consumption in the EU27+3 increases by more than 20% between 2025 and 2050, reaching 74 Mt (see Figure 22). Most plastics remains to be consumed in packaging, followed by construction, others (e.g., medical applications, furniture, machinery), and textiles. While plastic consumption grows across all sectors, the growth rate differs by sector, ranging from a 14% growth in agricultural plastics to a 25% growth of packaging in the baseline scenarios. On single country level the growth rates of total plastic consumption vary substantially, ranging from -20% to more than 70% in the W.2.4 net0 baseline scenario.

In the circular scenarios, the plastic consumption reduces from ca. 60 to 50 Mt until 2050, resulting in a 32% lower consumption compared to the non-circular scenarios (see Figure 22). The circular scenario combines strategies such as refuse (elimination of some plastic applications or shared economy concepts), reduce (less material per product), lifetime extension (e.g., through behavioural change, repair & maintenance), reuse, and improved collection and sorting.

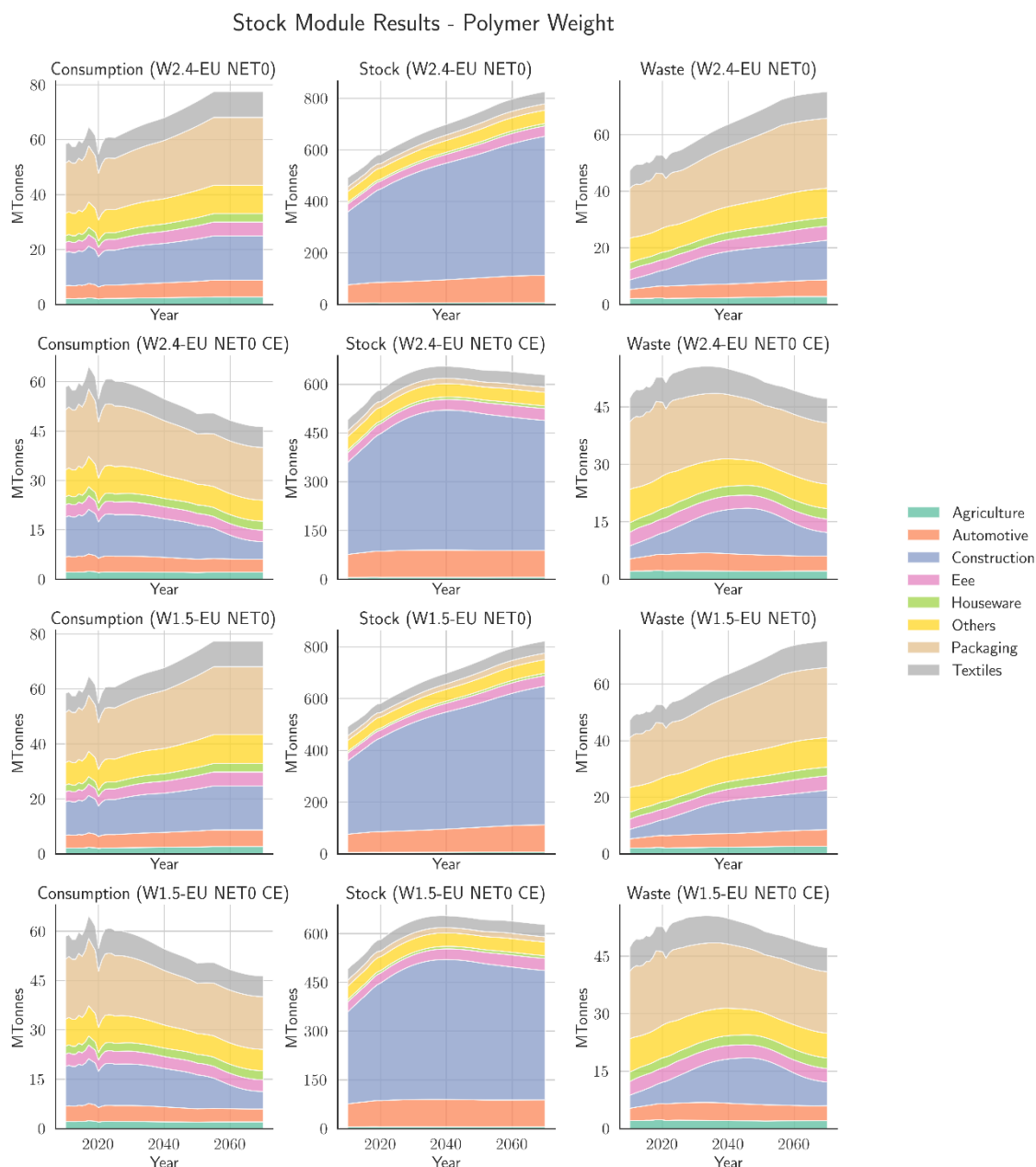


Figure 22. EU27+3 Plastic consumption, stocks, and waste generation by sector and scenario according to the CITS model. The consumption plateaus after 2055 since the EXIOMOD model which drives the consumption growth did not compute further than that.

While consumption grows in the non-circular scenarios, the EU27+3 plastic production stabilizes or even declines. In EXIOMOD (EU27 +3) and TIMES-Europe (EU27 + UK) olefin production, plastic production and manufacturing remain largely stable or even decline in the case of the W.2.4 net0 scenario. This decline is due to the competitive disadvantage compared to the rest of the world (see Figure 23 and Figure 17).

High-value olefins (HVO) are a key input into plastic production. Methanol-to-olefin production and bio-ethanol dehydration increasingly phase out steam-cracking in HVO production (Figure 23). Nevertheless, steam cracking still represents a significant share of production in the W1.5- EU net0 scenario. CC(U)S only plays a minor role in all scenarios.

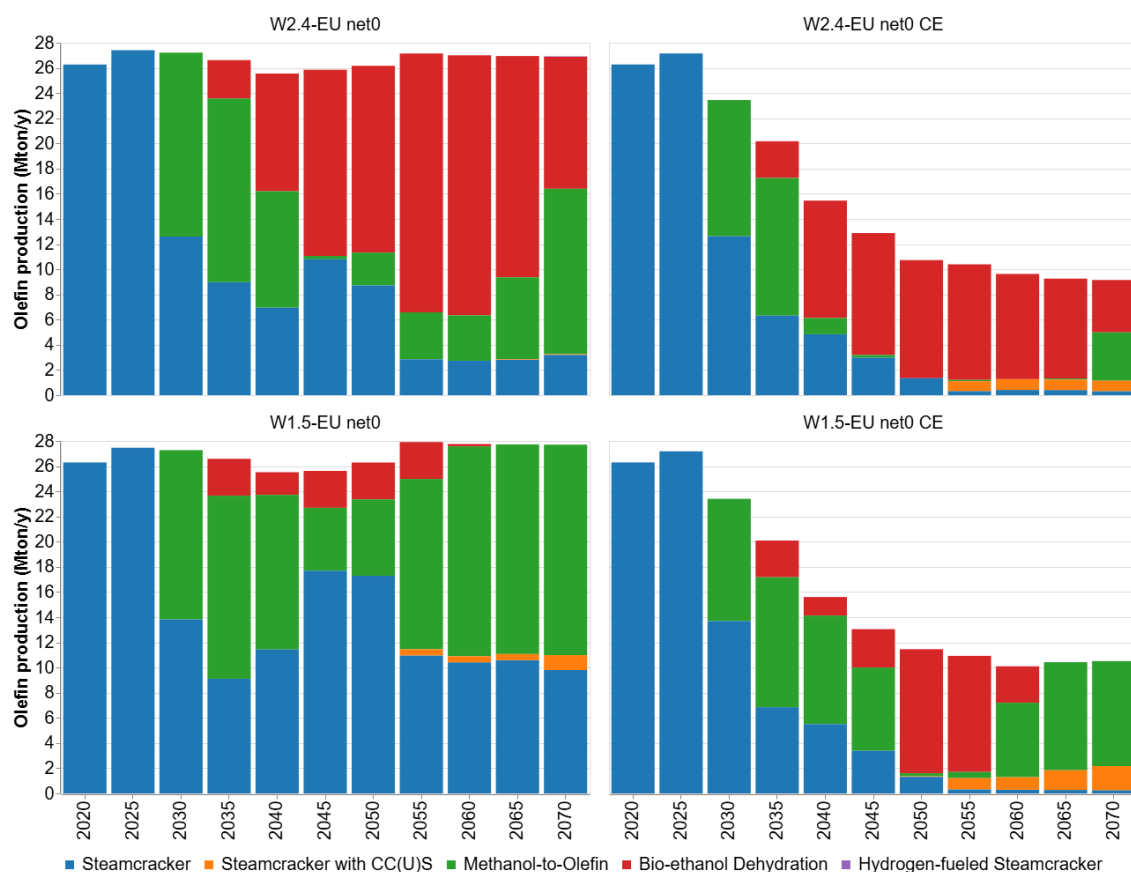


Figure 23. High-value olefin production technologies in the EU27+UK according to TIMES-Europe.

In the non-CE scenarios, a substantial part of the feedstock used in the steam crackers remains fossil based (see Figure 24). In combination with the limited deployment of CC(U)S for steam crackers, this indicates that, in some cases, it is cheaper to offset remaining emissions with negative emissions in the power/heat sector.

Bio-based feedstocks' import prices are determinant in defining chemical sector feedstock choices. Bioethanol and methanol become the most important feedstocks for HVO production in the W2.4-EU net0 scenario (see Figure 23 and Figure 24). The major share of the methanol is bio-based as well (results not shown). In contrast, in the

W1.5-EU net0 scenario a much larger fraction of the olefins is still produced from fossil resources. The main driver for this difference are the bio-feedstock (bioethanol and solid biomass) import prices. If the ROW has less ambitious climate goals, there will be less competition for biogenic resources leading to lower price levels. Over time, the dynamics between methanol and bioethanol-based olefin production stems from competition with other applications of methanol such as resource for the production of drop-in fuels for road and air transportation.

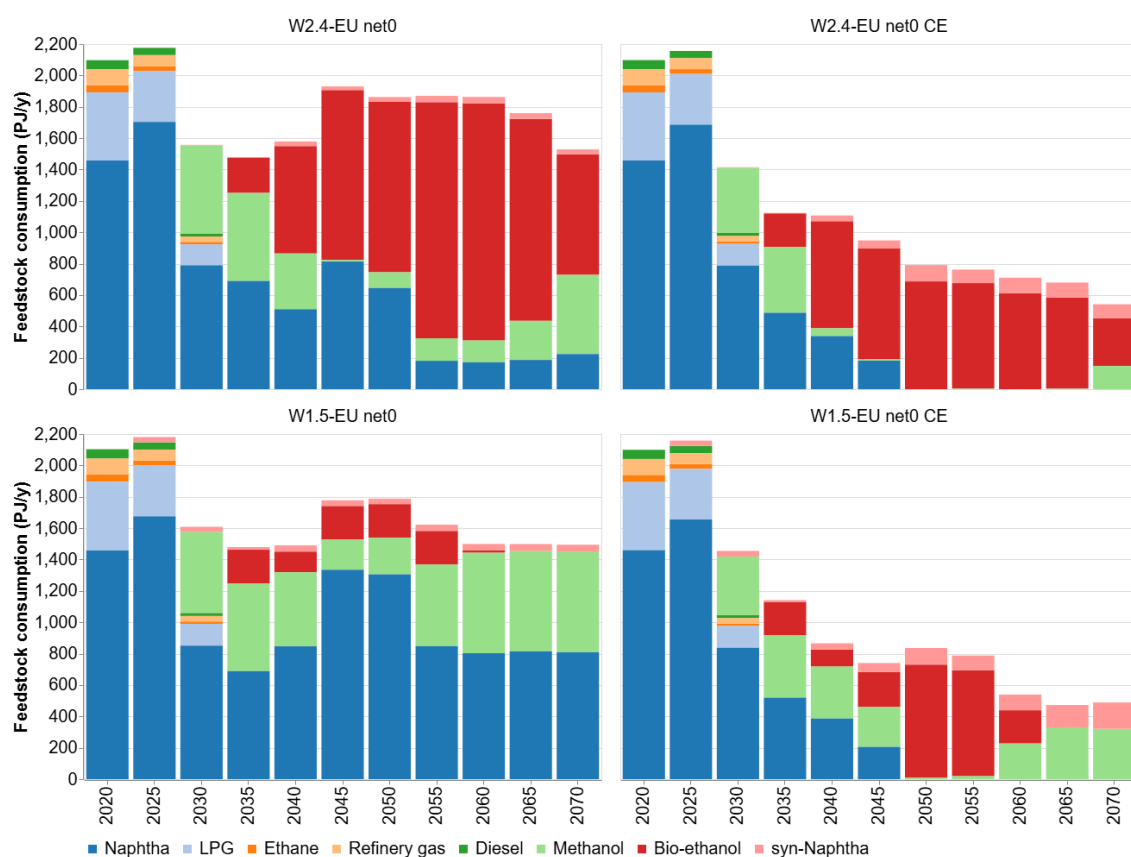


Figure 24. Feedstock use in High-value-olefin production in the EU27+UK according to TIMES-Europe.

Plastic waste generation increases from 53 Mt to 68 Mt by 2050 in the scenarios without circular policies (see Figure 22). This is a result of the growing plastic consumption, which is driven by the economic growth from the EXIOMOD model. Mixed waste is predominantly treated with pyrolysis while the separately collected waste streams are mostly mechanically recycled and complemented with some dissolution (see Figure 25). Due to the high CO₂ price and optimistic

assumptions regarding waste stream quality, energy recovery only plays a minor role.

In the circular scenarios, pyrolysis is increasingly phased out and replaced by mechanical recycling and dissolution (see Figure 25). This is driven by improved separate collection of plastics. This results in a higher amount of recyclates becoming available, despite the lower waste volumes. This is because of the higher efficiencies of mechanical recycling compared to pyrolysis. While the improved collection & sorting leads to better recyclate quality, mechanically recycled plastics cannot achieve virgin quality. To ensure the sufficient availability of recyclate for high quality applications, additional policy measures would be necessary to foster chemical recycling.

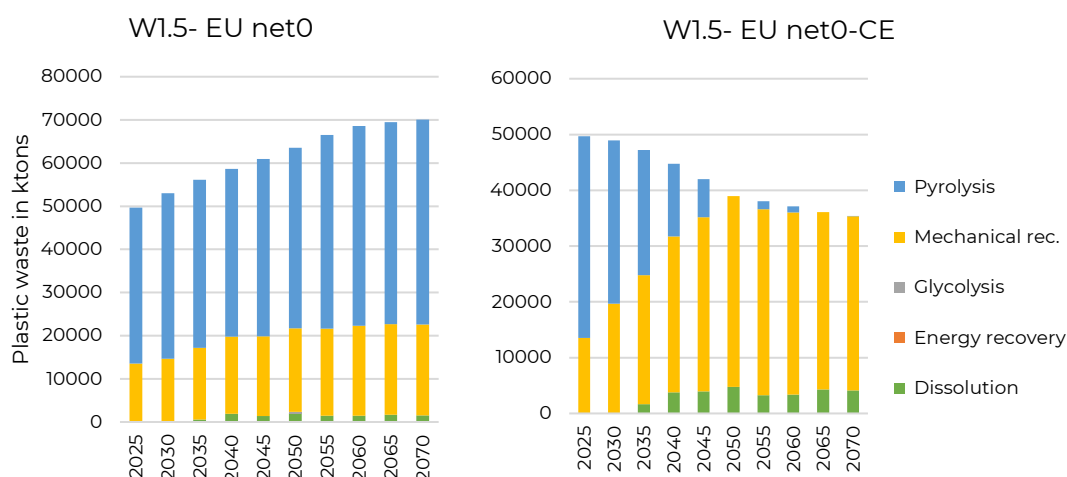


Figure 25. Technology shares in waste treatment acc. to the PRISM model.

Only in the circular scenarios fossil feedstocks are phased out in HVO production (see Figure 24). In the circular scenarios, the reduced demand for olefins through circular strategies and the banning of fossil feedstocks strongly reduces the application of steam crackers (Figure 23; compare CE and non-CE scenarios). The remaining steam crackers employ synthetic naphtha as feedstock.

There is substantial potential for intermediate negative emissions through bio-based carbon sequestration in plastic products. By 2050, more than 500 Mt of carbon is accumulated in EU27+3 plastic stocks. TIMES-Europe and CIMS (see section 4.5) project high biomass use in plastic production. However, the duration of the bio-based carbon sequestration in plastics depends on product lifetimes and waste management strategies, i.e. how often the products are recycled or if they end up in landfills or incineration plants. When linking those

bio-based production values with CITS carbon accounting, this potential can be quantified in future model runs.

4.4 Interregional modelling results

In addition to the system view on the economic, energy and environmental aspects of the EU climate transition, it is valuable to capture key geographical dynamics of energy supply and demand. The following results are interregional and cover Europe at a NUTS3 regional breakdown (98 regions across EU27, UK, and neighbouring countries). For AMIGDALA, the specification of the industrial transition is improved, allowing to analyse infrastructural needs with respect to power, natural gas and hydrogen networks and storage. Within the PoC, we addressed this by linking Calliope with the TIMES-Europe model, disaggregating national-level inputs into regional industrial energy and feedstock demand. Due to the high computational cost of Calliope runs (~12 hours per scenario), this report focuses for the year 2050 on two scenarios without Carbon Capture and Storage (CCS): the W1.5-EU net0 and W2.4-EU net0. We will give 2 examples, firstly on the European electricity network and secondly on its hydrogen networks.

The results highlight major transmission expansion needs in Western Europe—due to high industrial demand—and in regions with strong renewable resources, such as offshore wind in the North Sea and solar PV in Portugal and Spain, see Figure 26. Both scenarios exhibit similar spatial patterns of grid expansion, with W1.5 requiring a 58% increase in Net Transfer Capacity, slightly higher than the 52% increase in W2.4. The expansion of electricity transmission infrastructure across Europe will be essential to enhance system flexibility and reduce regional disparities in electricity prices, which remain a challenge today. A more integrated grid will facilitate the efficient flow of renewable electricity across borders, helping to harmonize electricity prices continent-wide.

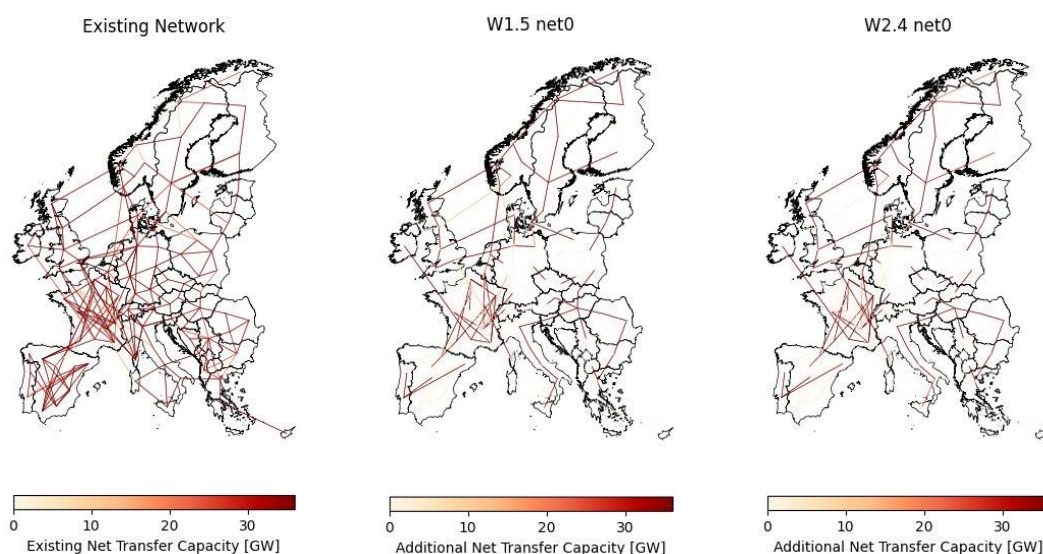


Figure 26. Existing electricity transmission network and additional grid capacity investments by 2050 (source CALLIOPE).

In the 2050 scenarios regional price differences are expected to become smaller, thanks to a higher share of renewables across all regions and a more interconnected European transmission network. Currently high-price regions—such as Italy, Germany, and Poland—are often characterized by a high share of fossil-based marginal generation, which drives up electricity costs. Figure 27 illustrates the average electricity prices in the W1.5 scenario, which are also representative of the W2.4 scenario.

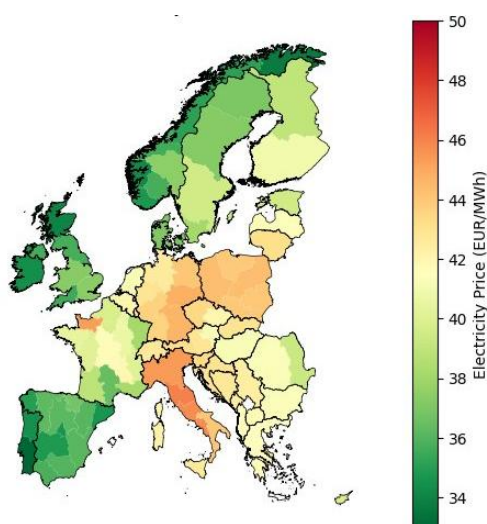


Figure 27. Regional marginal prices of electricity in W1.5 scenario in 2050 (source CALLIOPE).

Figure 28 illustrates the optimal hydrogen network configuration derived from the model, including the location of electrolyzers (pink

dots) and the spatial distribution of hydrogen demand (background shading). The network is optimized based on two main criteria: areas with high hydrogen demand and regions where hydrogen can be produced at low cost. Moreover, the model allows synthetic fuels—except for synthetic methane, which must be transported via pipelines—to move freely across all model regions at no additional cost. This means synfuels can be produced in regions with higher supply potentials and transported to other areas. It is important to note that the assumption of zero transport cost for synthetic fuels is a strong simplification, and this can be refined in future phases of the project.

Western Europe emerges as the most suitable region for hydrogen infrastructure development due to the high concentration of iron and steel, as well as chemical industries, which are major consumers of hydrogen and methanol. In addition, the region's strong wind energy potential along the western coastlines makes it an economically attractive area for hydrogen production and distribution via pipelines—currently the most cost-effective form of hydrogen transport.

As a result of the free-flow of synfuels, regions with greater hydrogen supply potential and access to carbon capture become more attractive for producing e-fuels, which can then be delivered to demand centers across Europe. This significantly reduces the need to expand the hydrogen pipeline network solely for transporting hydrogen to synfuel production sites. Instead, direct hydrogen demand becomes the main driver for developing new hydrogen infrastructure. Consequently, the model favors a high share of repurposing existing natural gas pipelines for hydrogen transport.

The W1.5 scenario shows marginally higher levels of infrastructure investment, which can be attributed to increased direct and indirect hydrogen demand in this scenario.

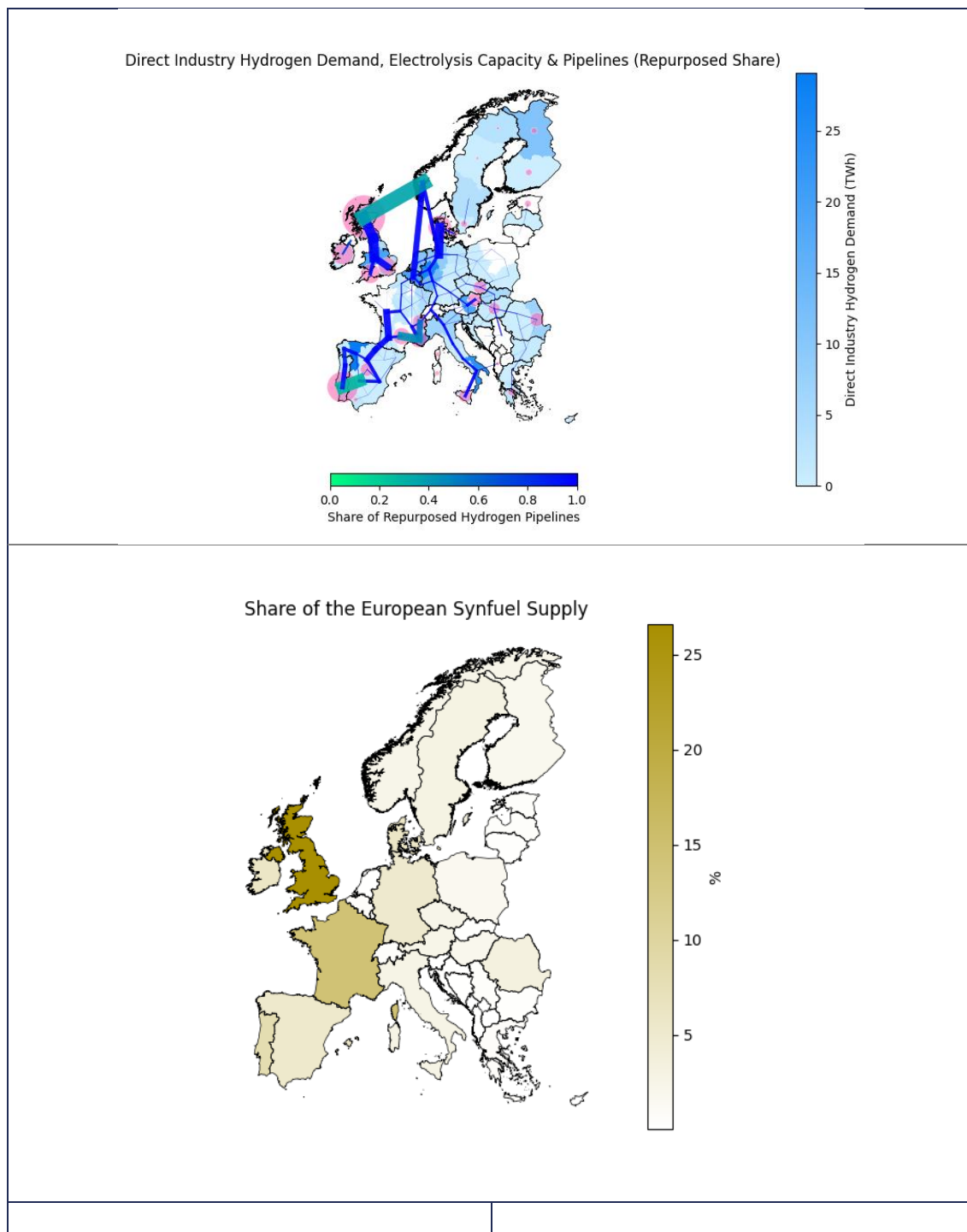


Figure 28. Hydrogen infrastructure in W1.5 scenario (upper) and share of European Synfuel supply in W1.5 scenario (lower) (source CALLIOPE).

4.5 Local modelling results

At local level, two model approaches are available in the Integrated Model Suite, viz. techno-economic system optimization of the Chemelot chemical site (CIMS) and agent-based modelling of the electricity market in Belgium (ELDEST).

At local level, CIMS implemented the Circular Economy scenarios by assuming that the use of fossil-based naphtha, natural gas and blue hydrogen was constrained to zero in 2050. Additionally, all commodity prices needed in CIMS (like electricity, hydrogen, biomass, natural gas, etc.) were taken from TIMES-Europe results, except for sorted plastic waste price. Prices and price development were derived from EuroStat data in this case. The future demand for plastic production at Chemelot was derived from the CITS results.

The availability of commodities for the chemical sector for the Netherlands is available from TIMES-Europe results. However, it was decided not to limit the availability of commodities in CIMS to allow more room for optimization, otherwise the CIMS results would be forced towards mimicking the TIMES-Europe results. In order to use the availabilities generated by TIMES-Europe in CIMS, it will be required to better align the techno-economic assumptions on the plastic related production processes between the two models. In addition, iterations will improve results as it facilitates taking into account location specific conditions. The only availability that was limited was for the mixed plastic waste, which was limited based on the results of CITS, applying a fair-share principle (availability based on current share of Chemelot steam cracker capacity in EU).

Both non-CE scenarios, W2.4-EU net0 and W1.5-EU net0, still rely on fossil resources for the production of plastics in 2050. Naphtha is still used in steam crackers. However, next to that, the Methanol to Olefin (MTO) process is also implemented to cope with the increasing demand. The methanol, in this case, is produced by gasification of Municipal Solid Waste (MSW). The additional hydrogen needed to convert all the carbon in the MSW is imported as green hydrogen. Ammonia production at Chemelot, is achieved by a combination of gasification of MSW, gasification of biomass and autothermal reforming using natural gas. These three processes generate pure CO₂ streams that are captured and stored, providing negative credits for the biogenic CO₂ originating from the biomass and the biogenic part of MSW. Those credits are needed to compensate the fossil based

emissions of the cracker and of the MTO process in order to reach net zero emissions at Chemelot.

In the CE scenarios, W2.4-EU net0 CE and W1.5-EU net0 CE, olefins are produced only via the steam cracker (no implementation of MTO nor ethanol to ethylene). The feedstock for the steam cracker is a mix of pyrolysis oil and of Fischer-Tropsch products produced via gasification of MSW. The additional hydrogen needed to convert all the carbon in the MSW and for the hydrotreatment of the pyrolysis oil is produced by electrolysis. Ammonia is produced by gasification of MSW and biomass, combined with CCS, providing the necessary negative credits to get to net zero, as in the non CE scenarios.

Total feedstock imports on Chemelot in 2050, Coloured for polymer production

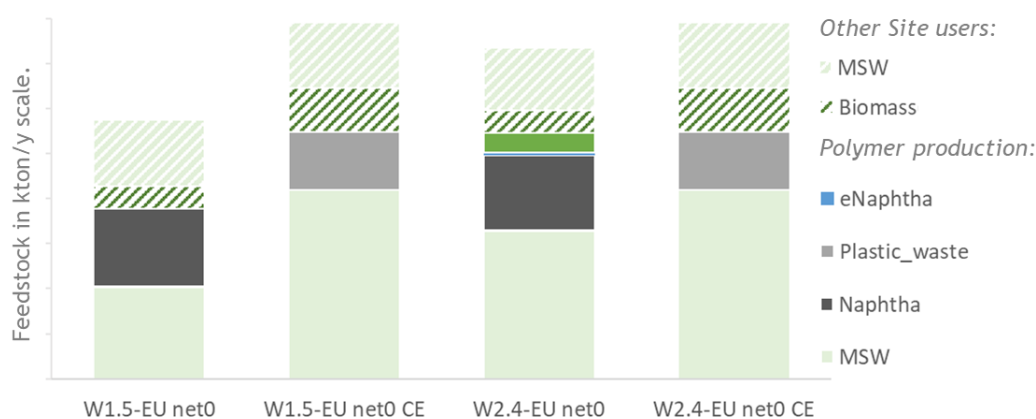


Figure 29. Overview of the feedstock imports on Chemelot in 2050 per scenario (source CIMS).

Biogenic content of polymer products in 2050, for Chemelot

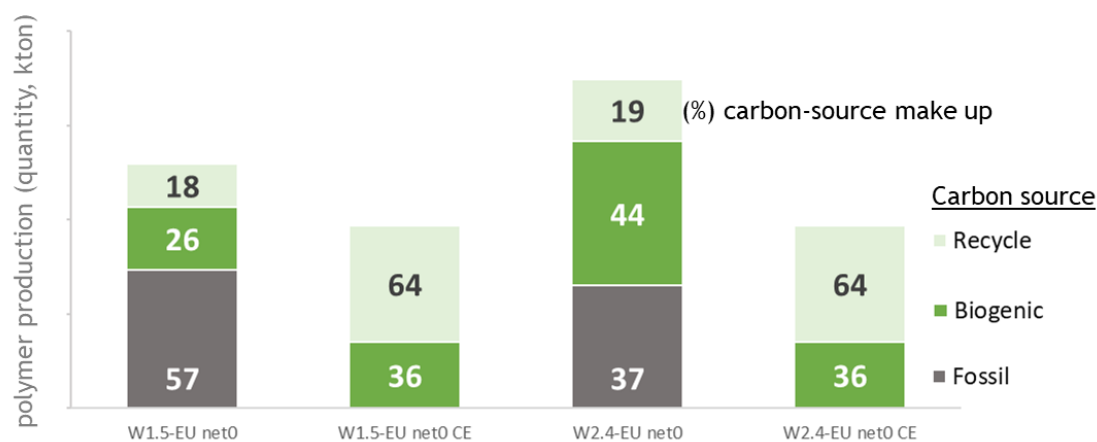


Figure 30. Origin of the carbon content in polymers in 2050 per scenario (source CIMS).

An overview of the carbon based feedstock origin per feedstock is shown in Figure 29 and the resulting composition of plastics in Figure 30. Most of the commodities demand of Chemelot are used as feedstock and some energy is recovered during the processes on site, in a complex integrated steam system. The only specific energy demand modelled in CIMS is the electricity demand. The electricity demand in 2050 resulting from the CIMS optimization for the different scenarios is shown in Figure 31.

In the non-CE scenarios, the electricity demand increases by a factor of 3, while in the CE scenarios the electricity demand jumps to 15 times its current demand. This is because in the non-CE scenarios, additional hydrogen needed in the MTO process is imported as green hydrogen, while in the CE scenarios, the additional hydrogen needed for the hydrotreatment of the pyrolysis oil and for Fischer-Tropsch process is produced by electrolysis, which is very electricity intensive. This difference is related to the hydrogen prices, resulting from TIMES-Europe, which is cheaper in 2050 in the non CE scenarios compared to the CE scenarios (1.8 €/kg vs 3.4 €/kg), while the electricity prices are similar in all scenarios (40-48 k€/GWh).

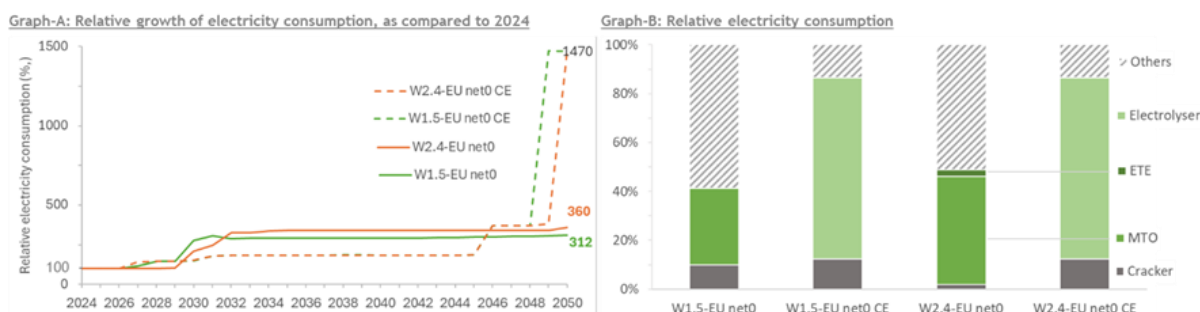


Figure 31. Overview of the relative (as compared to 2024) electricity demand for Chemelot over time (graph A) and the distribution of the demand (graph B). For polymer production, the Electricity requirements are coloured per process.

In the short run (2030 – 2040), production costs in the non CE scenarios increase with about a half and remain more or less stable with CE measures, see Figure 32. In the non-CE scenarios, production costs return to current levels in 2050. There is little difference between the W2.4 and the W1.5 scenarios. Mainly on the short term the costs in a W1.5 scenario are somewhat higher.

It is striking that on the long term, the site production costs in the CE scenarios are much higher towards 2050 than in the non-CE scenarios. This is very much related to the assumption on green

hydrogen import and relative electricity prices, but also to the phasing out of fossil feedstock. Circularity measures at European level contribute to reaching climate targets by generating recycled feedstocks and reducing demand for virgin materials, hence expecting reduced energy transition costs. This is not reflected in the CIMS results, the Chemelot site has to deal with additional constraints due to circularity, e.g. on the limited availability of fossil and waste feedstocks and green hydrogen, which result in higher production costs. It shows the importance of different perspectives but also how important good and harmonized assumptions are.

Change in production cost, as compared to 2023

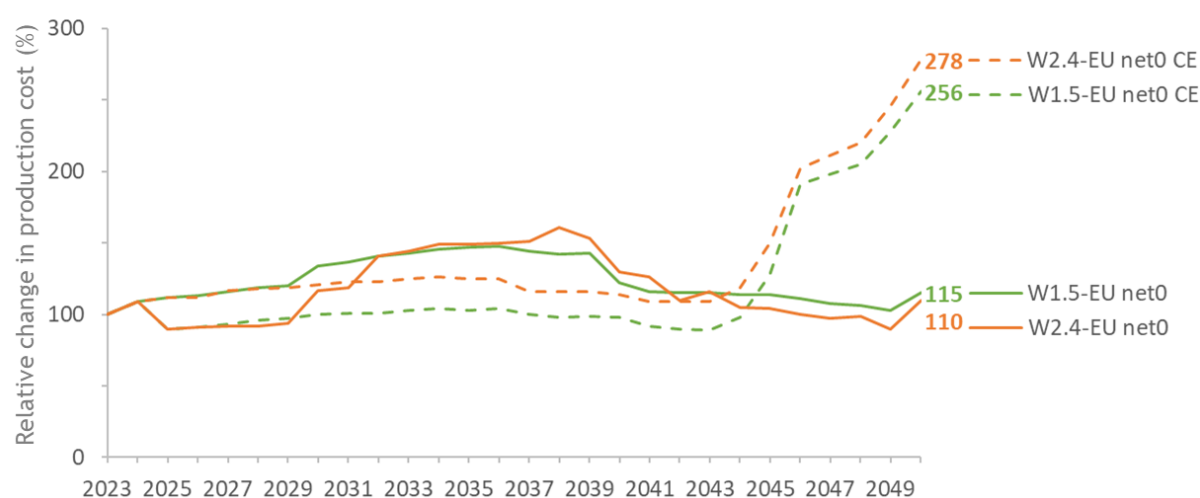


Figure 32. Relative production costs (for total Chemelot product portfolio) as compared to starting year 2023. (100%), per ton of products. The productions costs include variable costs and capex (source CIMS).

The agent-based model ELDEST, which models investor behaviour, projects solar PV to be dominant in electricity generation capacity (Figure 33). Open cycle gas turbines (OCGTs) are also expanded to cope with peak residual load in Belgium.

The projected expansion of gas turbines would likely be lower, if import or storage possibilities were to be considered in the model. Linking further to CALLIOPE could potentially provide a more realistic playing field for the agents' decision-making.

A lack of trust in emission pricing pathways could lead to more fossil-based electricity investment and generation. When agents do not trust in the rising CO₂ emission pricing, they tend to invest more in fossil technologies such as gas turbines instead of solar PV (see Figure 33, scenarios with 60€). However, actual lower carbon prices would also

suppress average electricity prices, as carbon prices affect marginal electricity prices.

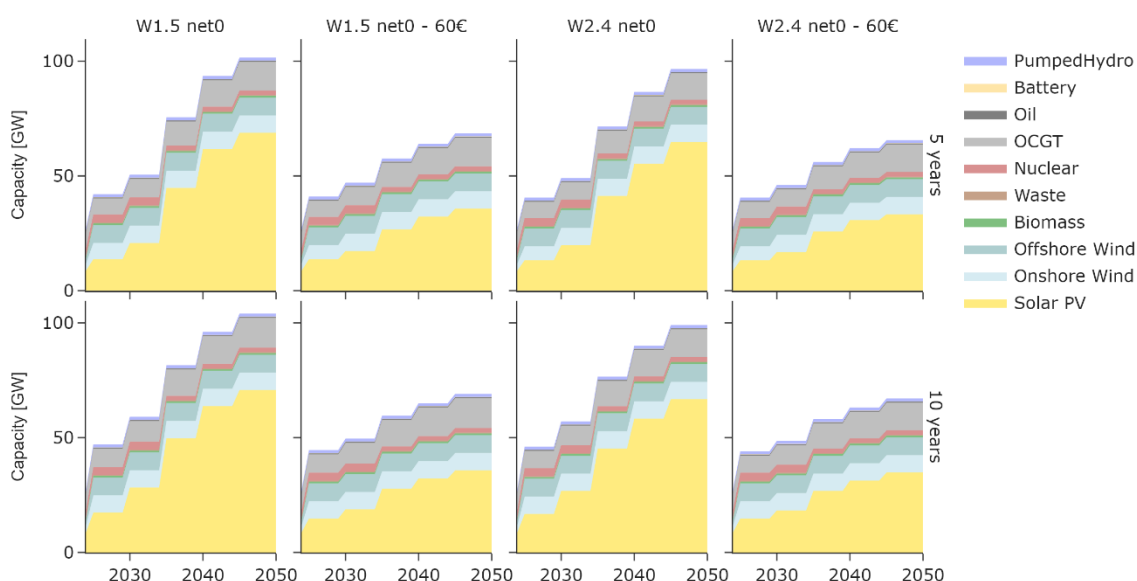


Figure 33. Installed electricity generation capacities in Belgium according to the ELDEST model, with different foresight of agents (5 vs 10 years) and varying trust in carbon pricing pathways (rising vs constant at 60 Euro)

For Belgium, ELDEST projects a strong increase in the range of electricity prices. This result can be explained by the increased volatility of electricity supply as weather-dependent renewables become more dominant and the fact that Belgium was modelled as an energy-island without electricity in- and exports.

The foresight of agents affects the range of electricity prices. With longer foresight of agents, electricity prices are on average slightly lower and show a significantly reduced variance (compare upper and lower row of Figure 34). This is a result of an adapted investment behaviour and highlights the importance of providing stable, long-term guidance on investments. Agents with a shorter perspective perceive the creation of additional renewable electricity generation capacity as less profitable, even if carbon prices are increasing.

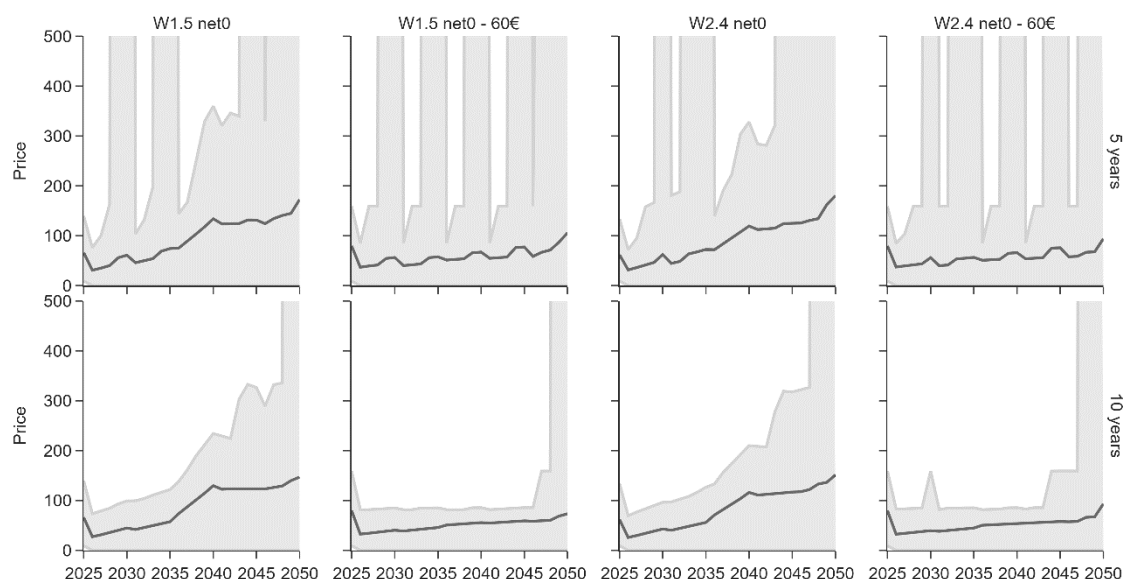


Figure 34. Average electricity prices (black lines) and range of electricity prices (grey area) in Belgium acc. to the ELDEST model for different investment foresights (5 or 10 years) and varying trust in carbon price pathways (rising or constant at 60 Euro)

4.6 Decision dashboard Excel PoC

The Decision dashboard Excel PoC is a powerful prototype designed to model and visualize the complex interplay of various factors in the future development of the EU industry, specifically within the plastics sector (for this PoC). The Excel file's structure is designed to facilitate analysis of different scenarios, demonstrating how control levers influence Key Performance Indicators (KPIs), operational dimensions, and critical assessment dimensions over a projected timeline, typically from 2020 to 2070. Thereby, it supports strategic decision-making and impact assessment, with a particular focus on environmental sustainability, energy consumption, and emissions. The structure of the Decision dashboard in Excel is described in detail in [Annex 11](#).

We put the prototype through its paces by testing it with outputs from several models, ensuring its compatibility with real-world data. A crucial step in this process was normalising raw output data so that it can be aggregated and assessed by the decision dashboard. To this end we decided to align with the Pyam [Gidden et al., (2019)] standard, which is foundational to the data explorer.

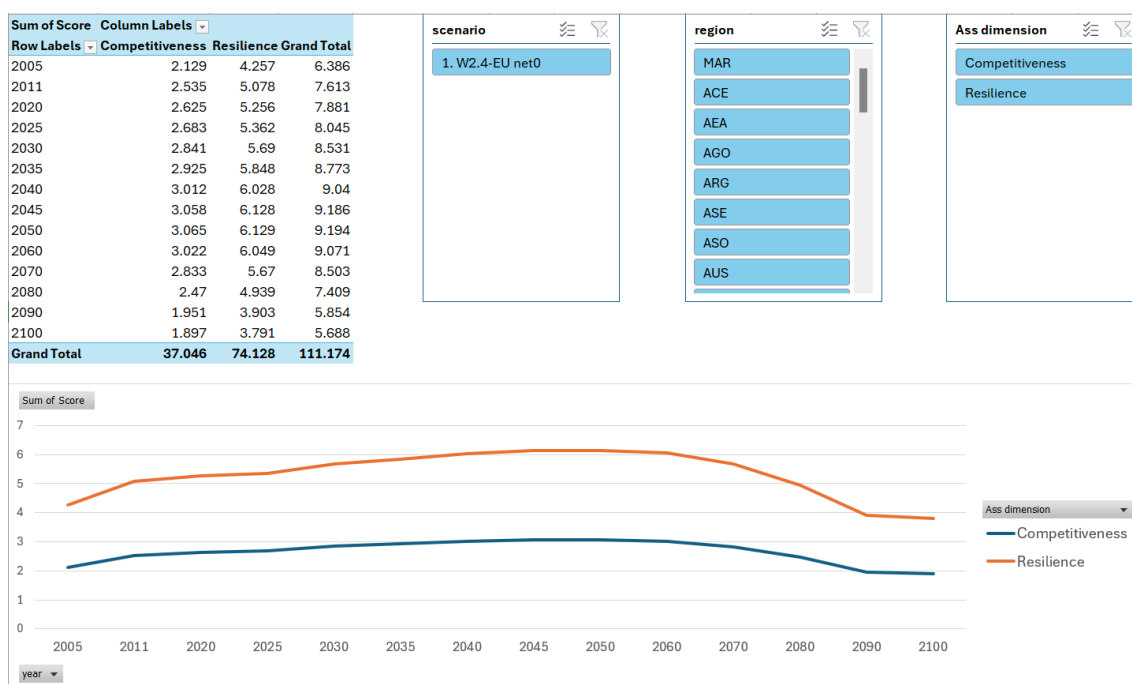


Figure 35. Decision dashboard Assessment Dimensions chart obtained with partial application of PoC model results.

In Figure 35 an example screenshot of the prototype Decision dashboard is included, showing the Assessment Dimensions chart. It displays aggregated scores by Assessment dimensions such as Competitiveness and Resilience over time, allowing for the analysis of performance within specific areas.

The Multi-Attribute Value Theory (MAVT) methodology used in this PoC was intentionally kept simple to prioritize feasibility testing over precise calculations. For this reason, normalizations were performed using linear functions between minimum and maximum values, and aggregations were done via averaging. Future iterations will incorporate more advanced techniques to address the complexity of the decision-making process.

The main challenge encountered during this test was the limited scope of model runs. Each model was only executed with four scenarios, meaning we couldn't fully exercise the tool's decision-making capabilities. Consequently, our attention shifted away from detailed results and towards the valuable lessons learned throughout this PoC phase.

The primary insights gained from this application are:

- **Standardizing Data:** It's essential to align data formats and geographical scope of the model data—also in terms of granularity—*before* it's fed into the decision dashboard.
- **Aligning Outputs with KPIs:** The connections between model outputs and KPIs require rigorous checking and adaptation to truly reflect the available output data.
- **Defining Scenario-Lever Links:** The relationships between scenarios and control levers need to be defined with great precision.
- **Clarifying Input-Lever Links:** Similarly, the relationships between control levers' categories and allowed input ranges also require more specific definitions.

The results sections in this report show that AMIGDALA covers a broad range of topics for a large variety of geographical domains, which makes it highly complex to present and interpretate the results and use these for decision making. The PoC Decision dashboard Excel file is a multi-faceted analytical tool designed to analyse and visualize complex interdependencies between control levers and KPIs of the industrial transformation. It provides a structured framework for exploring the long-term environmental and economic impacts of various strategies and conditions, making it invaluable for data-driven decision-making and scenario planning.

5 Conclusions

The newly developed AMIGDALA framework has been put to action and tested for the first time in a Proof of Concept study focused on the plastic value chain. This has enabled us to evaluate our approach and draw preliminary conclusions on the results. **The preliminary results are not solid yet and cannot be used as a basis for decision making** because of alignment between the models on certain assumptions will be improved in the next phase and because feedback iterations between the models were not considered yet. Model results can change significantly when small changes in the assumptions are made.

This section will start with the main preliminary conclusions derived from the model outputs, followed by the conclusions on the approach.

5.1 Preliminary conclusions on results

The preliminary conclusions on the results are presented by geographical level, first in general and then for the plastic value chain. This subsection concludes by answering the research questions.

5.1.1 General

From Global analysis:

- At global level, the scenarios for a W2.4 and W1.5 world are primarily shaping the global energy system. Circularity is not taken into account in the global scenarios.
- In both scenarios, GDP growth in the EU is relatively low compared to the ROW; in the W2.4 scenarios slightly lower compared to the W1.5 scenarios. In W1.5 scenarios, the ROW also increases energy transition efforts which slightly improves the competitive position of the EU region. Impact of the scenarios on GDP in the ROW is larger and shows the opposite result. GDP for the ROW is higher in the W2.4 scenario.
- The impact of the scenarios is more visible, but still small, in the changes in sectoral structure in the economy, where energy intense sectors have relatively lower growth when climate neutrality is being pursued.
- The industrial sector, which accounts for around 35% of baseline emissions, begins immediately a steep decarbonisation pathway in the W1.5 scenarios. In a W2.4 world however, the ROW

industrial abatement efforts lag behind Europe and only pick up after 2060.

- These differences are reflected in the energy mix used for industry worldwide, where a general shift from coal towards gas is observed. Interestingly, the role of electricity in industry remains relatively stable at around 25% of energy demand, even in the W1.5 scenarios.
- The W1.5 scenarios with increased demand for bioenergy also display higher carbon prices, leading to an increase in the afforestation level and utilization of crop residues, with concurrent expansion in the area of short rotation plantations.

From EU analysis:

- The CO₂ reduction pathway in the EU27 is similar in all scenarios.
- Until 2050, the final energy demand in the EU27+UK reduces by ca. 20% for the baseline scenarios, while the circular scenarios achieve a slightly higher reduction, up to 25%.
- The electricity production (nearly) doubles between 2020 and 2050 in the CE scenarios, in the non-CE scenarios the growth is around 70%.

From local analysis:

- At local level, global W2.4 and W1.5 generate similar results (because in both scenarios EU becomes CO₂ neutral); CE scenarios have not been applied for CALLIOPE and ELDEST.
- Europe's power transmission network will require significant upgrades to support increased electrification and maintain system flexibility.
- In the power sector, credible increases in carbon prices and stable investment environments are important to create incentives for investments into renewable energies and reduce variance of electricity prices.
- Projected hydrogen demand remains modest enough that repurposing existing natural gas pipelines could suffice in the near term. This assumption may be revisited in the next project phase, when full multi-sectoral modelling is deployed in Calliope as well.

5.1.2 Plastic value chain

From global analysis:

- The basic plastic sector in the EU grows slower than the average EU sectoral growth, mostly due to the increasing carbon prices and higher capital costs in this energy intensive industry.
- The manufacturing of rubber and plastic industry even declines towards 2055, largely explained by the increase in energy costs in this sector. This makes the competitive position of the EU in this sector worse compared to the ROW.
- The global temperature scenario plays a large role in the shape of the global abatement pathways. For instance, under W2.4, China's chemical industry emissions show no signs of decline until 2090.
- In the W1.5 scenarios, the global chemical industry achieves near-net zero emissions in 2045, much earlier than for example the iron and steel industry.
- The impact of circularity measures on EU level on its competitive position w.r.t. the ROW has not been investigated yet. Potentially, this can be achieved through feedback from EU-level to global level modelling.

From EU analysis:

- Without circular strategies, the plastic consumption in EU27+3 increases by more than 20% between 2025 and 2050, reaching 74 Mt
- While consumption grows, the EU27+3 plastic production stabilizes or even declines, as consequence of increased imports.
- High-value olefin production (HVO) from steam cracking is reduced or even phased out and replaced by primarily methanol-to-olefin production and bioethanol dehydration in the CE scenarios
- In the non-CE scenarios, a substantial part of the feedstock used in the steam crackers remains fossil based.
- The feedstock choices in the chemical sector are heavily dependent on bio-feedstock import prices and competing uses.
- In the circular scenarios, the plastic consumption reduces from ca. 60 to 50 Mt until 2050, resulting in a 32% lower consumption compared to the baseline scenarios.

- The mixed waste is predominantly treated with pyrolysis while the separately collected waste streams are mostly mechanically recycled and complemented with some dissolution.
- In the circular scenarios, pyrolysis is increasingly phased out and replaced by mechanical recycling and dissolution, however losses in quality have not been taken into account yet.
- The complete phasing out of fossil resources as feedstock in HVO production is only achieved when forced (the CE scenarios).
- There is substantial potential for negative emissions through bio-based carbon sequestration in plastic products.

From local analysis:

- Production costs at chemical site level increase on the short term and come back to current levels in 2050 in the non-CE scenarios, while production costs are being decreased by circularity measures on the short term to become much higher on the long run due to high green hydrogen costs;
- Electricity demand increase 3- (none-CE) to 15-fold (CE) in 2050. The extreme electricity demand in the CE scenarios is related to the increased hydrogen demand necessary for processes such as hydrotreatment of pyrolysis oil and syngas conversion to Fischer-Tropsch products;
- MSW is used as one of the main *feedstock for polymer production* in all scenarios. In the none-CE scenarios, naphtha still remains in use in 2050, while in CE scenarios it is replaced by mixed plastic waste (pyrolysis).
- It should be noted that in all scenarios net zero on Chemelot site as modelled in CIMS is achieved via negative credits for biogenic CO₂ CCS taking place in the ammonia production. If the plastic intermediates were produced separately, other solutions would be needed to reach net zero.

5.1.3 Research questions

Based on the previous conclusions, taking into account the uncertainties due to current imperfections in the approach for the PoC, we can answer the research questions posed in chapter 2 as follows.

1. A. What is in general the impact of ROW climate policy?
 - The level of climate ambition in the ROW impacts the economic growth projections. In particular, for the ROW and to a lesser extent for the EU. The scenario with higher

climate ambition in ROW results in lower economic growth in ROW regions, while the impact on EU GDP is slightly positive.

- Higher forest area and increased cropland area for both food, feed and bioenergy production by about 190 M ha for W2.4 scenario, and 218 M ha for W1.5 (from which ~50 M ha are energy crops)
 - Completely different energy mix in the ROW leads to more competition for scarce fossil carbon free resources and higher CO₂ prices and abatement costs, also for the EU, compared with the W2.4 scenario
1. B. What is the impact on the competitiveness and mitigation strategies of the EU, notably the process industry?
 - Limited impact on general EU economy, though shift to less energy intensive sectors
 - A stable plastic production in EU despite increased demand
 - Since bioethanol is more expensive for EU in a W1.5 world, other options are needed to produce plastics (e.g. MTO)
 2. How can EU Circular Economy contribute to reaching EU climate neutrality?
 - CE as 'No fossil carbon' increases the CO₂ price
 - Plastic demand does not grow with 20% but reduces with 10%
 - Compared to a non-circular scenario where production is stable, virgin plastic production is halved in a circular scenario
 - Plastic recycling increases and contributes to CO₂-mitigation strategies in end-of-life; Mechanical recycling is a preferred option in circular scenarios where collection and sorting is advanced, chemical recycling when this is not the case in non-circular scenarios.
 - However, at local level, CE measures result in drastic increase in production costs in 2050 due to the imposed ban on fossil feedstock and the increased demand for

electricity and/or green hydrogen, necessary in the processes based on recycled feedstock.

- Power and hydrogen infrastructure has to grow in all scenarios; it is not very different in baseline or CE scenarios; but use of chemical assets differ.

5.2 Conclusions on approach

In this section, conclusions are drawn on the approach, starting with the historic data, then the Integrated Model Suite and finalising with the Decision Dashboard.

5.2.1 Conclusions on the historical data collection

The inclusion of historical data on the five dimension marks an important step for this project. Ultimately, because the functionality of the data explorer (DE) can be shown with this, which itself is a milestone of this project (cf. Milestone 5).

However, displaying historical data together with the models' projections requires adjustments that need to be addressed in the next work package, when the sector perimeters will be aligned. For example, regarding the final energy consumption, the sectors considered in Eurostat, such as non-metallic minerals, are broader than those considered for the modelling, i.e. cement. Moreover, modelling indicators that are currently used to monitor the progress towards climate neutrality requires to consider all the parameters for their calculation.

Additionally, the DE will include much more than historical data and part of the next work package's tasks will be the inclusion the raw model outputs, as well as the basic data, which are e.g. harmonized techno-economic data used by multiple models. Moreover, the data explorer already provides an application programming interface. However, the decision dashboard (DD) will need to access the results of the model runs directly from the DE, as soon as they will be uploaded.

5.2.2 Conclusions on the Integrated Model Suite

In general, we conclude for the IMS:

- Product, energy carrier and sectoral aggregates have been aligned among the economic, energy and material models. This alignment has been effective, requires less exogenous assumptions but remains challenging, since not all model results

seem fully consistent yet (e.g. biomass use, growth of chemical industry, electricity consumption).

- Different perspectives (national or business, multi-sectors or mono-sector) can generate different (optimal) results, e.g. pyrolysis oil use; policy measures should account for these differences.
- Automated testing & post-processing saved time and flagged bugs & anomalies early-on.
- Post-processing of model results facilitated easier data exchange towards other models and allowed for quicker fixing of mistakes due to the replicability offered by standardised scripts.

From Global analysis:

- The macroeconomic scenario assumptions show limited impact on economic growth (GDP). This is partly due to the model specifications (exogenous capital and no alignment of energy prices).
- Implementation in the macroeconomic model of changes in energy mix in sectors, changes in household energy demand, carbon price implementation and a proxy for capital cost increases has been effective.

From EU analysis:

- Linking the models had substantial impacts on the EU results.
- The TIMES-Europe outputs, in particular in Chemical Industry, were heavily influenced by the global biomass prices (from TIAM-ECN) and the circular strategies (from CITS & PRISM).
- At the same time, the link with EXIOMOD allowed CITS to include economic dynamics and country- and sector-specific developments. PRISM results were very sensitive to the energy and commodity prices it received from TIMES-Europe.

From local analysis:

- A key contribution of the project is the integration of TIMES-Europe with Calliope, enabling a more realistic, endogenous representation of industrial energy demand in high-resolution energy system models.
- CALLIOPE and ELDEST provide a partial analysis (in time and/or scenario detail).

- Feedstock constraints have a strong impact on the technology selection at local level. Iterative model linking could solve this.

In general, we conclude positively on the methodology:

1. The IMS soft-linking and harmonization of the scenarios across all models, at all geographical levels and all domains (economy, energy, circularity, and environment), enables consistent modelling limiting the need for exogenous assumptions;
2. More consistency;
3. Sometimes different results from different geographical levels, reflecting different stakeholder perspectives, relevant for policy

Methodological challenges for the IMS are:

1. Further alignment on techno-economic data and scenario assumptions is needed (some models need specific foreground scenario data which is not readily available from the global and EU scenarios);
2. Some feedback iterations are needed to further align models, e.g. for a geographical scope;
3. Aligning, running, analysing and validating IMS is labour intense, partial automation using a multi-model platform may improve this;
4. Some KPI's are challenging, e.g. taxation and broader environment;
5. Global-EU economic model is not very sensitive for trade and prices;
6. Circularity scenarios are 'what-if' and can only be specified for EU;
7. Resource extraction is an omission in the IMS.

Hence, the IMS is having large benefits in terms of model coverage and integration, but the large scope, complexity and required labour effort forces us to limit model linkages as much as possible and focus on problem relevant topics only.

Except for the omission on resource extraction, the challenges mentioned will be addressed in the next phase of AMIGDALA.

5.2.3 Conclusions on the Decision dashboard PoC

The Decision Dashboard Excel PoC file represents a sophisticated and multi-faceted analytical instrument. Its primary design objective is to track, and visually inspect the details of the projected pathways of industrial transformation.

The tool was developed by making use of advanced Excel functionalities, such as power query and pivot charts, to perform dynamic calculations and enable interactive elements. The Decision Dashboard transcends singular analysis, integrating economic, environmental, operational, social and strategic dimensions to provide a holistic view of the system.

Its assessment capability allows users to conduct "what-if" analyses on the set of available pre-run scenarios by altering key input variables and instantly observing the projected impact on critical outputs. The "dashboard" aspect emphasizes its visualization abilities, utilizing various charts, graphs, and interactive elements to transform complex data into easily digestible insights. The main characteristic of this PoC prototype lies in its ability to map and account for the complex interdependencies within an industrial system, recognizing that changes in one area inevitably ripple through others.

The long-term perspective is crucial, as the Decision dashboard is geared towards understanding the sustained effects of decisions over extended periods, not merely short-term adjustments. Its focus on environmental, social and economic impacts is particularly vital in today's industrial landscape, allowing for an integrated assessment of how sustainability initiatives influence profitability and vice-versa. The versatility of the Dashboard is evident in its capacity to explore a wide array of strategies, from new technology adoption to varying external market conditions. This makes it an invaluable asset for data-driven decision-making, shifting the reliance from intuition to quantitative insights. Crucially, the Decision dashboard is a cornerstone for robust scenario planning, enabling the development of multiple plausible futures rather than a single prediction. This allows organizations to stress-test proposed strategies against adverse conditions, develop effective contingency plans, and ultimately gain a strategic foresight to anticipate future challenges and opportunities proactively.

During the current PoC phase, as a first step in the integration of the Decision logic / Dashboard in the AMIGDALA framework, our attention was focused on running the limited scope of four scenarios and the trial

integration of model outputs. Therefore, the primary insights we obtained are related to data handling and definition as summarized in section 4.6 of this report.

6 Outlook

The AMIGDALA framework proved that soft-linking diverse models is feasible, with structured data exchanges enabling scenario-based analysis. Key challenges include data harmonisation and feedback alignment.

The next phase, WP3, will expand sectoral coverage, refine scenarios, include global trade aspects and launch a web-based decision dashboard, improving integration, validation, and stakeholder usability.

6.1 AMIGDALA framework

Lessons learnt

Six of the nine modules, excluding those with public interfaces, were successfully integrated through soft-linking, enabling scenario-based decision support. Key lessons include the need for better data harmonisation and streamlined data exchange protocols to support iterative workflows.

Outlook - what to expect?

In WP3, the framework will be technically completed. This includes finalising and operationalising the integrated model, data reservoir, and stakeholder dashboard. Full sectoral coverage will be achieved, and the framework will incorporate feedback from a stakeholder workshop. Milestone outputs will include a ready-to-use decision dashboard and a validated connection between the data explorer and online interface, enabling full implementation of scenario translation, model runs, and visualisation of outcomes

6.2 AMIGDALA Integrated Model Suite

Lessons learnt

The proof-of-concept demonstrated the feasibility of soft-linking multiple models across global, EU, and local levels. Shared assumptions and harmonised inputs enabled basic interoperability between models such as TIMES-Europe, TIAM-ECN, EXIOMOD, and GLOBIOM. Challenges emerged in aligning temporal and spatial resolutions and maintaining consistency, especially when feedback loops were absent. Calliope provided valuable spatial granularity but proved computationally intensive. At the local level, models like CIMS showed that consistent upstream inputs are essential. Overall, better

coordination of model interfaces and data flows is needed to reduce complexity and improve the robustness of integrated outputs

Outlook - what to expect?

Under WP3, the model suite will reach technical completion. Modelling for all key sectors, prioritising cement, steel, and chemicals in line with Process4Planet objectives, will be completed. Model interaction will be refined to improve interoperability and reduce iteration time. Final foreground scenarios will be run across the full model suite. Model outputs will feed into intermediate pathway narratives and visualisations for stakeholder engagement. The full system will be prepared for running and evaluating scenarios under different decision-maker settings using the decision dashboard.

6.3 AMIGDALA scenario analysis

Lessons learnt

The proof-of-concept scenario development demonstrated the value of separating background and foreground scenarios. Global pathways (SSP-inspired) were effectively combined with EU-focused policy levers, especially for circularity and climate neutrality. However, transforming narrative scenarios into quantitative model input remains labour-intensive. The lack of circularity representation in some global models limited consistency. Foreground scenario assumptions also had to be simplified due to differences in model capabilities, particularly in feedback loops between EU and global levels.

Outlook - what to expect?

WP3 will deliver complete scenario sets with full sectoral coverage. Foreground scenarios will be finalised by narrowing down the control lever choices and incorporating feedback from stakeholders. These scenarios will be implemented across the entire model suite, feeding into intermediate pathway development and decision analysis. Model outputs will feed into intermediate pathway narratives and visualisations for stakeholder engagement. The narratives will support the production of stakeholder relevant information.

Outlook – global trade

WP11 will enrich these scenario outcomes by integrating global trade data and advanced machine learning models to project bilateral trade patterns for green goods. This global trade layer complements the system-level outputs from EXIOMOD and allows for a nuanced

assessment of EU industry's competitiveness and trade exposure under different scenario conditions. WP11 insights—particularly on green trade dynamics—will feed into the refinement of model assumptions and foreground narratives, helping to identify strategic opportunities and vulnerabilities for EU industry. This linkage strengthens the capacity of the scenario analysis to reflect geopolitical uncertainties and international market developments relevant to the industrial transition

6.4 AMIGDALA decision framework

Lessons learnt

The Excel-based PoC confirmed that MCDA can effectively link scenario outcomes to stakeholder priorities using KPIs. Challenges remain in managing complexity from control lever filtering, ensuring traceability, and designing an intuitive yet transparent dashboard interface.

Outlook - what to expect?

The migration of the Microsoft Excel PoC prototype presented in this document into an online reactive web application is the core component of WP3. This software tool will be built leveraging Amazon AWS services, adhering to a serverless architecture. This design choice ensures that all application needs are met through specific web services, effectively distributing the workload and enabling seamless scaling to manage rare, heavy demands.

The decisional tool itself will be a JavaScript application, with Node.js serving as the backend server and MongoDB handling data storage. This initial prototype focuses on fundamental user management, encompassing sign-up and login functionalities, though sharing and permissions will be integrated in a subsequent, final version. It will feature a basic graphical user interface and, at this stage, will not have a direct connection to models; instead, data will be uploaded manually. The prototype's capabilities include storing user preference profiles and applying selected MAVT (Multi-Attribute Value Theory) aggregation methods. Results will be presented both in tabular form and through basic charts. This prototype will be applied to the developed case studies, with the insights gained used to refine data flows from the models and to select the most appropriate user interfaces and result chart visualizations.

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Annex

8 Sector coverage

Based upon CO₂ and material relevance, the following ASPIRE sectors have been selected for coverage within AMIGDALA in the next phase:

- Cement
- Ceramics
- Chemicals (fertilizer, chemicals and plastics)
- Non-ferrous (aluminium, zinc, copper, lead, etc.)
- Minerals
- Paper & pulp
- Refining
- Steel

We exclude Food processing, Water and Engineering since these sectors are not represented in detail in our model suite.

The Circular Economy material streams are highly relevant to assess the demand for materials from the process industry and require modelling of product application groups in the CITS model. This will be done except for Food, water and nutrients:

- Electronics and ICT & textiles
- Batteries and vehicles
- Construction and buildings
- Plastic products & packaging

The plastics value chain from the PoC will be refined in the next phase.

9 Overview of the AMIGDALA models

The models of the AMIGDALA Integrated Model Suite can be shortly characterized as follows :

Global models

- EXIOMOD: Global economic Input-Output and equilibrium model for analysis up to 45 countries. It includes consumption (industries, households, government, investors), sectoral production and trade. It is a monetary model that links to physical materials flows (e.g. metal, mineral, biomass use) and GHG emissions
- TIAM-ECN: Techno-economic cost-optimisation and partial equilibrium calculation of energy supply and demand including energy intensive industrial sectors and GHG emissions for the whole world (divided into 36 regions)
- GLOBIOM: Global partial equilibrium model of land based production and demand for food, feed, forest, fibre and bioenergy of world regions

EU MS models

- CITS: Physical representation of plastic & metal materials and products production and demand and associated environmental impacts for EU MS
- PRISM: Techno-economic cost-optimisation of plastic waste recycling and GHG emissions
- TIMES-EUROPE: Integrated, energy-economy-environment, partial equilibrium, techno-economic cost-optimisation of energy supply and demand including energy intensive industrial sectors and GHG emissions of each individual EU MS

Local models

- CALLIOPE: Techno-economic, spatiotemporal and sectoral specification of energy demand and production in EU MS
- CIMS: Techno-economic cost-optimisation of chemical production and GHG emissions at industry cluster level
- ELDEST: Agent-based representation of investment and consumption behaviour in the electricity sector of an EU MS (now Belgium)

Table 5 gives an overview of the models and their characteristics, showing that all domains (economy, energy & climate, materials &

environment) are covered. The challenge will be to integrate them in a consistent and sensible way to reduce exogenous parameters.

Level	Model	Application field	Goal of the model: Problem(s) to be solved	Output KPI's	User Expertise Level Needed	Resource Demand / Calc Time
GLOBAL	EXIOMOD	Economy	Economic model able to measure the environmental impact of economic activities	Effects on total output by sector, trade, household demand, prices, emissions. It is an economic model, so most output is in monetary units.	Advanced	In general no longer than 5 minutes for 2011-2050.
	GLOBIOM	Agriculture, forestry, bioenergy	Maximization of consumer and producer surplus	AFOLU, prices, production, trade. Land cover, land use, AFOLU emissions, food production, water and fertilization demand, biodiversity indicators	Advanced	~3 hours for one scenario
	TIAM-ECN-ECN	Energy system	Global cost-optimization model that minimizes discounted global energy system's cost based on a partial equilibrium that supplies end-use service demands.	All energy system characteristics (CAPEX, OPEX, CO2 emission, technology capacity, primary and secondary energy commodity use/production, trade flows, marginal costs)	Advanced	~20 minutes
MS / EU	CITS	Material Transition	Analysis of energy & material use of products throughout society and the related environmental impact of different interventions (R strategies) when applied in the metal and plastics industries in NL & Europe	Circularity of system, Material Uses, Impacts	Moderate to high	Moderate
	PRISM	Material Transition / Recycling impact model	Analysis of the impact and cost of recycling technologies applied to mixed streams, providing balanced / optimal choices	Circularity of system, Material Uses, Impacts	Moderate to high	Moderate
	TIMES-Europe	Energy system and related sectors	Partial equilibrium, EU level cost-optimization model that minimizes discounted total system costs of the modelled regions over the full time horizon, within the context of EU / national policy scenarios.	All energy system characteristics (CAPEX, OPEX, CO2 emission, technology capacity, primary and secondary energy commodity use/production, trade flows, marginal costs)	Advanced	~20 minutes
LOCAL / MS	CALLIOPE	High resolution Operational and Planning Energy System Optimization, strategic planning of E&M	To support decision making support for industry stakeholders by providing insights into impact of policies and investments in the member state levels with higher resolutions (such as local and industrial sites) on costs and availability of energy "upstream"	All energy system characteristics (CAPEX, OPEX, CO2 emission, technology capacity, primary and secondary energy commodity use/production, trade flows, marginal costs) at hourly resolution	Advanced	Hours to days (depending on the resolution of the model and number of constraints, can range from 10 hours to 3 days)
	ELDEST	Electricity systems	1. Understanding the impact of different decision making models on the deployment of electricity generation capacity; 2. Understanding the impact of loss and risk aversion on the deployment of electricity generation capacity	Energy capacity mix; electricity prices; production and consumption of electricity	Advanced	Hours to days
	CIMS	System modelling of large industry	Calculate optimal pathway accounting for given options and constraints using NPV (for Chemelot towards zero CO2 emissions)	Pathway showing which investments and raw materials are used to comply with constraints	Advanced	Low, calculation time about 5 minutes per scenario

Table 5. Short overview of models and characteristics in the AMIGDALA model suite (see Appendix for an extended overview)

10 AMIGDALA improvements per model

10.1 TIAM-ECN

10.1.1 Model improvements

To align the TIAM-ECN global energy system model with the AMIGDALA scenarios, two existing native scenarios were adapted: one for a low climate ambition world, with a GHG budget aimed at 2.4C global warming, and one for a high-ambition world with a GHG budget for 1.5C. In addition, these scenarios were expanded with a circular economy (CE) dimension, which constrained the European use of fossil-based feedstocks after 2050. Together, these adaptations led to the required combination of four scenarios.

Besides the scenario adaptations, several improvements were made to the TIAM-ECN model. Firstly, the baseline assumptions up to 2020 were calibrated using historical data, to allow for a better representation of the brownfield situation: CO₂, N₂O and CH₄ emissions per region were calibrated using the EDGAR database⁴ as a reference point. This included a separate disaggregation for emissions from LULUCF sources. Secondly, a detailed calibration of electricity generation capacity took place, with adjustments disaggregated by region and type of electricity generation, using data from EMBER⁵. Furthermore, two key demand drivers in TIAM-ECN (population and GDP statistics) were updated using the latest SSP2 projections quantified by IIASA⁶. Besides calibration efforts, several improvements were made to the post-processing of model results. This allowed for automated exporting of model data, facilitating the data exchange with other models in the AMIGDALA framework. Finally, a few technical bugs within the model were fixed.

10.1.2 Conclusions on methodology

The most beneficial model improvements were those in the post-processing of model results. This facilitated much easier data exchange towards other models, and allowed for the quicker fixing of mistakes due to the replicability offered by standardised scripts. In addition, an improved script for the visualisation of model results allowed for better verification of results with respect to historical data. Further

⁴ https://edgar.jrc.ec.europa.eu/report_2024

⁵ EMBER, 2025. <https://ember-energy.org/data/yearly-electricity-data/>

⁶ <https://iiasa.ac.at/models-tools-data/ssp>

improvements could be made to the modelling of the CE assumptions, as the current implementation of circular economy policy is still quite coarse, due to the aggregated nature of TIAM-ECN's feedstock modelling.

10.1.3 Recommendations for next phase

The setup of automated data exchange was a step in the right direction, but it could benefit from further standardisation, for example in the naming of commodities. Mapping out key model assumptions (e.g. on technology costs) across AMIGDALA could also improve transparency and alignment of models, especially if certain assumptions fall outside of the scenario bounds. Finally, the current set-up of the serial runs allowed for iterative feedback (especially after the first test runs). This could be further improved by 'modularising' the models into thematic groups, each of which could have its own feedback sphere, which would allow for closer model alignment.

10.2 EXIOMOD

10.2.1 Model improvements

In this study, the macroeconomic model EXIOMOD 2.0 is used for analysing the AMIGDALA scenarios. Improvements have been made to the underlying database and to the modelling framework.

Database

Until end 2024, the model was able to run on two underlying databases: EXIOBASE (base year 2011), and FIGARO, (base year 2019). However, both databases were not ideal for the AMIGDALA study. Where the sectoral and geographical detail of the EXIOBASE is quite good (it includes industries like ‘basic plastic industry’ and ‘plastic and rubber industry’, and has a lot of detail in the energy producing sectors), the data is rather outdated (Stadler et al (2025)). FIGARO, a database developed by JRC and Eurostat (Eurostat (2024)) is a relatively new database based on the latest statistics and is updated annually. However, the sectoral detail is quite low, it includes 64 sectors and 64 corresponding commodities. The electricity and gas producing sectors are aggregated into one sectors.

At the end of 2024 a new version of EXIOBASE was published⁷. This version of the database is calibrated to the latest FIGARO tables, and still provides the sectoral details of the initial EXIOBASE tables. Tables for base year 2019 has been implemented in the model.

Model improvements

EXIOMOD receives a lot of input from the energy models TIMES and TIAM. Most of the improvements in the model involve the ability to process and embed this external data as shock to the model:

- Product and sectoral aggregates have been chosen specifically to align best with the energy models and CITS.
- A module to process exogenous data and transform it into usable data for the model (in most cases we transformed physical values into growth rates, to overcome the issues that EXIOMOD works with monetary values where input is provided in physical values).
- A spline module has been developed to smooth out steep changes in the input values

⁷ The latest database (v3.9.4) was provided to us in December 2024 via a private Box-invoke by one of the developers Richard Wood.

- Biomass is used as energy input. However, EXIOMOD does not have a specific biomass commodity, the model does contain agricultural and wood commodities. However, an assumption has to be made which share of this commodity is for food use and which share for energy use.

Other improvements in the model include:

- Endogenizing labour supply in the model
- Development of a competitiveness indicator that shows the relative competitiveness of regions due to the scenario shocks.
- Updating the Armington elasticities using values from the literature.

Scenario input

The following input from the energy models and the exogenous scenario models have been implemented:

1. Capital and labour productivity improvements have been calibrated from the SSP2 GDP scenarios; this is the same for all four scenarios.⁸
2. Electricity mix from TIMES and TIAM;
3. Energy demand for industries from TIMES and TIAM;
4. Energy demand (shares) for households from TIMES and TIAM;
5. CO2 prices from TIMES and TIAM;
6. Higher capital costs for industries (based on assumptions and information from TIMES and TIAM).

10.2.2 Conclusions on methodology

Implementation of the electricity mix, changes in energy mix in sectors, changes in household energy demand, carbon price implementation and a proxy for capital cost increases in sectors that heavily changed their energy mix.

10.2.3 Recommendations for next phase

- The model only runs until 2055. A lot of effort has been placed on finding the reason why the model cannot find a solution after 2057. There is still no answer to this question.

⁸ Initially also population growth was taken from the SSP2 scenarios, this to inform labor supply in the model (exogenously). However, eventually it was decided to endogenize labor growth in the model.

- Energy prices from TIAM and TIMES have still not been implemented in the model.
- We should make a difference in our model between natural gas and synthetic gas (and corresponding emission coefficients). A sector that makes use of a cleaner gas should not be charged the same carbon price as a sector that uses natural gas.
- The model assumes exogenous and fixed capital supply, hence the energy scenarios result in limited impacts on GDP.

10.3 GLOBIOM

10.3.1 Model improvements

To equip GLOBIOM with the ability to answer to research questions and scenario dimensions addressed by the AMIGDALA project, the model has been extended to address endogenously the biomass potentials from crop residues, in addition to the previously existing biomass feedstocks for material and energy use (e.g. lignocellulosic crops, fuelwood, harvesting residues, forest industry residues, among others). To this end, we have drawn on the analysis conducted in Holmatov et al. (2021) on the potential availability of primary and secondary crop residues globally, differentiated for each of the main crops represented in GLOBIOM. This dataset was combined with the biophysical productivity estimates provided by the EPIC model, generating estimates of the crop residue biomass availability. The final biophysical potentials then assume that 50% of the available crop residues can be removed from the field for energy or material uses.

Apart from the enhancement of the thematic representation of biomass feedstocks in the model, to improve the consistency with the overall modelling framework deployed in the project, the macroeconomic drivers driving the demands in the model (GDP and population) were updated, according to the latest SSP dataset. To fully align the impacts of different scenarios given by the energy sector models, regional mappings between the GLOBIOM economic regions, TIAM and TIMES models were defined. With this, the corresponding biomass for bioenergy demands to be matched by GLOBIOM were established, and the carbon prices across economic regions, according to the outputs provided by the energy sector models were implemented in the GLOBIOM regions.

10.3.2 Conclusions on methodology

The coupling with the energy sector models in the scenarios required the alignment of the region across the models, but were successfully ran in sequence.

10.3.3 Recommendations for next phase

Further improvements can be achieved by a more detailed representation of biomass for bioenergy demand split by feedstock.

10.4 CITS

10.4.1 Model improvements

The goal was to enable CITS to assess the consumption, stocks, waste generation and flows of plastics by sector and by EU27+3 country until 2070. To that end, a new EU CITS model version was created and socio-economic data as well as plastic production, conversion & consumption data collected. In the absence of a longer historic time series of plastic consumption, the relative historic plastic production growth was used as a proxy to simulate historic consumption. Consistent consumption data is not available for all countries, which is why a country's GDP share was used as a proxy to break down the EU plastic consumption by member state.

Moreover, data on the shares of plastic sectors and their respective polymer composition was collected and used to disaggregate the plastic market by sector and polymer. This includes the following sectors: Packaging; Building & Construction; Automotive; Electrical & electronics; Houseware, Leisure & Sports; Agriculture, farming & gardening; Others. Additionally, synthetic textiles are added.

For a stand-alone CITS version, plastic consumption projections up to 2070 were established based on the historic relationship between GDP and plastic growth. For the serial runs, country and sector specific growth rates from EXIOMOD were taken to simulate future plastic consumption.

We used assumptions on average lifetime distributions per plastic sector to endogenously calculate the plastic waste generation and the plastic stocks. Furthermore, current country and sector-specific waste treatment data was collected to establish a baseline situation for the year 2022.

Lastly, a circular scenario was developed for all plastic sectors that includes assumptions on refuse & reduce of plastics, life-time extension of products in plastic sectors, reuse, and improved collection and sorting of plastic waste.

10.4.2 Conclusions on methodology

In the serial run, sectoral economic growth via EXIOMOD was driving plastic consumption in CITS. This provided the benefit of incorporating economic dynamics in the CITS demand projections and allowed CITS to move from fixed sector shares to dynamic sector shares. For that

purpose, plastic sectors in CITS (largely based on Plastics Europe data) had to be matched with the sectors in EXIOMOD. While this was straightforward for some sectors such as electronics or construction, it proves to be difficult for others such as packaging or houseware products. Here proxies had to be applied. Moreover, the growth factors from EXIOMOD do not consider a reduced material intensity with rising GDP/cap, which could be observed when looking at historic data.

CITS provided TIMES, PRISM and CIMS with the total volume of available plastic waste and its composition. However, a key limitation was the simplified scenario on collection and sorting of plastic waste streams, due to missing consistent sector and country specific data. Hence, the results CITS shared with PRISM likely present a very optimistic scenario regarding the quality and purity of waste streams.

10.4.3 Recommendations for next phase

Automated testing of inputs and outputs prove to be essential to discovering bugs early in the process and should be extended. Moreover, exchanging data as early as possible is advisable, even if it is wrong, so the data pipelines can be implemented and tested well in advance. Further alignment in the naming of variables and scenarios and in the scope of data would reduce modelling errors during the serial runs. In the next phase, CITS aims at adding the impacts of material flows on 17 environmental and health indicators. This might require a reduction in scope for some materials and process steps, depending on data availability.

10.5 PRISM

10.5.1 Model improvements

The goal was to enable PRISM to model potentials for waste flows to, and recycled outputs from plastic recycling technologies. This includes the costs and environmental impacts of these technologies per EU27+3 country, in the main plastic waste producing sectors until 2070. These volumes were supplied via the CITS model, in addition, the aim was to include regional pricing of inputs and commodities to plastic recycling technologies based from the TIMES EUROPE model. Representative technologies have been chosen which cover both mechanical and chemical recycling and towards 2nd life inputs and plastic feedstocks.

To enable this, a new modular version of PRISM has been made which can handle both regional and sectoral data. This new data handling includes but is not limited to; regional and sectoral material flow outputs from CITS, per polymer; regional commodities data from TIMES, with associated CO2 emission factors; and EU LCCA data which forms a matrix of the costs and impacts at a regional and sectoral level. Life cycle data is European but the inventories are not regionalised per EU 27+3 country, as this is not common data. It was assumed that the regional costs and impacts can be represented to a large extent by adding the TIMES EUROPE inputs, to make a regional version of prism.

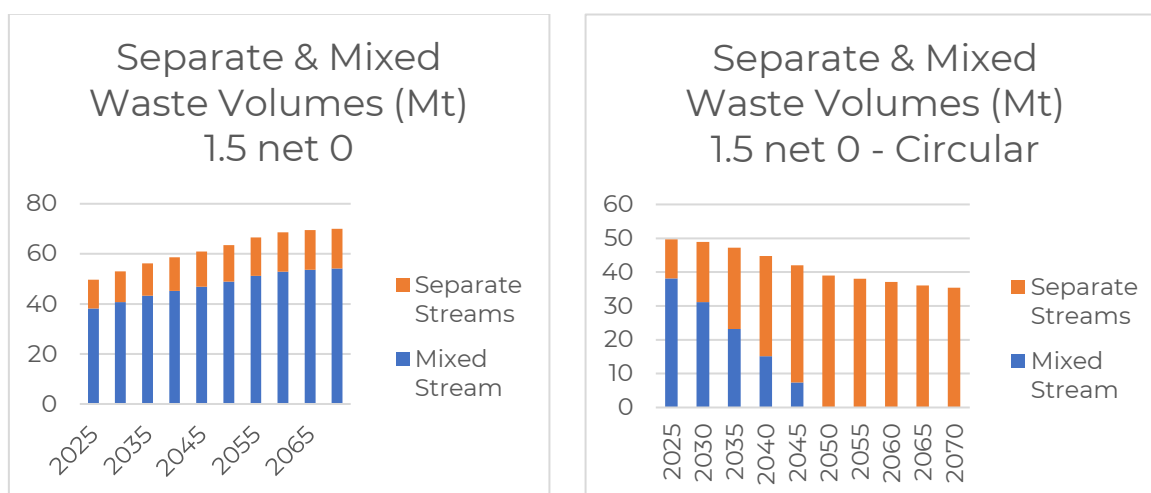


Figure 36. The shares of mixed and separated waste streams in Non-circular and circular scenarios (separate share increases with circular strategies).

The scenario choices for the modelling have been based on an assumption that there will be both mixed and pure streams of plastic waste entering the recycling stream. In the circular scenarios, this would mean that the plastic waste streams become more pure over

time as it is assumed that better to separation and sorting of polymer streams in combination with other circular measures would take place.

For the Fossil Carbon reduction scenarios, the TIMES EUROPE model supplied the requisite energy, commodity and CO₂ pricing necessary to represent the changes to meet the targets in these scenarios. All PRISM scenarios have been run as an optimisation on costs with CO₂ tax, but other optimisations are possible, such as environmental impact dimensions.

10.5.2 Conclusions on methodology

The integration of both regional and sectoral data into prism has been successful.

For the integration of the TIMES EUROPE model the PRISM outputs were modified in a number of different ways. At first it was hypothesized that the intermediate chemical and gas outputs of the recycling technologies could be used in the TIMES model. In the end, for simplicity, PRISM outputs were generated as a polymer feedstock. For the link with CIMS, it was decided to not use the optimised outputs from PRISM, as CIMS does it's own optimisation.

10.5.3 Recommendations for next phase

For plastics modelling, there is the potential to integrate a more detailed Material Flow model, including all of the processing steps involved in the recycling value chain. This could allow for a regionalised version of the end of life value chain in EU27 countries, if required. This would give a more complete picture of the chains of dependencies within plastic recycling technologies & their associated impacts.

For the development of KPIs, PRISM can contribute to the picture of environmental impacts of plastic recycling. While all of the dimensions of LCA can be chosen, Key Impact indicators should be chosen, to reduce the complexity of decision making.

Another approach not yet explored in this serial run is on the optimisation of the recycling technologies towards stated EU targets. It would be possible in PRISM to develop a constraint-based optimisation towards a minimum plastic recycling target on a per-country basis in the EU.

10.6 TIMES-Europe

10.6.1 Model improvements

TIMES-Europe incorporates all energy producing sectors and demand sectors on the level of EU member states. For industry it includes all energy-intensive industry subsectors, including one or more material production demands per subsector [Luxembourg et al. 2025]. The TIMES-Europe reference energy system includes the production of high-value olefins (HVO), ethylene, propylene and butadiene, from steam crackers. At present, this is the dominant production route. Production from Fluid catalytic cracking and Propane dehydration are not represented in the model. For the PoC several future HVO production routes were added to the model:

- Methanol-to-Olefin (MTO)
- Bioethanol to ethylene

In addition, to improve alignment with the CIMS model, an additional pathway for the production of methanol was added to the model:

- Municipal waste to methanol

An important innovative aspect of linking the models for the PoC concerns establishing the HVO production requirement taking into account demand side and circular strategies. To this end, the way-of-working outlined below was used.

1. 2015 HVO production was estimated by combining country-specific ethylene production capacities [Wong et al. 2020], feedstock consumption from Eurostat and standardized, feedstock dependent, production yields of propylene and butadiene from literature [Ren et al. 2006, Boulamanti et al. 2017].
2. Sectoral (Basic Plastics) growth projection from EXIOMOD
3. A decrease in production requirement in circular scenarios based on a reduced demand for plastics projected by CITS
4. In all scenarios, a reduction of the production requirement resulting from increased recycling as projected by PRISM

In the scenario projections of country-specific requirement of olefin production it is assumed that production is limited to countries, which currently have an HVO producing petrochemical industry. CITS considers the following strategies to lower plastics demand: refuse (elimination of an application, making them obsolete), reduce (less material per application/product), reuse (behavioural change reusing

products) and life time extension. This results in a country specific, decrease in the demand for plastics with respect to the baseline (non-CE scenarios). Subsequently, this was used to determine an EU-wide relative decrease in plastics demand. In the CE scenarios this factor is applied to the production requirement established based on 1) and 2). Finally, for all scenarios the impact of recycling was incorporated. For this purpose, PRISM considers various recycling strategies, which include pyrolysis, gasification and mechanical recycling. Taking into account the availability and quality of plastic waste and specific scenario parameters (circular vs non-circular, commodity energy prices and CO₂ emission factors) PRISM determines the preferred recycling routes and availability of recycled material. For HVO producing countries the increase in recycling (w.r.t. 2015) is deducted from the country's production requirements. The increase of the recycling output from the remaining countries is aggregated and subsequently applied as reduction in production requirement for the producing countries, using a distribution key based on the country-specific production levels in 2015.

10.6.2 Conclusions on methodology

The level of the country-specific HVO production requirement is strongly affected by the CITS and PRISM model outputs. Using the current approach we have successfully endogenised the HVO production requirement.

Bioenergy prices are strongly dependent on the climate ambitions in the rest of the world. Importing bioenergy prices from TIAM-ECN (and in future runs from GLOBIOM) affects the primary and final energy mix.

10.6.3 Recommendations for next phase

Currently, the multiple plastics recycle streams from PRISM have been converted into one polymer recycle commodity, which has been implemented directly as reduction in HVO production requirement. In future IMS runs, as a refinement, we will implement generalized plastics recycling processes in TIMES-Europe. The processes will be characterized by techno-economic parameters based on the process representation in PRISM. The recycle output from PRISM will in this case be treated as potential, which may or may not be used in TIMES-Europe to fulfil the HVO production requirement.

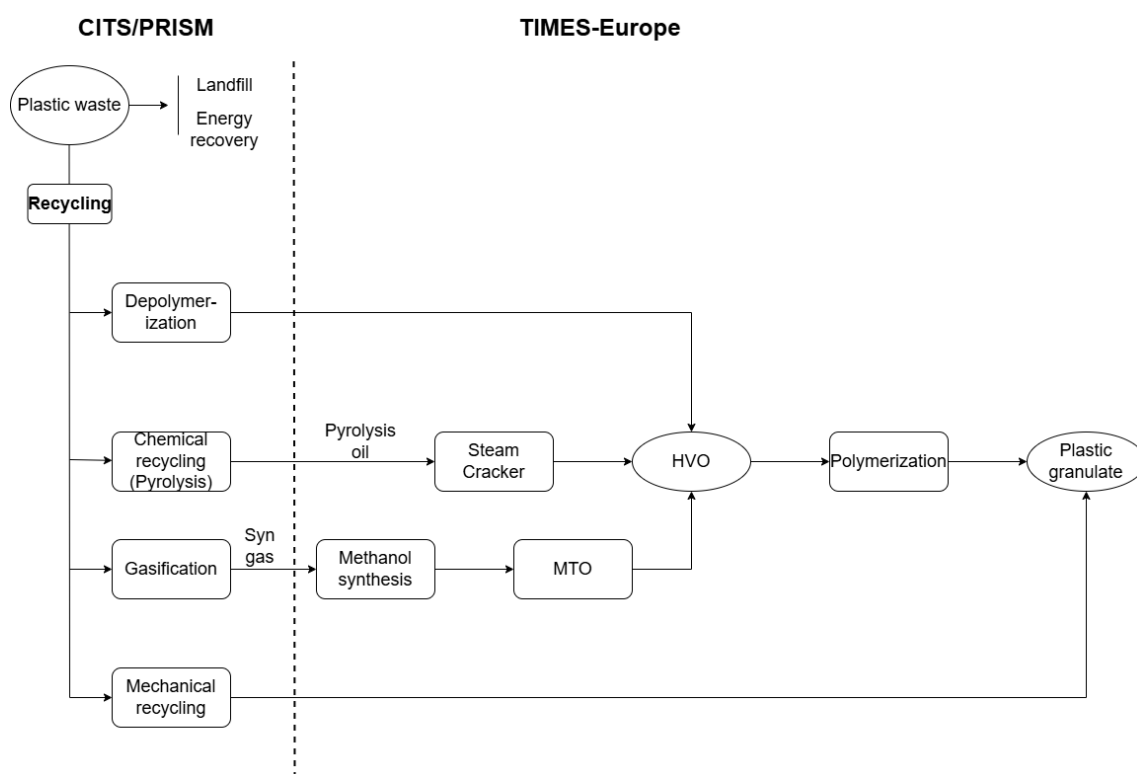


Figure 37. Extension of the representation of plastics recycling in TIMES-Europe.

10.7 CIMS

10.7.1 Model improvements

Scenarios

The features of the 4 scenarios were implemented in CIMS by:

- Forcing the net CO_{2,eq.} emissions to zero in 2050.
- The import of fossil-based naphtha, natural gas and blue hydrogen was constrained to zero in 2050 in the CE scenarios.

Technologies

Two new options were implemented in CIMS to match with the other models (TIMES-Europe and CALLIOPE in particular):

- The import of methanol was added. Methanol can be converted to ethylene and propylene via the Methanol-to-Olefin (MtO) process. The option to have MtO on Chemelot was already in CIMS, but only for local production of methanol, not for import.
- The conversion of (bio)ethanol to ethylene (EtE), based on import of bio(ethanol) was introduced in CIMS, as this route was one of the preferred routes in the TIMES-Europe initial results but not yet available in CIMS.

Price assumptions

For the stand-alone run, commodity prices were provided from the scenarios, but not all needed prices were available, therefore other sources were also used, creating an inconsistent set of data. For the serial run, all commodity prices needed in CIMS were taken from TIMES-Europe results, except for sorted plastic waste price, which was not available. Prices and price development were derived from EuroStat data in this case.

Availability and demand assumptions:

The future demand for plastic production at Chemelot was derived from the CITS results. Previously, a constant production was assumed.

The availability of commodities for the chemical sector for the Netherlands are available from TIMES-Europe results. However, it was decided not to limit the availability of commodities in CIMS to allow more room for optimization, otherwise the CIMS results would be forced towards mimicking the TIMES-Europe results. Some exceptions were made:

- The availability of mixed plastic waste was limited based on the results of CITS, applying a fair-share principle.

10.7.2 Conclusions on methodology

- CIMS is highly dependent on good value predictions for feedstocks and CO₂ (credits & taxation). If unrealistic prices are used unreliable results will be produced.
- Feedstock constraints have a strong impact in the technology selection. It was decided for this serial run not to constraint the resources, but as a next step, it would be valuable to repeat the same run with constrained availability of feedstock based on the output of TIMES-Europe to investigate what would be the consequences for Chemelot of such potential scenarios in the future.

10.7.3 Recommendations for next phase

The same technologies are used in different models (for instance in CIMS, TIME-Europe, Calliope and PRISM). The assumptions related to these technologies, like feedstock and energy consumption, CO₂ emissions and CAPEX, have not been aligned. We recommend aligning on these assumptions in the next phase to ensure consistency between the models and the results obtained.

The connection between Calliope and CIMS was abandoned in the PoC, in favour of TIMES-Europe – CIMS connection. The value of the connection to Calliope should be re-considered in the next phase. Also, in view of future iterative runs.

10.8 Calliope Europe

10.8.1 Model improvements

The original Calliope Europe Sector-Coupled model, based on Pickering et al. (2022), represents a high-resolution snapshot of Europe's energy system for a target year, using a custom NUTS3 regional breakdown (98 regions across EU27, UK, and neighboring countries). It is designed to capture key geographical dynamics of energy supply and demand while managing model complexity.

For the PoC, we focus on the year 2050 to reflect the EU's net-zero ambition. The original model assumes a fossil-free, self-sufficient Europe with exogenously set industrial energy demands, based on expected adoption of clean technologies. However, industrial demand is not endogenously modelled, limiting realism.

Within the AMIGDALA PoC, we addressed this by linking Calliope with the TIMES-Europe model. This integration enables endogenous modelling of the industrial transition: TIMES-Europe determines industrial energy demand, which Calliope then uses to optimize energy supply and system coupling.

In addition, the original Calliope model lacked representation of hydrogen and natural gas networks. It assumed:

- Natural gas (or synthetic gas) could be supplied to every region without transport limitations.
- Hydrogen demand must be met via local production only, leading to potentially suboptimal system configurations.

These assumptions are particularly limiting in the context of the plastics sector, where both natural gas and hydrogen play critical roles. As a result, the PoC introduced key extensions:

- **Natural Gas and Hydrogen Network Modules:** These modules were added to the original model, enabling regional transport and interconnection decisions. The model can now evaluate whether to refurbish existing infrastructure or invest in new pipeline capacity between regions.
- **Hydrogen Storage Representation:** At the regional level, the model now includes the option for hydrogen storage in either

pressurized tanks or salt caverns, depending on geological availability.

10.8.2 Conclusions on methodology

A key contribution of the project is the integration of TIMES-Europe with Calliope, enabling a more realistic, endogenous representation of industrial energy demand in high-resolution energy system models. Traditionally, models like Calliope-EU and PyPSA-EU have relied on fixed, exogenous demand assumptions for industry, which limits their ability to reflect feedbacks between system design and industrial transitions.

Likewise, TIMES-Europe, while strong on sectoral dynamics, lacks the spatial and temporal resolution required to simulate systems with high shares of renewables. Their integration represents a methodologically significant step, allowing for complementary strengths to be leveraged and delivering more robust and holistic insights for policy and planning.

10.8.3 Recommendations for next phase

Since the primary focus of the PoC phase was to develop and test the methodological approach for model integration, some important steps—particularly the harmonization of technology definitions and techno-economic data across models—were not fully addressed. This may lead to discrepancies in outputs between TIMES-Europe and Calliope, potentially limiting the ability to draw fully consistent conclusions from the integrated modelling.

Addressing this issue should be a priority in the next project phase, ensuring full alignment of input data and assumptions across both models. In addition, further model development will be necessary—particularly to enhance the representation of CO₂ supply, capture, utilization, transport, and storage—as this will play a critical role in shaping future net-zero energy systems.

10.9 ELDEST

10.9.1 Model improvements

Techno-economic data on costs and technical parameters of generation technologies stem from CALLIOPE, as well as the hourly electricity demand. As only demand time series for the year 2050 is supplied, the data for the remaining years between 2025 and 2050 is interpolated. Installed generation capacities and demand in 2025 is based on historical data from 2024. Future carbon prices stem from TIMES, in which prices are interpolated between the available years.

ELDEST has recently experienced several updates and improvements. New which new technologies have been added, parameters have been updated to be in line with other AMIGDALA models. Storage technologies, although not yet part of the investable technologies, are part of the legacy technologies. Decommissioning has been added as a feature, an improved scenario module allows running complex sets of scenarios in which all kinds of inputs can be changed.

10.9.2 Conclusions on methodology

The overall model set-up of ELDEST, and it's linking to the other models in AMIGDALA works well. Current model results are still very stylized and should be interpreted with caution. The decision to model Belgium as an energy island has strong implications for capacity investment, dispatch, and electricity price formations. Investment expansion paths are impacted by costs parameters, as well as by upper bounds. In the current version, agents can add infinitely generation capacity per period, which leads to a strong investment push in the first period.

10.9.3 Recommendations for next phase

For the next phase, it is recommended to discuss and possibly implement the following points:

- Currently, ELDEST is missing a link to the industrial sector. This link should be added to adequately model the power sector-industry nexus and to shed some light on that relationship.
- It should also be discussed, whether the local-level approach (i.e., only Belgium is modelled) is sufficient, or whether the geographical scope should be extended. Model complexity and computational burden have to be considered if the model was further extended.

- The coupling of ELDEST to other models should be improved to harness the advantages of the AMIGDALA framework. This could also include the comparison of results between models, if possible. In general, the positioning of ELDEST within AMIGDALA framework should be enhanced.
- To ensure that results are comparable, input data should be harmonized between models

11 Prototype Decision logic and dashboard in Excel

MetaData: This sheet acts as the central dictionary for the entire dashboard. It defines:

- **Scenarios:**
Detailed descriptions of hypothetical futures or strategic contexts, such as "SSP 1 - IT: Low for mitigation and transformation." Each scenario comes with a narrative explaining its underlying assumptions regarding economic development, technological advancements, market integration, and investment climate.
- **Control Levers:**
These are the actionable variables that users can manipulate to explore different outcomes. They are categorized (e.g., "Investments," "Industry") and typically offer binary choices like "Decrease" or "Increase" (e.g., "Markets," "Operating assets").
- **Preferences:**
User-defined priorities that dictate the analytical focus. Examples include specific energy demands or emission targets, which can be weighted as "Low," "Medium," or "High" importance.
- **Dimensions & Assessment Dimensions:**
These are the frameworks for evaluating performance. "Dimensions" refer to broad categories of impact (e.g., "Energy demand," "Emissions," "Production," "Fossil carbon replacement in the Energy Intensive Industry," "Use of raw materials, chemicals and water"). "Assessment Dimensions" represent higher-level strategic goals (e.g., "Climate neutrality," "Resilience") against which the dimensions are measured.
- **Key Performance Indicators (KPIs):**
These are the quantifiable metrics tracked and analysed. The sheet lists specific KPIs such as: "(Fossil) Carbon based feedstock consumption - Chemical industry", "By fossil, recycled, biobased, air", "CO2 price", "Manufacturing production value (real & volume)", "Process industry (or process) energy demand (Final + Primary), by energy carrier", "Process industry CO2-eq. emissions (process, energy, upstream, downstream)", "Process industry raw material input", "Product group material demand".
- **Model Inputs & Outputs:**
Clearly defines the data fed into the simulation (e.g., "Sell total," "Operated goods," "Product prices," "Raw materials") and the resulting calculated values (e.g., "Gas Energy price," "Solar Energy price," "Nuclear Energy price," "Demand," "Emissions"). Each input

and output include its ID, Name, Unit, and Min/Max values where applicable.

Relations: This critical sheet maps out the intricate relationships between different elements defined in the MetaData. It links:

- Scenarios to specific control levers and their selections.
- Control levers to the various KPIs, dimensions, preferences, and assessment dimensions they influence.
- Control levers to the precise inputs and outputs of the underlying model. For example, it might show that a "Decrease" in "Markets" (control lever) leads to changes in "Product prices" (input), which in turn affects the "Process industry (or process) energy demand" (KPI).

Inputs: This sheet contains the numerical values for the various inputs (e.g., "Sell total," "Operated goods," "Product prices," "Raw materials") for each distinct simulation run. These values likely represent different initial conditions or policy settings for each run.

Outputs: This sheet presents the quantitative outcomes of the simulations. It provides time-series data (from 2020 to 2070) for key outputs like different energy prices (Gas, Solar, Nuclear), overall demand, and emissions. The data is broken down by Run ID, Sector (Plastics), and Country (EU), allowing for detailed temporal and categorical analysis.

Weights: This sheet assigns numerical weighting factors to user preferences, KPIs, dimensions, and assessment dimensions. These weights are crucial for aggregating and scoring the results, reflecting the relative importance of each element in the overall evaluation framework. For example, "Resilience" as an assessment dimension might be assigned a higher weight, indicating its greater importance in the decision-making process.

App: This sheet represents the current state or configuration of the dashboard. It records the Scenario currently selected, the Default and Override settings for Control Levers, the Selected state of these levers, and the User Selection for each Preference. This allows the dashboard to reflect user choices and run simulations based on those inputs.

KPI: This sheet holds the core time-series data for each KPI across different simulation runs, sectors, countries, and years. Each row provides a Value for a specific KPI in a given Year and Run. This data is the foundation for all subsequent aggregations and visualizations.

KPI chart, Score chart, Dim chart and Ass chart: These files sheets contain pre-aggregated and summarized data specifically formatted for generating charts and graphs within the Excel dashboard. KPI chart presents averaged KPI values over time, ideal for visualizing trends and comparisons between KPIs across different years. Score chart displays the prioritized aggregated scores across different simulation runs for each year, providing a high-level performance overview. Dim chart, Figure 35, shows scores aggregated by dimensions of climate neutrality over time, allowing for the analysis of performance within specific areas.

