

Deliverable:

D7.1 Scenarios for plastic waste generation - spatial determination of quantities and qualities of current and future plastic and bio waste streams in the tri-lateral ARRRA region

Title:

Plastic waste scenarios for the ARRRA region

Current and future quantities and qualities of regionally available plastic waste and biowaste



D7.1 Scenarios for plastic waste generation

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^{1.} PU=public, SEN=Sensitive, only for the members of the consortium

^{2.} R= report, DEM= Demonstrator, pilot, prototype, DEC= Websites, patent, filings, videos, etc. ,DMP= Data Management Plan, Ethics.

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Executive summary

This report is a deliverable of work package 7 of the SYSCHEMIQ project. The goal of the SYSCHEMIQ project is to find circular systemic solutions to achieve a good quality processable feedstock for both mechanical and chemical recycling. The project focuses on the Tri-lateral Rhine-Meuse Euregion (NL, BEL, GER), surrounding the Chemelot Circular Hub, a unique chemicals and materials community as well as an industrial park, that will take the lead in this transition process.

This report provides quantitative projections on the future plastic packaging waste and biowaste streams in the tri-lateral ARRA region up to 2060 and their spatial distribution via a geographical (GIS) model. Moreover, it provides a set of scenario data on future energy prices, policy assumptions, and plastic waste compositions, to be used in a model framework. To our knowledge, comprehensive scenarios for the plastic system covering this wide range of aspects from socioeconomic parameters to pricing and policies have not been developed so far. The model framework has the goal to evaluate societal (in our case socio-economic, environmental, and circular) and business performance of collection, sorting, transport and mechanical and (thermo)chemical recycling of plastic waste and biobased streams to support technological and policy development as well as upscaling and implementation of optimal organized circular plastic business cases and value chains in the ARRA region.

The plastic sector is influenced by a multitude of external factors such as socioeconomic developments (e.g., GDP, population, energy system). We define those factors as external to our analyzed foreground system (i.e., the plastic sector), as background scenarios. We chose projections of the future energy system from PBL's IMAGE model as inputs for our background scenarios, based on the shared socioeconomic pathways used in climate modeling. Here we compare a baseline scenario (no climate action) with a scenario reaching the 1.5 degree climate target from the Paris Agreement. For population and GDP projections we used data from OECD and Eurostat.

Based on historic data and their relationship to GDP and population development, we created projections on plastic packaging waste and broke it down to regional level (NUTS2³). For biowaste streams, we made use of existing projections. We project that plastic packaging waste generation in the ARRA region (NL, BE, North Rhine Westphalia) will increase by 37%: i.e., from 1602 kton in 2020 to 2189 kton in 2060. Moreover, a total of 8236 kton biomass waste and residues were available in the ARRA region in 2020, increasing by 24% to 10.180 kton in 2060. This data was integrated into a newly developed GIS tool, which visualizes the spatial distribution of the waste streams and allows the exploration of the results over time for different scenarios (see Figure 1). Together, plastic packaging and biowaste streams in the

³. The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the European Union. NUTS 2 level represents the provinces in Belgium and the Netherlands and the government districts in Germany.

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ARRRA region equal approximately 197 PJ in 2020, which corresponds to almost half of the estimated 402.5 PJ feedstock needs of the Dutch chemical sector.

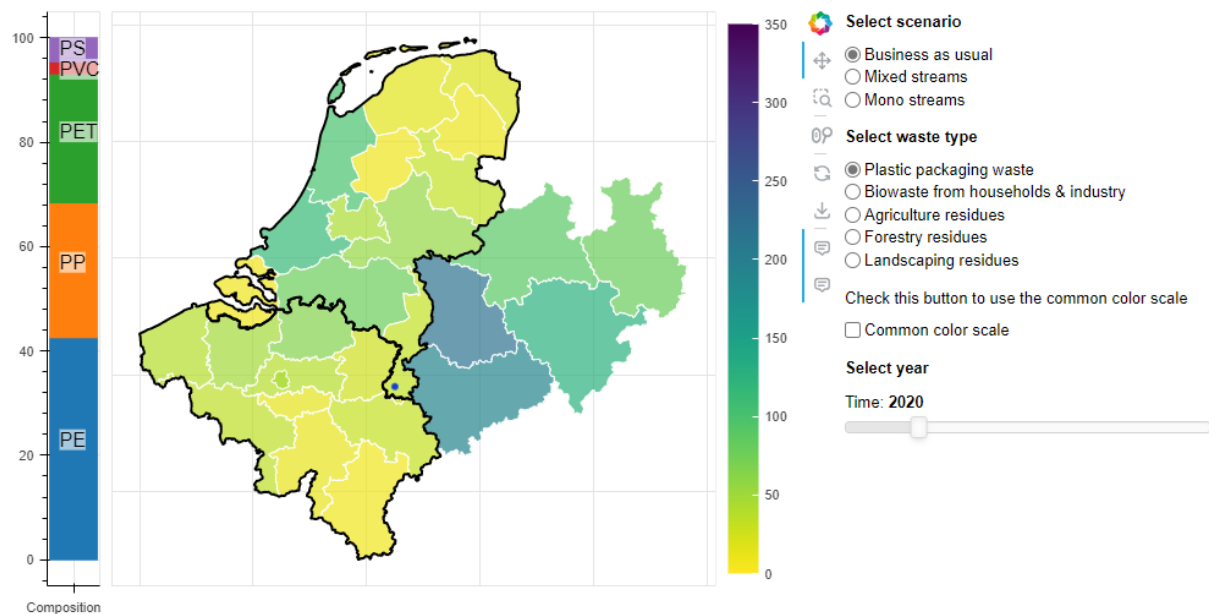


Figure 1: The GIS browser tool visualizing waste streams projections

Based upon three main principles: plastic waste qualities, plastic waste quantities and plastic waste policies, we developed three what-if foreground scenarios. Those foreground scenarios provide assumptions that cover factors that are part of the analyzed foreground system, i.e., the plastic sector, contrary to the background scenarios that cover socioeconomic and other aspects and developments in other parts and sectors of society (e.g., the energy sector).

The main variation within the foreground scenarios concerns the degree of mixed plastics in waste, which is key for the quality of recycling:

1. Baseline scenario: extrapolation of current plastic mix
2. Mixed plastic waste policy scenario: a shift towards more mixed plastics
3. Monoplastic waste policy scenario: a shift towards several monoplastic streams

For each scenario, also preliminary policy measure packages have been presented, which will be further developed in cooperation with SYSCHEMIQ work package 1 on governance.

The background and foreground scenarios to be used as inputs for a first model quick scan are summarized in Table 1.

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Table 1: Selected background and foreground scenarios for the quick scan analysis

		FOREGROUND SCENARIOS		
B A C K G R O U N D S C E N A R I O S		Baseline	Mixed plastic policy	Monoplastic policy
	SSP2 3.5 °C No climate target	Current service growth; current plastic mix; fossil dominated energy mix; no CO2 price		
	SSP2 1.5 °C Climate target	Current plastic mix; renewable & CCS energy mix; CO2 price		
	SSP2 1.5 °C Climate + CE policies	Current plastic mix + CE policies	Mixed plastic due to (lack of) interventions in design & post-consumer separation + CE policies	Several monoplastic due to interventions in design & separate collection + CE policies
	Policy measure package	CE + Climate targets + D4R; innovative pre-post-consumer sorting + Forbid incineration + Diftar plastic waste fee + Deposit systems	CE + Climate targets + Bulk post-consumer sorting + CR standards + Quality standard + Forbid incineration + Technology investment grants	CE + Climate targets + D4R; innovative pre-post-consumer sorting + MR / Quality standards + Deposit systems + Diftar plastic waste fee

Optional: sensitivity analysis on low and high growth of waste

In a next step, this scenario set will be implemented in the SYSCHEMIQ model framework for a quick scan to assess and learn about the models and the plastic system in the ARRRR region, as a basis for further research in the project.

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List of abbreviations and definitions

Abbreviation	Definition
ARRRA	Antwerp, Rotterdam, Rhine, Ruhr Area
BAU	Business As Usual scenario
CAGR	Compound Annual Growth Rate
CE	Circular economy
CIMS	Chemelot Integrated Model System
CR	Chemical Recycling
D4R	Design for Recycling
Diftar	Differentiated Tariff system
GDP	Gross Domestic Product
IAM	Integrated Assessment Model
IMAGE	Integrated Model to Assess the Global Environment
InReP	InReP – An Integrated approach towards Recycling of Plastics, Dutch research project funded by MOOI
MR	Mechanical Recycling
NRW	North Rhine Westphalia
NUTS	Nomenclature of territorial units for statistics in the EU
OECD	Organization for Economic Cooperation and Development
PRISM	Plastic Recycling Impact Scenario Model
RQ model	Recycling Quality model
SBR	Solvent Based Recycling
TIMER model	The IMage Energy Regional model

1 Introduction

1.1 Background

1.1.1 The SYSCHEMIQ project

In SYSCHEMIQ, 21 consortium partners in industry, science, education, government as well as cities and EU networks across Europe, work together to close the plastics cycle and speed up the circular economy in Europe. The project will last 48 months.

Currently, more than 85% of municipal plastic waste and 58% of plastic packaging waste is lost, landfilled or incinerated in Europe. The remaining 42% of plastic packaging waste is sent to recycling, but only a much smaller part actually enters new products as recycled plastics, and mostly in lower quality applications (Plastics Europe 2019). This is in sharp contrast to the EU target on Packaging and Packaging Waste, which specifies a recycling target of 50% for plastic packaging by 2025 and 55% by 2030.

The main objectives of the SYSCHEMIQ project are to find circular systemic solutions to achieve a good quality processable feedstock for both mechanical and chemical recycling. In SYSCHEMIQ, the Tri-lateral Rhine-Meuse Euregio (NL, BEL, GER) will demonstrate how to align regional stakeholders in a systemic approach on the roadmap towards a circular urban-industrial plastics district, overcoming the main technical and non-technical barriers to close the feedstock resources loop. This EU-region surrounds Chemelot Circular Hub, a unique chemicals and materials community as well as an industrial park, that will take the lead in this transition process.

SYSCHEMIQ will set up a joint governance model and develop technical, industrial and societal solutions, while investing in commercial-scale plastic recycling plants. The project fosters dissemination and replication of learnings throughout Europe leading to a potential step-change in plastic recycling. Above all it's the project's ambition to prepare for upscaling into a higher-volume circular plastics economy towards 50% recycling of municipal plastic packaging waste within the tri-lateral region by 2025 and 55% by 2030 (EU Directive 2019/852 on Packaging and Packaging Waste). Therefore, the project supports the active participation of all relevant actors, i.e. public administrations and utilities, private sector services and industries, scientific institutes, industry organizations and civilians.

To prove the regional business case for a redesigned plastic value chain, the consortium aims at:

- The creation of circular systemic solutions, including:
 - New design rules for plastic packaging products;
 - New aligned plastic waste collection and sorting;
 - New sorting installation, mechanical & chemical recycling technologies.
- Developing a joint circular governance model and tools to support governance of the regional circular plastics economy.

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- Replication strategies (based on cross-regional business model and business case) and scenarios towards the other EU-regions.

1.1.2 WP 7 Society and business impact assessment

The main objective of WP 7 of the SYSCHEMIQ project is to evaluate several societal performances (socio-economic, environmental, and circular) and the business performance of collection, sorting, transport and mechanical and (thermo)chemical recycling of plastic waste and biobased streams to support technological and policy development as well as upscaling and implementation of optimal organized circular plastic business cases and value chains in the ARRA (Antwerp, Rotterdam, Rhine, Ruhr Area) region and Europe. To this end, scenarios and forecasts will be developed and implemented in the SYSCHEMIQ model framework, see Figure 2 for an overview.

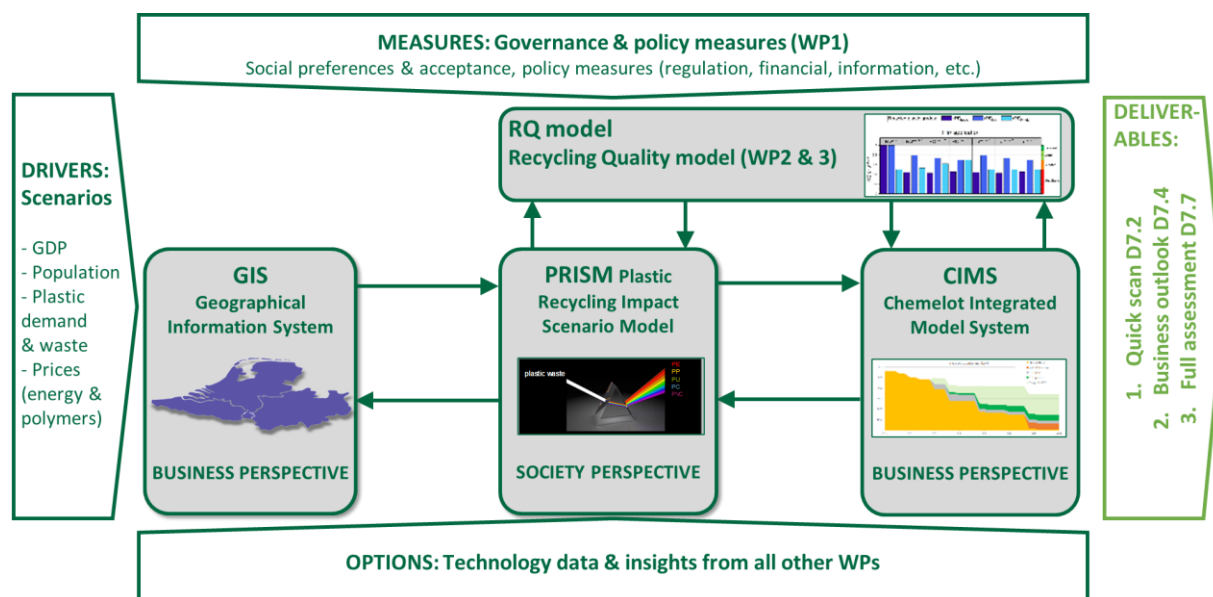


Figure 2: Overview of model framework of linked models including inputs and outputs as applied for the society and business impact assessment within SYSCHEMIQ.

The model framework consists of the following models:

- Plastic Recycling Impact Scenario Model (PRISM). PRISM will be used to assess the economic and environmental performance of plastic value chains from a societal perspective (see Chapter 2.2 for further introduction).
- Recycling Quality (RQ) model. The RQ model of Maastricht university (Demets et al 2021) defines the quality of recycled plastics from different plastic waste streams in comparison to virgin plastics. In work package 3 the model is further developed and eventually integrated into the model framework for the final assessment towards the end of the project.
- The CHEMELOT Integrated Model System (CIMS). CIMS will be applied to assess chemical industry business opportunities, the impact on the integrated CHEMELOT site of the different recycling options and the impact on the energy and raw material system outside CHEMELOT (and mismatches), see 2.3 for further information.

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In a first step the GIS, PRISM and CIMS model are soft-linked and a quick scan conducted to test and learn about the model framework. Next, the models are updated, the recycling quality model integrated, and the technological recycling options, business and pilot data from other WPs are included to conduct a full economic and environmental policy scenario assessment of the plastic value chain network in the ARRRRA cluster, including regulatory, financial, and behavioral policy interventions. This is used to prepare a Regional Business Case and Regional governance for decision making in WP1 on Governance (interactively during the project period).

1.2 Goals of this deliverable

The goal of this deliverable is to provide the **quantitative scenario data** for a first quick scan with the PRISM and CIMS models (Deliverable 7.2). Next to this report, also a **GIS tool** is delivered, that presents the spatial distribution of the waste streams.

This deliverable provides national quantitative projections for the tri-lateral ARRRRA region on the volume and the composition of future plastic packaging waste streams in so called **foreground scenarios on the plastic system**. These are assessed as a function of national socio-economic developments such as population and economic growth, so called **background scenarios on the wider societal developments**. Additionally, this report provides background scenario projections for energy prices and emission factors which are needed in the model framework as well.

The national plastic packaging waste streams are being **spatially distributed for the tri-lateral ARRRRA region** and presented in a newly developed geographical (GIS) model. Additionally, **alternative waste streams with a bio origin**, i.e. biowaste streams are included into this GIS tool as well.

1.3 Structure of the report

Chapter 2 introduces the models used in work package 7, how they are extended and which approach was taken when choosing and developing scenarios for the quick scan. Chapter 3 presents the selected background and foreground scenarios and Chapter 4 introduces the methodology behind the newly developed GIS tool to visualize waste flows for the ARRRRA region. Chapter 5 presents the projection results of the different waste streams. Chapter 6 reflects on the process and draws general conclusions on the results and provides insights in the next steps of the project.

2 Approach

2.1 Requirements

The goal of SYSCHEMIQ WP7 is to evaluate the societal (in our case socio-economic, environmental, and circular) and business performance of mechanical and (thermo)chemical recycling of mixed plastic household waste and biobased streams for the ARRA (Antwerp, Rotterdam, Rhine, Ruhr Area) region and Europe.

To achieve this goal, the modelling framework needs to consider several requirements:

1. It has to include the most important parts of the value chain ranging from plastic production, waste production, collection and recycling.
2. Consequentially, it has to include quantities and qualities of plastic (products and waste), including contaminations, resource and product prices, technological options for production and recycling and policy measures.
3. Since knowledge and methods are scarce, it is explicitly highlighted here to include behavior as a basis for business and consumer decisions and design of effective policy measures.
4. Both technoeconomic and environmental aspects need to be considered at a technology-specific as well as at an aggregated system level to allow for decision-support from a societal and business perspective.
5. Since system transitions are already unfolding and take considerable amounts of time, the time period considered has to be from 2020 to 2050 and preferably 2060 (as most projections are already being updated to this target year), also taking into account that policy strategies see that as an appropriate time horizon.
6. The interaction with socioeconomic developments and other transitions, e.g., on energy and climate need to be included via background scenarios.
7. Geographical focus is the ARRA region but at a generic level, the analysis has to yield conclusions for the EU as well
8. To have an impression of availability of resource potentials and transportation demands, geographical resolution has to be below country level in the ARRA region, so at least at NUTS2 level (representing the provinces in the Netherlands and Belgium and the government districts in Germany).

Besides these plastic specific demands, several general requirements are important:

1. accurate (fact based, focus on materiality and relevant aspects)
2. transparent (methodology)
3. credible (aligned with state-of-the-art approaches)
4. verifiable (data sources)

This extensive set of requirements implies that not a single model can meet all of them. In fact, there are only a few models which can meet part of the specific requirements. Hence, we combine several models in one framework. To this end, the models need to be (soft) linked and extended for some aspects and functionalities.

Soft linking means that inputs and outputs are exchanged (in a single iteration). In order to generate consistent results, also scenario inputs should be aligned as much as possible. For instance, socioeconomic forecasts, plastic waste projections, energy

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and product prices and policy measures have to be aligned within the framework of models, for as far as they are relevant.

2.2 Extending the Plastic Recycling Impact Scenario Model (PRISM)

The Plastic Recycling Impact Scenario Model (PRISM) analyses plastic waste flows to identify available plastic waste streams and how to treat these optimal in terms of costs, resources, circularity, CO₂ and other environmental impacts (PRISM, 2022). The effect of potential policy interventions such as subsidies or taxes (e.g. CO₂ tax) in the Netherlands is included. The model operates in an annual resolution.

The plastic waste flows are specified on polymer level and use sector, such as packaging or automotive. These specifications are useful for indicating potential recycling barriers through design, chemical structure or through collection methods. This allows for higher accuracies in predictions and extrapolations compared to other plastic models, which only model plastic packaging waste or a selection of common polymers. Furthermore, PRISM includes GDP based growth scenarios to predict future plastic waste stream quantities. The model includes data on various innovative and state-of-the-art recycling technologies, including economic, environmental and health data (see Figure 3).

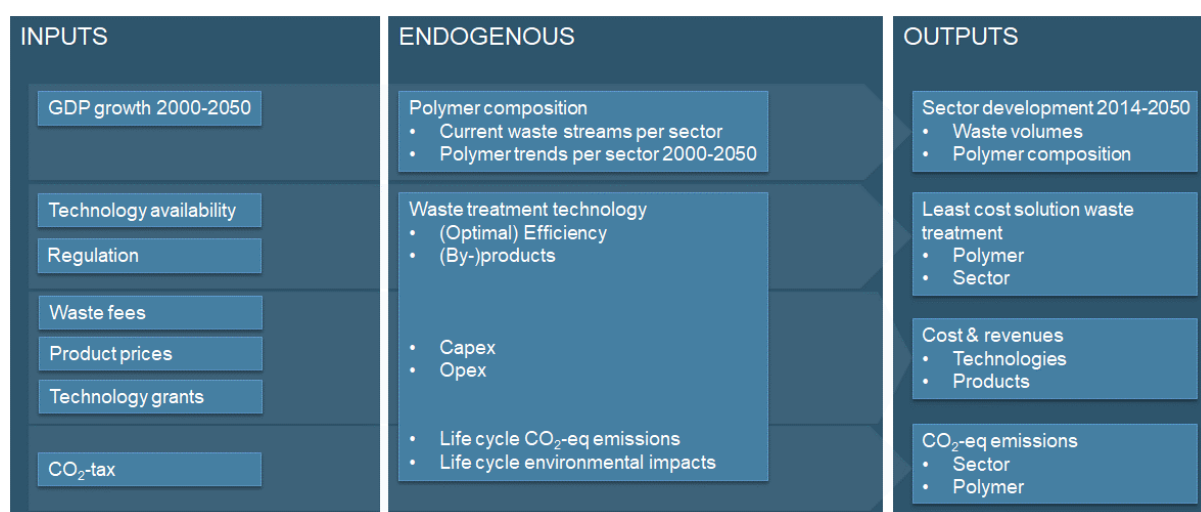


Figure 3: Overview of PRISM inputs, endogenous parameters and outputs

The environmental impact of recycling technologies of PRISM is supported by Life Cycle Assessment (LCA) data and implemented through the LCA matrix model (Schwarz et al 2021). This model includes a wide range of recycling technologies, including multiple chemical recycling options, and therefore increasing the scope compared to models focusing on mechanical recycling only.

In this project, the PRISM model is extended by adding an optimization module, specific policy measures researched in WP1 on governance and a GIS model that shows the spatially specific distribution of plastic packaging waste and biowaste flows for the ARRRR region (meaning Netherlands, Belgium and Nord Rhein-Westphalia).

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Furthermore, PRISM will be soft-linked with other models such as the RQ model and CIMS.

2.3 Alignment with the CIMS model

The Chemelot Integrated Model System (CIMS) is a cost-optimization model that calculates technological pathways to reach CO₂-equivalent targets over time at least system costs (see Figure 4). It includes the current and potential future technological process capacities at Chemelot and their costs, energy and resource consumption and prices, and CO₂-equivalent emissions. The model is designed for system-level analysis and it is based on publicly available data whenever possible. It helps to understand how individual measures and techniques impact the complex, integrated process structure of the Chemelot chemical production site in Geleen, which consists of many companies, as a whole. It also provides insights into the effects of external factors such as energy prices, and helps to evaluate several scenarios for reducing emissions. See for instance Brightsite Transition Outlook 2023 as an example of a CIMS study (BTO 2023).

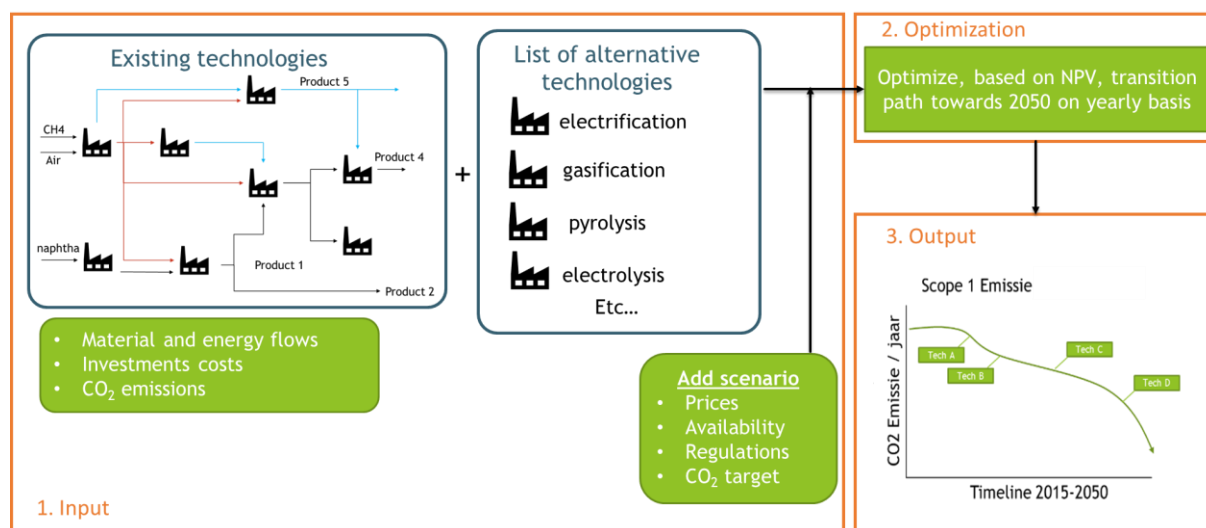


Figure 4: Simplified overview of the CIMS model

For SYSCHEMIQ, CIMS will provide a system analysis of polyolefin production by conventional or alternative technologies, such as electrified steam crackers, based upon different resources, i.e., the current fossil crude oil, plastic waste based pyrolysis oil or biobased pyrolysis oil. CIMS will also consider alternative options to provide a least cost solution from a business (Chemelot) perspective, given the common scenario framework of WP7.

In the later stages of the SYSCHEMIQ project the CIMS model is supposed to run in conjunction with the PRISM model (see Figure 2). This requires an alignment of the scenarios that should be used coherently throughout the models. For this purpose, the CIMS model team was consulted in workshops and bilateral meetings (see

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chapter 2.4) to ensure that the scenario data requirements for both the PRISM and CIMS models are met.

2.4 Scenario approach

2.4.1 Scenario requirements

We distinguish between background and foreground scenarios. The **background scenarios** provide information and data on possible demographic developments, the natural environment, and the wider economy which all affect our analyzed foreground system, i.e., the plastic sector.

Key **background scenario** variables that are necessary for our analysis of the ARRRR region are:

- GDP and population development
- The climate targets and the corresponding CO₂ prices
- Availability and prices of energy and resources, in particular: oil, natural gas, electricity, hydrogen, biomass
- The production mix of electricity and hydrogen and the respective emission factors

The **foreground scenarios** provide information and data on possible developments in our foreground system, i.e. the plastic sector, consisting of different plastic types, production and recycling technologies. Required scenario inputs include:

- Technology developments, e.g., new recycling technologies becoming available, technological learning.
- The waste composition and their quality (e.g., which plastic types are used in the scenarios)
- Specific policies affecting the plastic sector (e.g., plastic tax, recycling quotas)

We are aware that there exists no sharp boundary between background and foreground. In fact, these are model dependent; what is foreground for one model (e.g. waste collection and waste treatment in PRISM) can be background in another model (CIMS). Nevertheless, background and foreground scenarios help to distinguish SYSchemeIQ relevant system developments from generic socio-economic developments and align with existing scenarios on global developments. At the same time, these scenarios help to create a consistent scenario environment for the model framework with its different models.

Ideally, the selected scenarios are supposed to fulfil requirements in line with those of the modelling framework in chapter 2.1:

- cover at least the time period until 2050, ideally until 2060.
- be region-specific to adequately cover the ARRRR region
- be future-proof, i.e., the scenario data is regularly updated
- be widely accepted and applied to allow interoperability and comparability with other models
- be coherent between the applied models (PRISM, CIMS).

Last but not least, it is desirable that the number of scenarios is limited in order to keep work feasible and results clear.

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2.4.2 Scenario review & data collection

The starting point was to make use of existing scenarios where possible. Suitable scenarios were identified, compared and adapted to the project via literature review, workshops and individual meetings.

Two hybrid workshops and two online progress meetings were conducted with the partners of SYSCHEMIQ work package 7 to discuss the advantages and disadvantages of various scenario approaches. Additionally, bilateral meetings were conducted for further discussions with individual project partners, TNO colleagues and external partners (e.g., PBL).

Based on these inputs, a scenario approach was defined and where necessary adapted to the needs of the SYSCHEMIQ project.

As basis for waste projections, historic data for plastic packaging waste generation, population and GDP development was collected from EUROSTAT.

3 Selected background and foreground scenarios

3.1 Socioeconomic background scenarios

3.1.1 Scenario selection

The discussions with the project partners revealed three promising sources for scenarios on the future development of the energy system which forms part of the background scenarios of the planned analysis (see chapter 2.4.1). These scenarios have to provide the prices and emission factors of the energy carriers relevant for the SYCHEMIQ models PRISM and CIMS (see chapter 1.1.2): oil, natural gas, electricity, hydrogen, and biomass.

The three scenario options are summarized in Table 2. Amongst them is the climate and energy outlook (KEV) published by PBL (PBL 2022), the EU reference scenario (Deppermann et al. 2021), and the shared socioeconomic pathways (O'Neill et al. 2017) for which several integrated assessment models provide scenario files, such as PBL's IMAGE model (Stehfest et al. 2014).

Table 2: Potential sources for background scenarios

	Climate and Energy Outlook (KEV) 2021	EU Reference Scenario 2020	Shared socioeconomic pathways (from integrated assessment models)
Geographical scope	Netherlands	EU by country	World, by regions (e.g., Western Europe); incl. trade
Temporal scope	2030	2050	2100, annual
Scenario type	Baseline	Baseline	different socio-economic assumptions (SSP 1-5); optimized for climate targets
Sectoral / environmental coverage	Energy, industry	Energy, industry	Energy, industry, agriculture, land-use, climate system, water cycle, soil quality, biodiversity,...
Advantages	Country specific, closer link to current regional developments		Linked to global, long-term developments; linked to environmental changes; set of consistent scenarios

The climate and energy outlook has its strengths in covering the short-term trends in Netherlands (up to 2030) but does not include further countries. The EU reference scenario provides a scenario for all EU countries until 2050 but is limited to one baseline scenario based on existing EU legislation.

3.1.2 The shared socioeconomic pathways

The shared socioeconomic pathways (SSP) were developed by the climate change research community as a set of alternative futures for societal development (O'Neill et al. 2017; Riahi et al. 2017). There are 5 SSPs (see Figure 5), and variations thereof, reaching different climate targets (e.g. 3.5 °C or 1.5 °C). These scenarios are widely used in global modeling efforts, and are also part of the assessment

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reports of the Intergovernmental Panel on Climate Change (IPCC) (Rogelj et al. 2018; Shukla et al. 2022; D. P. van Vuuren et al. 2011).

The SSPs provide the most comprehensive set of scenarios compared to the EU reference scenario and the climate and energy outlook, which only cover one baseline scenario. Moreover, as part of integrated assessment models (IAM), they allow for assessing the interlinkages between human and natural systems and how they impact the world's climate (Schwanitz 2013). IAMs usually consist of several sub-models that cover natural systems like water, land, biodiversity, and human systems like agriculture and energy use (Weyant 2017). Hence, the shared socioeconomic pathways were chosen as a source for our background scenarios on the future energy and resource systems.

For the purpose of the quick-scan we chose only one of them, the SSP2, which describes a middle-of-the-road scenario in which economic, demographic, technological and behavioral developments are closely linked to historical patterns (Fricko et al. 2017). **Two variations of the SSP2 will be used: The baseline, and a version that reaches the 1.5 degree Celsius target of the Paris climate agreement.** With this selection we want to capture a significant range of potential future scenarios, one with a continued focus on fossil fuels and one with a strong shift to a sustainable energy future.



Figure 5: The shared socioeconomic pathways (from O'Neill et al. 2017)

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3.1.3 The shared socioeconomic pathways as part of PBL's IMAGE model

PBL's IMAGE model is one of the leading IAMs and contributes to the IPCC reports. There are also other IAM's providing results for the IPCC scenarios, such as MESSAGE-GLOBIOM or REMIND. However, due to established cooperations with PBL we opted for IMAGE, as this enables us to get additional background data from the model and provides us with easy access to the IMAGE team when needed.

IMAGE is a model framework that explores the long-term dynamics (until 2100) between society, the climate and the biosphere, analyzing impacts of socioeconomic activities on issues such as land use, climate change and biodiversity, see Figure 6. (PBL 2020; Stehfest et al. 2014). An important part of the IMAGE framework is the TIMER model, which is a recursive dynamic simulation model of the energy system and provides most of the key inputs needed for the SYSCHEMIQ quick scan. TIMER projects the demand and supply of relevant energy carriers such as oil, electricity, hydrogen or biomass and the associated emissions (Daiglou et al. 2015).

Like IMAGE, TIMER is structured in 26 world regions (PBL 2018) and does not have a country specific resolution. This is a disadvantage, but given the focus on the transborder ARRRRA region within SYSCHEMIQ, the IMAGE region "Western Europe" is seen as a reasonable proxy for the geographical scope of this project. In particular, given the long-term nature of this analysis and the expected further integration of the European energy system.

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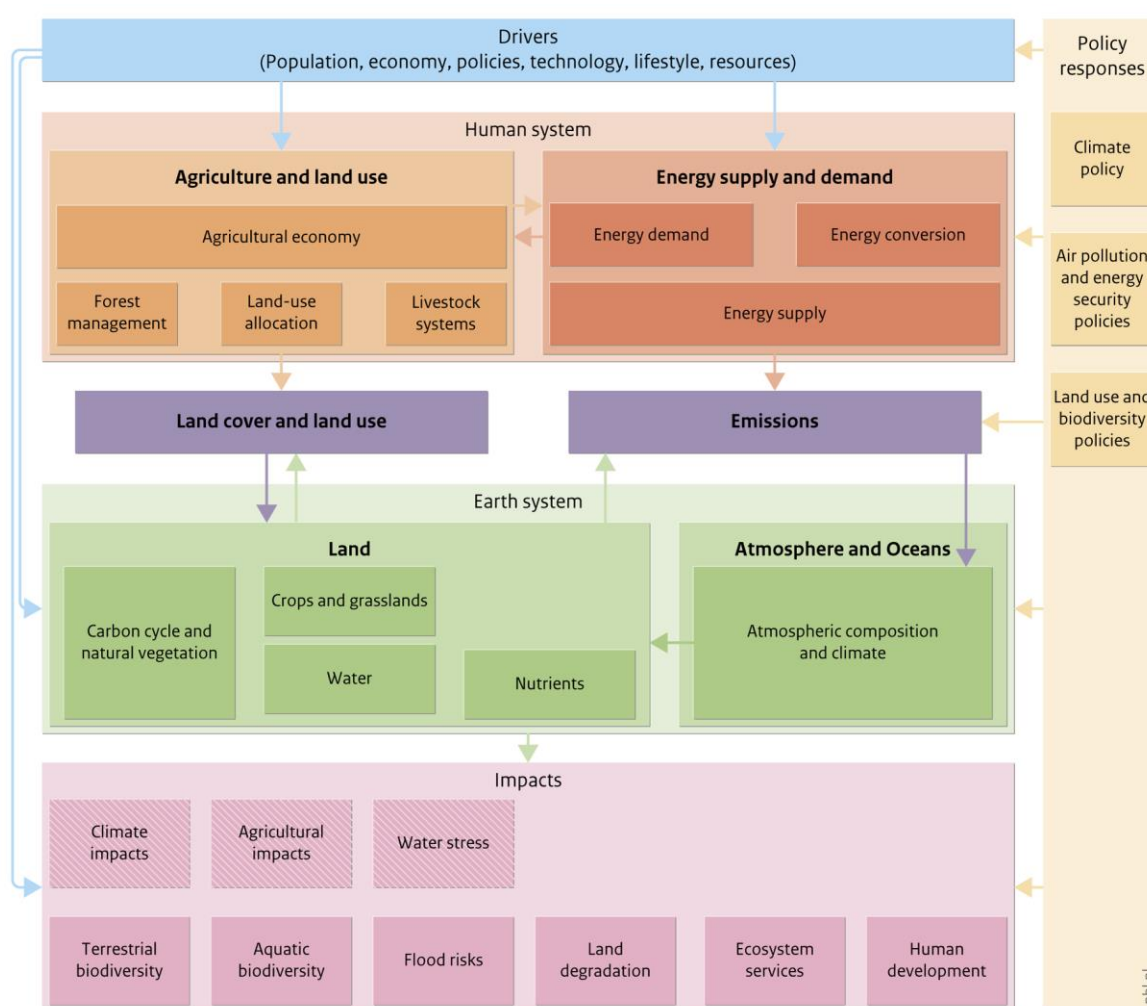


Figure 6: The IMAGE model framework

3.1.4 The selected background scenario data

We use output data from IMAGE 3.2, which was provided for the 6th assessment report of the IPCC (D. Van Vuuren et al. 2021). The scenario data is currently being updated by PBL and newer output versions can be included in further assessments within SYSCHEMIQ. This would also allow for a better representation of recent developments that had a substantial impact on the European and global energy system (COVID, war in Ukraine).

In this section we show the relevant scenario files, comparing for the selected SSP2 scenario the two selected variants, being the baseline scenario and the scenario meeting the 1.5 degree Paris Agreement climate target.

The SSP2 baseline scenario does not have a CO₂ price. Figure 7 shows the CO₂ price trajectory of the SSP2 1.5 degree scenario in IMAGE, which shows a steep increase from 2030 onward, reaching 545 Euros/ton CO₂ by 2060. This price trajectory does not necessarily reflect planned policies, but displays the CO₂ price needed to reach the 1.5 degree target by 2100 within the IMAGE model. Hence, it does not relate to

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the CO₂ price of the European Emission Trading System (ETS), which does not include all sectors and has free allowances for certain emission intensive industries. Within IMAGE, the CO₂ price applies to every ton of CO₂ equivalents emitted in all represented sectors.

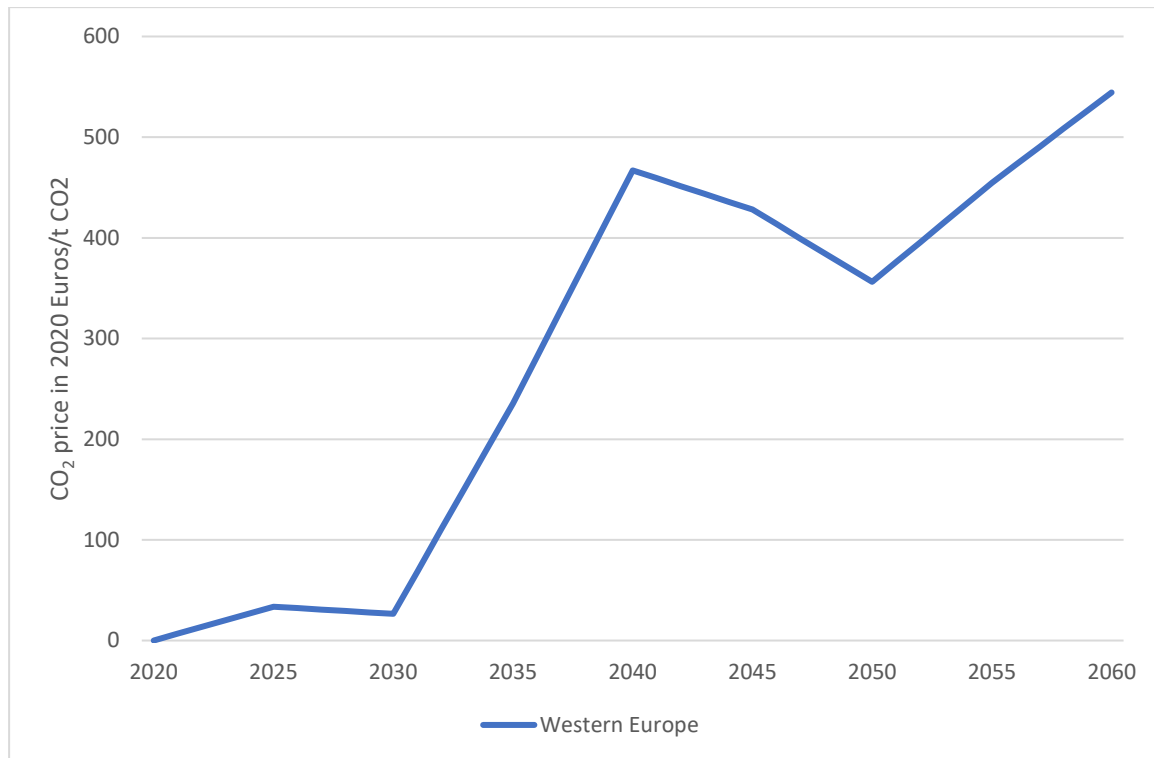


Figure 7: CO₂ price development for Western Europe in the SSP2 1.5 degree scenario in IMAGE

Figure 8 shows the price developments of the energy carriers. All prices are in 2020 Euros per GJ.

The fossil fuel (coal, oil, gas) price drastically increases in the 1.5 degree scenario due to the rising CO₂ price. The biomass price (liquid biomass like ethanol as an example here) is decreasing in the baseline scenario until the early 2040s, when the prices start increasing again. The prices in the 1.5 degree scenario are higher, due to an increased biomass demand in this scenario, particularly towards the end of the analyzed period.

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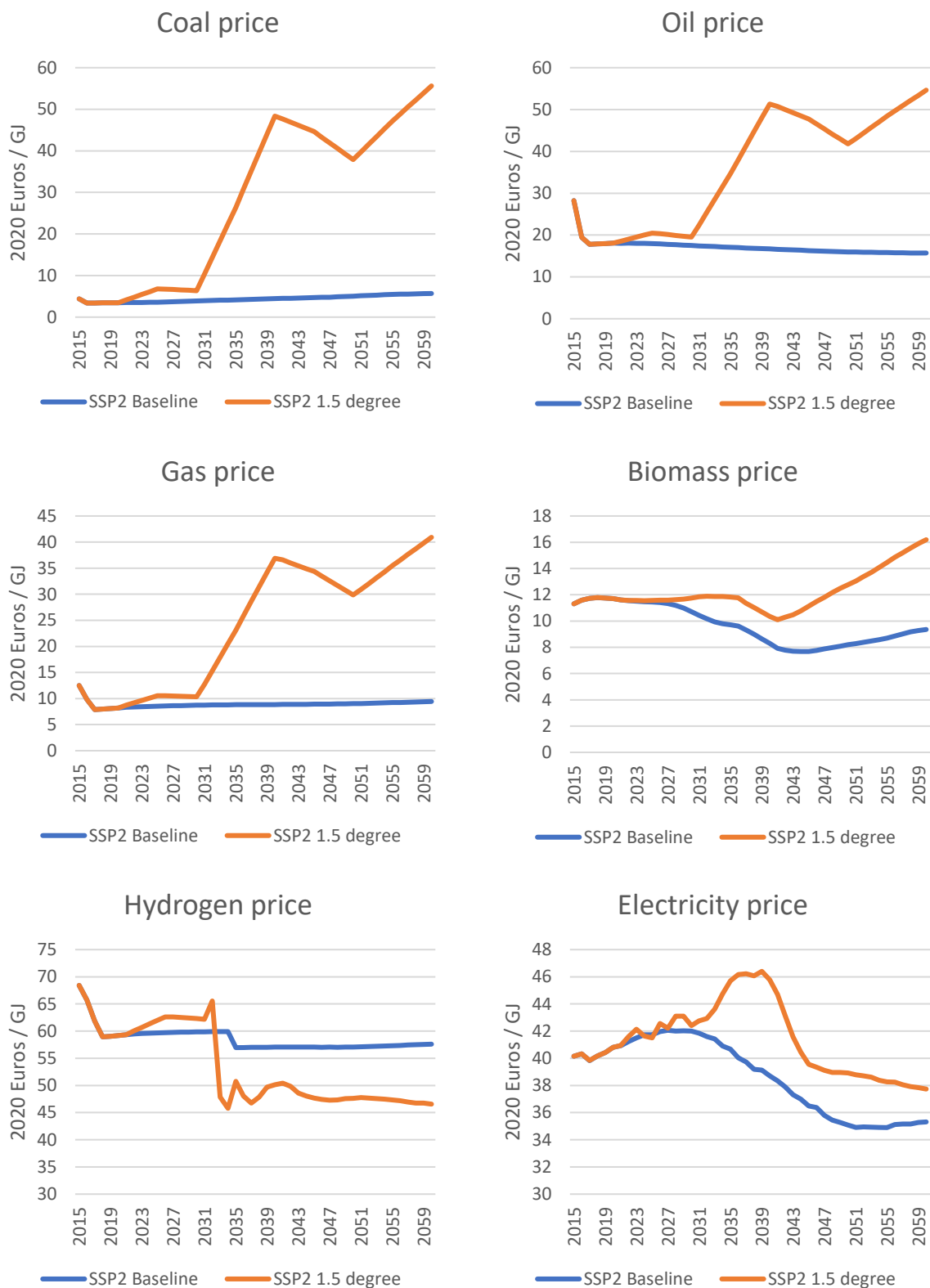


Figure 8: Prices of energy carriers in IMAGE

The electricity prices in the baseline scenario follow a downward trend, while the 1.5 degree scenario experiences a price increase in the shorter term, while transitioning to

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renewables and carbon capture technologies in electricity production (see Figure 22 in Annex 1).

The hydrogen prices are relatively stable, apart from the large price decrease in 2034 when more sustainable hydrogen production routes enter the market in IMAGE.

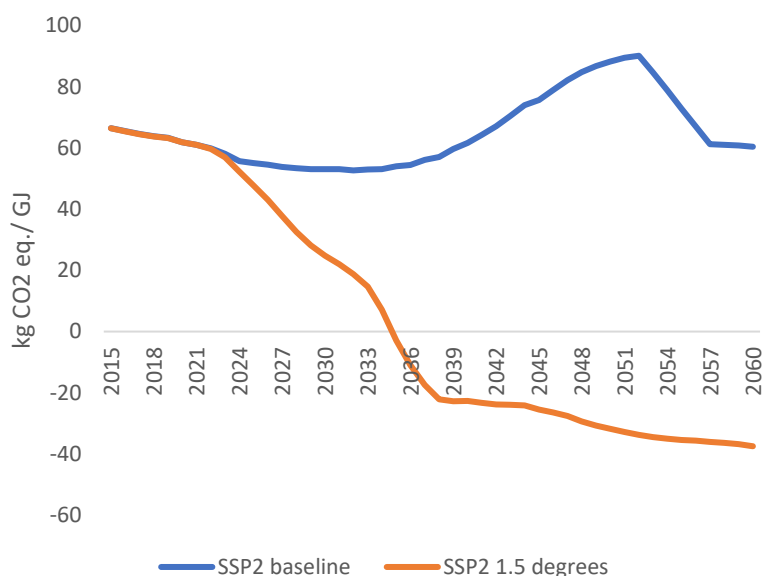


Figure 9: Emission factor for electricity

Because of the switch to renewables the emission factor of electricity (kg CO₂ eq. emissions per GJ, see Figure 9) drastically reduces and eventually even becomes negative due to the use of bio-based carbon capture & storage solutions in electricity production (see Figure 22 in Annex 1).

For Hydrogen, we use emission factors from the IEA (2023), whose Net zero emissions scenario (NZE) seems to largely relate to the SSP2 1.5 degree scenario, while the Stated policies scenario (STEPS) could serve as a proxy for the SSP2 baseline. For the NZE scenario the emission factor of hydrogen reduces from an average of ca. 108 kg CO₂ eq./GJ in 2021 to 8 kg CO₂ eq./GJ by 2050. In the STEPS scenario the emission factor reduces to 92 kg CO₂ eq./GJ in the same period. For consistency, the goal is to eventually use the hydrogen emission factors of the IMAGE model, which we could not obtain yet.

Note

We are also working on including future plastic (polymer) prices. However, plastic polymer price projections are scarce and not consistent with the SYSCHEMIQ scenarios. Hence, we are planning to calculate polymer prices ourselves, by using the energy carrier prices as a basis. This can be challenged, but for the moment nothing better is available. For the quick scan, this is sufficient and most importantly, consistent for a fossil based society. Before the final assessment, an approach has to be developed for a renewable based society.

3.1.5 Summarizing

In this section, we selected a background scenario on the wider socio-economic developments, i.e. the Shared Socio-economic Pathway 2, the middle of the road scenario extrapolating current trends, as depicted by the IMAGE Timer model. For this SSP2 scenario, different CO₂ mitigation variants are available (1.5 and 3.5 °C). Furthermore, the IMAGE Timer model provides us with the energy mix, emissions and price data needed in our SYSCHEMIQ model framework on plastics production and recycling.

3.2 Plastic foreground scenarios

3.2.1 Scenario selection

In discussions with the project partners, we defined the required information on possible future developments of the plastic system, i.e., the foreground scenarios that will be the central topic of this paragraph. Together with the background scenarios (chapter 3.1), these foreground scenarios form the basis of the planned exploration (see chapter 2.4.1). The foreground scenarios have to provide the following input into the SYSCHEMIQ model framework:

- waste volumes;
- waste composition;
- type of collection and sorting of waste streams.

These are particularly relevant inputs for the model PRISM (see chapter 1.1.2). These plastic waste quantities and qualities are believed to be influenced by consumer demand, awareness, perception and behavior, which may be country or even location specific (think of city versus rural areas). Furthermore, they are directly and indirectly influenced by a wide set of policy measures, being for instance (but not exclusively):

- Circular Economy strategies ranging from R0 Refuse to R7 Repurpose;
- Price or taxation policies influencing demand through above R strategies and/or material substitution;
- Other policy measures such as information and knowledge campaigns, nudging behavior in a certain direction;
- Awareness campaigns.

Furthermore, on a more detailed level, foreground scenarios have to provide techno-economic data on different process technologies available in the future for a given scenario. This relates to conditions and parameters of technologies available in a scenario. The model can optimize and decide which technology (combination) is the most cost-effective under the given scenario conditions. Regarding policy measures, one can think of:

- Technology standards and regulation;
- Investment grants;
- Material (circularity) regulations (quantity and quality);
- Pricing (plastics), taxes (e.g. plastic or CO₂-eq.) and fees (waste).

These types of scenarios with such a wide range of aspects and data covered are not readily available. A few interesting sources for scenarios are:

- Blanksma et al. (2021), *Circulaire kunststofketen in 2050, Scenario's voor een gesloten keten en randvoorwaarden om er te komen (In Dutch) commissioned*

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by the Dutch Ministry of Infrastructure & Water management: here, three backcasting scenarios have been developed, each having its own strategy to become circular. These what-if scenarios have been designed top-down, hence, assuming recycling pathways and yields without any technological detail.

- *SystemIQ, PLASTIC IQ Methodology Document, V2.0_updated May 2, 2021*: here, a few scenarios have been distinguished, viz. Business As Usual (BAU) and System change, where parameters of the system change drastically towards a more advanced, circular system. It's scope is US and it is unclear where it is based upon, we regard it as a what-if scenario. Users of the model can vary a lot of parameters for a specific packaging type such as yields, etc. to design their own plastic circularity strategy for a type of packaging product. Hence, it is a product life cycle approach and not a system dynamics approach.
- *Lase, Irdanto Saputra, et al, How much can chemical recycling contribute to plastic waste recycling in Europe? An assessment using material flow analysis modeling, Resources, Conservation & Recycling 192 (2023)*: here, scenarios are technological pathways (current status quo, Mechanical Recycling, Chemical Recycling and Solvent Based Recycling in various combinations and degrees). Hence, these can be regarded as technologically inspired what-if scenarios.

The scenarios developed by Blanksma et al. (2021, 2022) for the Dutch Ministry of Infrastructure & Water management come closest to our needs and are presented in Figure 10.

	Scenario name	Philosophy	Growth	Collect & sort	Treatment
Transite agenda Kunststoffen REBEL / Min. IenW	Plastic Fantastic PF	Close the loop, "back end"	2.5%	Mixed waste (MSW recovery)	Chemical Recycling
	Reuse Society RS	Slow the loop, "application"	-0.5%	Source separated waste	MR (mono) & CR-mono (mix)
	Precious Plastic PP	Narrow the loop, "front end"	1%	Innovatively sorted streams	High quality MR
InReP	Business As usual BAU	"current situation"	2%	Combi sorted mixed streams	Mediocre quality MR

Figure 10: Example of a what-if scenario set by REBEL developed for the Dutch Ministry of Infrastructure & water management (Blanksma et al. 2021) and extended by the Dutch MOOI InReP project with respect to technological detail (Blanksma, Vink, and Bruijnes 2022)

These scenarios are very high level, what-if scenarios, starting with assumptions on developments. In the InReP project, an attempt was made to enrich these scenarios with consistent narrative assumptions on the collection, sorting and treatment technologies (Blanksma, Vink, and Bruijnes 2022). Furthermore, a BAU (Business As Usual) scenario was added to have a baseline.

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It is valuable to align with such a scenario set, but it still leaves gaps in the scenario data that we need for the analysis within the SYSCHEMIQ model framework.

To our knowledge, complete socio-economic scenarios for the plastic system covering a wide range of aspects from socio-economic parameters to pricing and policies have not been developed so far. Since we need a consistent data set, we want to avoid selecting scenario parameters from many different studies. Hence, the decision has been taken to build the scenarios ourselves in a consistent manner.

3.2.2 Selected foreground scenario set

A major concern of the project partners is that a large number of foreground scenarios and variants is possible. On the one hand, a wide range of scenarios is desirable to tackle the most relevant aspects and complexity needed for learning and understanding the models and systems. On the other hand, it is undesirable to drown in many scenario calculations which hinders from seeing the wood for the trees and which require substantial amounts of time.

The main goal of the quick scan is to develop and test the model framework to learn about the plastic system and refine the modelling for the more advanced and realistic final assessment at the end of the project. Therefore, a simple what-if scenario set to test the model behavior is sufficient for the quick scan.

Hence, it has been decided to select a few simple principles and build the foreground scenarios ourselves around these in a consistent manner. The main relevant scenario principles that we derive from the scenario studies above, for instance from InReP, are:

1. Plastic waste qualities
2. Plastic waste quantities
3. Plastic waste policies

Since technology is endogenous to our model framework, we do not consider this as a scenario principle for the moment.

Principle 1. Plastic waste qualities

Regarding plastic waste quality, we see that the degree of mixing of plastic waste types is key for further treatment and the quality of the recycled products being produced. Of course, contamination is another related issue, but this is tackled partly by the degree of mono-streams versus mixed streams. More detailed assessments of contamination are reserved for the next stage when more realistic scenarios are being made.

Hence, we designed three simple what-if scenarios:

1. Baseline: extrapolation of the current plastic mix
2. Mixed plastic waste policy: the plastic packaging types and their material composition remain the same as in the current situation. Most plastics are collected in a mixed stream and post-separation increases compared to the current situation in the Netherlands (see chapter 5.2).

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3. Mono-plastic waste policy: packaging is designed for recycling, leading to more mono-plastics and improved separate collection compared to the current situation in the Netherlands (see chapter 5.2).

The underlying assumptions of these scenarios can be derived from the InReP scenarios, where a detailed analysis has been made of what these shifts mean in terms of collection and sorting of the different waste streams and their polymer composition (Blanksma, Vink, and Bruijnes 2022; Harmelen et al. 2022). The mixed plastic policy corresponds to the “plastic fantastic” scenario in InRep and the mono-plastic waste policy to the “precious plastic” scenario, see chapter 3.2.1.

For The Netherlands, we apply the respective material compositions of InRep (Blanksma, Vink, and Bruijnes 2022; Harmelen et al. 2022) to the projected waste volumes. For Germany (North Rhine-Westphalia) and Belgium, we have country specific plastic waste data from the KPMG study (KPMG 2023). In the baseline scenario, these current mixes of plastic waste remain the same over time and are applied to the projected waste volumes. For the mixed plastics and the mono-plastics scenario, we apply the relative shares of mixed and mono-streams and their respective composition from InRep to the country specific streams and composition. It means that by 2050, country mixes in the mixed plastics and mono-plastics scenarios are the same for all three countries. The volume growth is country specific though, see chapter 4.1.

Principle 2. Plastic waste quantities

It is both hard and easy to assess future plastic waste quantities. It is hard to make realistic scenarios which include all factors behind plastic waste generation, including changes in design, behavior and policy, but it is relatively simple when current trends can be extrapolated. Since we are primarily interested in a baseline for the quick scan, we chose to take the simple approach and estimate a waste growth based upon the correlation with GDP and population. In chapter 4.1.2 this method is explained in detail. This growth depends on GDP and population forecasts and is country dependent and even region specific (for as far as it is related to population). This is an important factor to account for.

For the quick scan, it is optional to vary the growth in a sensitivity analysis (e.g. lower or higher growth) if the results give indication that volume is an important factor.

Principle 3. Plastic waste policies

The most difficult factors to account for in the scenarios are the plastic waste policies. In our view, plastic waste policies determine the context for actors (producers and consumers and many more) in which they make decisions on products, materials and technologies and show specific behavior. In this sense, policy measures are amongst the most important elements in the model framework. It is therefore of the utmost importance that policy measures are being prepared and arranged in more or less coherent sets (See Diepenmaat and Kemp, 2023, deliverable WP 1).

Any policy starts with setting policy targets. We will focus here on planet features of sustainability. Firstly, climate change policies will influence the whole plastic system massively, not only by pricing but also by target setting. Climate change policies regarding the energy system, land-use and CO₂ pricing are included in the background scenario (see chapter 3.1). For the plastic sector, policy packages start with the objective to strive for 0 greenhouse gas emissions. In addition, we assume also that each policy package has the intention to strive for 0 fossil resources. Secondly, a high level of circularity could be another target, but this is more difficult to measure; we should distinguish waste to fuel, waste to chemical and waste to plastic, for instance. This is feasible in the model framework at hand. Please note that full circularity is impossible to realize, both for thermodynamic and practical reasons. Therefore, a third long term target might be the wish to avoid irreversible pollution of our biosphere, for example by leakage (Bruijnes et al, The State of Sustainable Packaging). However, at the moment our models are not capable of addressing leakage in sufficient detail.

Given these policy targets on climate and circularity, the question is which type of policy measures should be included in the 3 foreground scenarios. Therefore, the SYSCHEMIQ WP7 partners brainstormed about a list of policy measures which could in one way or another influence the plastic waste treatment.

The policy measures should be consistent with the scenario narrative. Therefore, we distributed these policy measures over the three scenarios. When conducting the quick scan, it will become clear to what extent the circularity and climate targets in the scenarios will be reached by these selected packages of policy measures. Then further measures can be added in the final assessment to fill potential gaps to the climate and circularity goals.

Foreground scenario overview

The three resulting what-if foreground scenarios are summarized in Table 3. For each scenario, also preliminary policy measure packages are presented, which will be further developed in cooperation with SYSCHEMIQ work package 1 on governance.

The baseline policy package reflects as much as possible current policies but also improvements of the current approach in order to (try to) reach the policy objectives on circularity and climate. Hence, a mix of policy options is considered improving current recycling, by e.g. Design4Recycling, innovative sorting of both pre- and post-consumer waste, more deposit and Diftar (Differentiated Tariff system) and also

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banning incineration (that is, only treatment losses are allowed to be burnt or used to produce hydrogen).

The mixed plastic policy is mainly focused on recycling of mixed bulk plastics. For that, post-consumer sorting is needed in combination with Chemical Recycling (CR) standards and input quality standards as well as investment grants. Also here, incineration is banned.

In the monoplasic policy scenario, D4R is enabling monoplastics use, innovative sorting can be either at pre- or postconsumer level, mechanical Recycling (quality) standards will be introduced, as well as more deposit systems and Diftar plastic waste systems.

For the final assessment more elaborated scenarios will be designed that include a combination of these measures more optimized for the climate and circularity targets. Those new scenarios will also consider additions from other work packages on governance and technologies.

Table 3: Characterization of the three designed plastic waste foreground scenarios

	Baseline / Current plastic mix	Mixed plastic policy	Monoplasic policy
Short description	Current plastic mix	Mixed plastic waste due to (lack of) interventions in design & post-consumer separation	Several monoplasic waste streams due to interventions in design & separate collection
Policy package	<u>CE + Climate targets</u> + D4R; innovative pre-post-consumer sorting + incineration ban + Diftar plastic waste fee + Deposit systems	<u>CE + Climate targets</u> + Bulk post-consumer sorting + CR standards + Quality standard + incineration ban + Technology investment grants	<u>CE + Climate targets</u> + D4R; innovative pre-post-consumer sorting + MR / Quality standards + incineration ban + Deposit systems + Diftar plastic waste fee

3.2.3 Summarizing

In this section, we designed a simple and consistent set of foreground scenarios based upon the three main principles for plastic recycling, viz. plastic waste qualities, plastic waste quantities and plastic waste policies. In relation to these, the key factor in the plastic (waste) system is the level of mixed or monoplastics. Hence, we chose the level of mono- or mixed plastic for depicting three what-if scenarios, i.e.:

1. Baseline: extrapolation of the current plastic mix
2. Mixed plastic waste policy
3. Mono-plastic waste policy

Finally, we designed a first list of accompanying policy measures for each of the scenarios.

3.3 Selected set of background and foreground scenarios for the Quick scan

Integrating the background and foreground scenarios results in nine possible combinations. In order to limit that to five scenario combinations, we calculate the background scenario impacts only on the plastic baseline scenario. This provides us with information on how climate policies and the related changes in the energy system impact the CO₂-eq. emissions of the analyzed plastic waste system. Next, the impact of CE targets will be calculated by applying consistent policy measure packages. This will be done in the three foreground scenarios, taking only the SSP2 1.5 degree climate target scenario as background.

In addition, it is optional to vary the growth in a sensitivity analysis (e.g. lower or higher growth) if the results give indication that volume is an important factor.

Table 4: Selected background and foreground scenarios for the quick scan analysis

		FOREGROUND SCENARIOS		
B A C K G R O U N D S C E N A R I O S		Baseline	Mixed plastic policy	Monoplastic policy
	SSP2 3.5 °C No climate target	Current service growth; current plastic mix; fossil dominated energy mix; no CO ₂ price		
	SSP2 1.5 °C Climate target	Current plastic mix; renewable & CCS energy mix; CO ₂ price		
	SSP2 1.5 °C Climate + CE policies	Current plastic mix + CE policies	Mixed plastic due to (lack of) interventions in design & post-consumer separation + CE policies	Several mono-plastic due to interventions in design & separate collection + CE policies
	Policy measure package	CE + Climate targets + D4R; innovative pre-post-consumer sorting + Forbid incineration + Diftar plastic waste fee + Deposit systems	CE + Climate targets + Bulk post-consumer sorting + CR standards + Quality standard + Forbid incineration + Technology investment grants	CE + Climate targets + D4R; innovative pre-post-consumer sorting + MR / Quality standards + Deposit systems + Diftar plastic waste fee

Optional: sensitivity analysis on low and high growth of waste

4 Structure and methodology of PRISM - GIS model

4.1 Introduction

Important aspect of plastic waste recycling is the geographical availability of plastic waste streams. This is important for answering questions on the available potential of plastic waste for a specific recycling plant, albeit a mechanical recycling or a pyrolysis plant. This may be relevant for a large scale steam cracker such as at Chemelot, exploring feedstock availabilities. In our modelling framework, we aim to explore possibilities for system optimization, including transport infrastructure and costs as well as plant sizes.

As a first step, we developed a GIS tool to assess and visualize the geographical distribution of waste potentials in the ARRA region. This chapter reports on the GIS methodology and data sources applied, in the first part on plastic waste and in the second part on biowaste. It concludes with a snapshot on the GIS tool itself.

4.2 Method for projecting plastic packaging wastes per NUTS2 region

We analyzed the historic relationship between plastic packaging waste generation and socioeconomic parameters (GDP, population) to develop a linear regression model that provides projections of future plastic packaging waste amounts and their spatial distributions. Based on this data we developed a GIS browser tool that explores changes in waste amounts and compositions over time and different scenarios.

4.2.1 Data sources

The historical plastic packaging waste on national level is sourced from Eurostat (2023), which contains *"any packaging or packaging material covered by the definition of waste in the Waste Framework Directive 2008/98/EC, excluding production residues."*, including packaging waste from household, commercial or industrial activities. Historical GDP (NAMA_10_GDP) and population data (DEMO_GIND) were also taken from Eurostat and are available down to NUTS 3 level.

Eurostat (2023b) also provides projections on population development down to NUTS3 level (table PROJ_19RP3). Long-term (up to 2060) GDP projections are not available on Eurostat. Instead, national OECD projections are used (OECD 2023). To align the OECD projections with historic GDP data from Eurostat only the relative growth from OECD was taken and used for GDP projections based on Eurostat data as starting point. The collected GDP and population data, both historical and projected is shown in Figure 11 and Figure 12.

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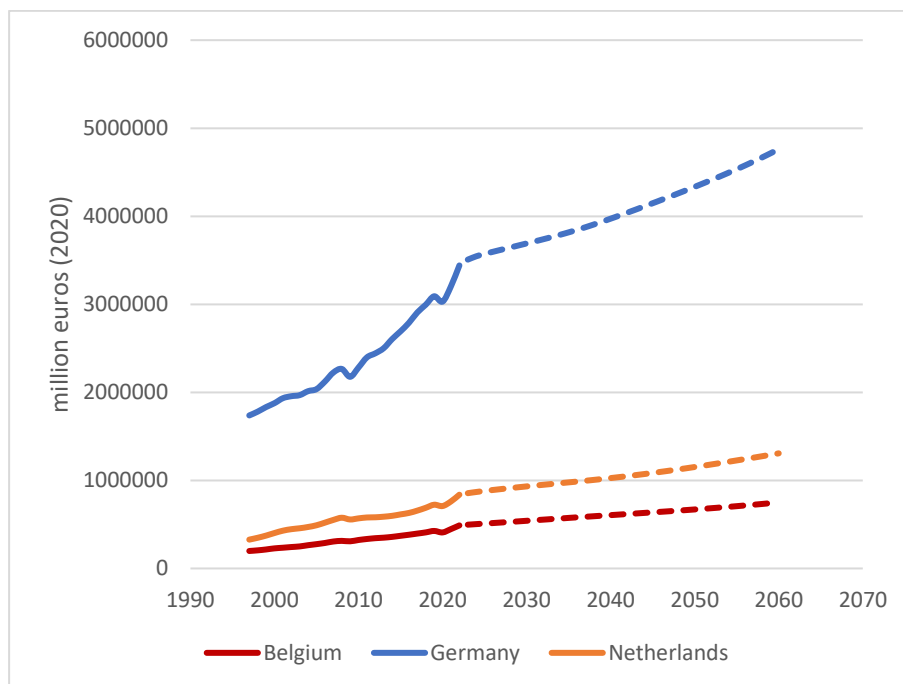


Figure 11: Historic and projected GDP based on Eurostat and OECD data

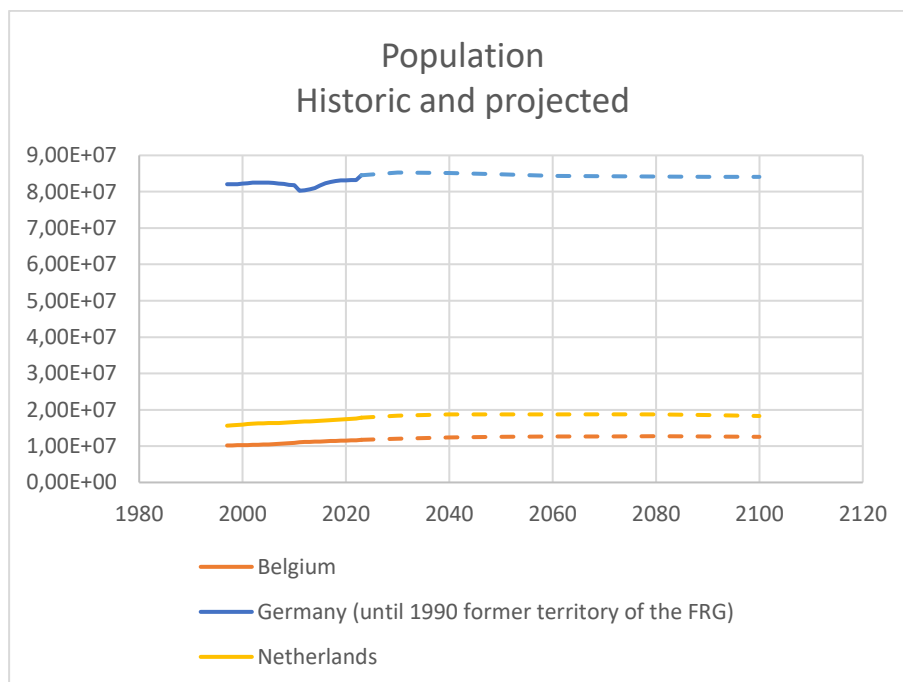


Figure 12: Population including projection from Eurostat

4.2.2 Model for projecting future plastic packaging waste amounts

Comparing the historic plastic packaging waste generation per capita with historic GDP/cap (Figure 13) reveals the rate in which plastic packaging waste follows an increase in GDP/cap, which is stronger in Germany compared to Belgium and the Netherlands. This is probably due to the fact that historic GDP growth in Germany was smaller than in Belgium and the Netherlands.

D7.1 Scenarios for plastic waste generation

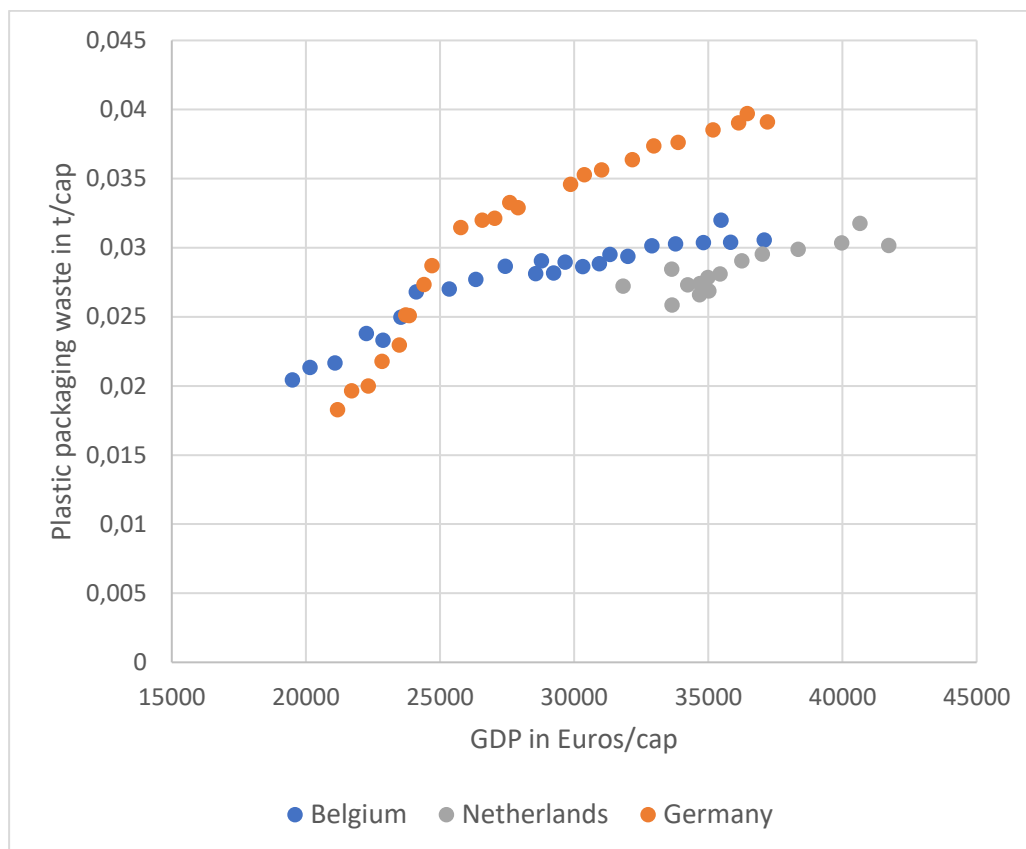


Figure 13: Historic relationship between plastic packaging waste per capita and GDP/capita (1997-2020)

This data was used to obtain a country specific estimator, which allows for projecting plastic packaging waste as a function of GDP and population projections. We assume a logistic growth relationship between plastic packaging waste generation per capita and GDP per capita. We selected the formula below since it proved to best match historical developments and expected behavior, i.e., that plastic demand and related waste generation levels off with higher GDP per capita.

$$\text{Plastic packaging waste generation} = \alpha \cdot e^{\frac{-\beta}{\text{GDP/capita}}} \cdot \text{population}$$

Where α and β are country specific. These parameters are fitted to historical data via a linear regression. The collected fitting parameters are:

	BE	NL	DE
Alpha	0.049	0.055	0.100
Beta	16041	23602	32646

Figure 14 shows that historically, plastic packaging waste has a good correlation with GDP/cap development and that our model simulates the historic patterns reasonably well. For the Netherlands there seem to be outliers in the data before 2006. Therefore, these earlier years were disregarded in the regression analysis. We could not identify the reasons for this data discrepancy (probably a definition change).

D7.1 Scenarios for plastic waste generation

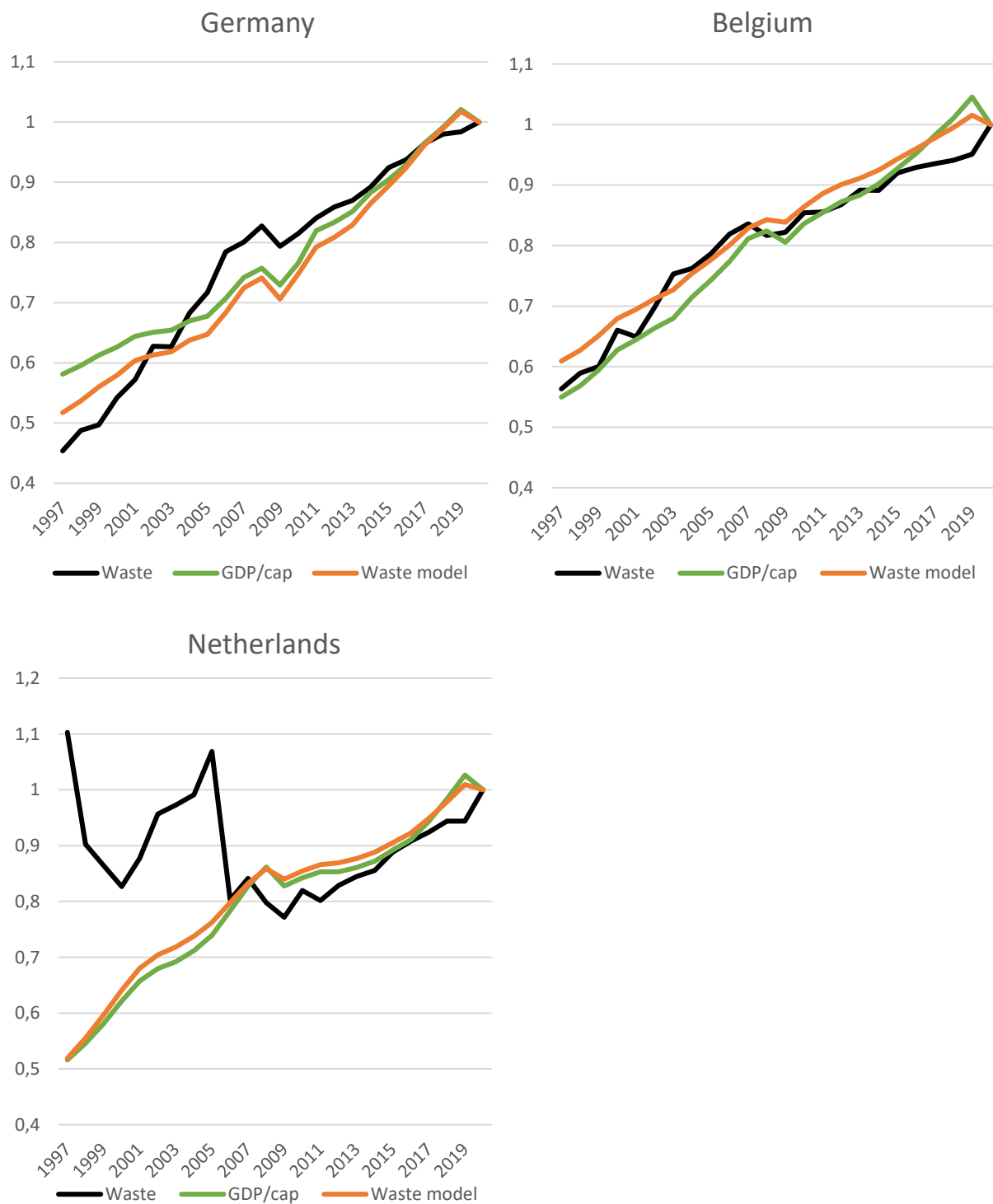


Figure 14: Comparing the relative growth (compared to 2020) of historic plastic packaging waste, GDP/cap, and the waste model

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4.2.3 Adapting the waste projections to NUTS2 level

Due to the regional focus of our analysis the GIS browser tool is supposed to display the data at NUTS2 level (equaling the provinces in the Netherlands and Belgium and government districts in Germany).

With the now known expected plastic packaging waste, the amount per NUTS2 location can be calculated. For this, the country specific alpha and beta is used. The regional GDP per capita is calculated using the relative GDP for the region (to the whole country) and the projected population of that specific region and time frame.

However, historic plastic packaging waste data is only available at national level. Thus, we assume that the historic relationship between plastic packaging waste and GDP/cap of the national level (and the resulting coefficients alpha and beta, see previous chapter) also applies to regional level. Hence, we use the formula and coefficients of chapter 4.2.2 with regional population projections from Eurostat and regionalized relative GDP projections for OECD.

Regional population projections (NUTS2) from Eurostat exist and are used for the regional projections. However, since the long-term GDP projections are only available on a national scale, we use the average GDP shares of the NUTS2 regions of the period 2012-2021 to break down the projected national GDP numbers. Therefore, we are assuming that the historic relative NUTS2 GDP shares will stay constant over time. Analyzing the historic regional GDP data from Eurostat reveals that the relative GDP shares of the NUTS2 regions compared to the national GDP indeed remained largely constant, with an average regional change of 0.3% over the available data period (2012-2021), and a maximum of 1.9% for an individual region over the years.

4.3 Projections for biowaste streams

Next to plastic packaging waste, also projections on biowaste streams are included in the GIS browser tool. For this, existing NUTS2 level data and projections from Elbersen et al. (2016) are used. Those are linearly extended until 2060, using the growth rates of Elbersen et al. (2016) of the selected wastes and residues streams, which cover the period 2010 to 2030. We used their baseline scenario data and included the following wastes and residues, aggregated in four categories:

- Biowaste from households and industry:
 - o separately collected vegetal waste from households (we excluded animal and mix food waste, as well as wood waste from households as it can include mercury or tar-based wood preservatives)
 - o vegetal wastes from food preparation and products, including sludges from washing and cleaning, materials unsuitable for consumption and green wastes. They originate from food and beverage production, and from agriculture, horticulture and forestry.
- Agriculture residues: straw, stubbles, and residues from pruning and cutting
- Forestry residues: Primary residues (from logging & thinning) and secondary residues from further processing (e.g. sawdust, sawmill residues), excluding black liquor.
- Landscaping residues: Landscape care wood from trees/hedges outside forests; roadside verge grass

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The data of Elbersen et al. (2016) is already a little outdated and our linear extrapolation of their data until 2060 is a simplification. Nevertheless, the inclusion of these biowaste streams provides an indication on the magnitude of this resource base and it serves as a basis for further improvements.

4.4 The GIS browser tool

Using the regional waste projection results and the plastic waste composition scenarios (chapter 5), a GIS browser tool was created, which allows for a dynamic exploration of the scenario results over time.

All data is being plotted on a so-called choropleth map. Using Python's bokeh library an interactive plot is generated, which could be made available as an online website.

A set of radio buttons is used to select the scenarios. A second set of radio buttons is used to select the waste streams. A glider allows for browsing through the yearly results. The color scale provides an overview of the waste amounts per region, with the darker colors symbolizing the largest amounts. The color scales are individual per waste stream, but it is possible to view all waste streams with a common color scale. When viewing online, moving with the mouse cursor over an area will show a popup with detailed information about that specific region. Figure 15 shows a screenshot of the tool.

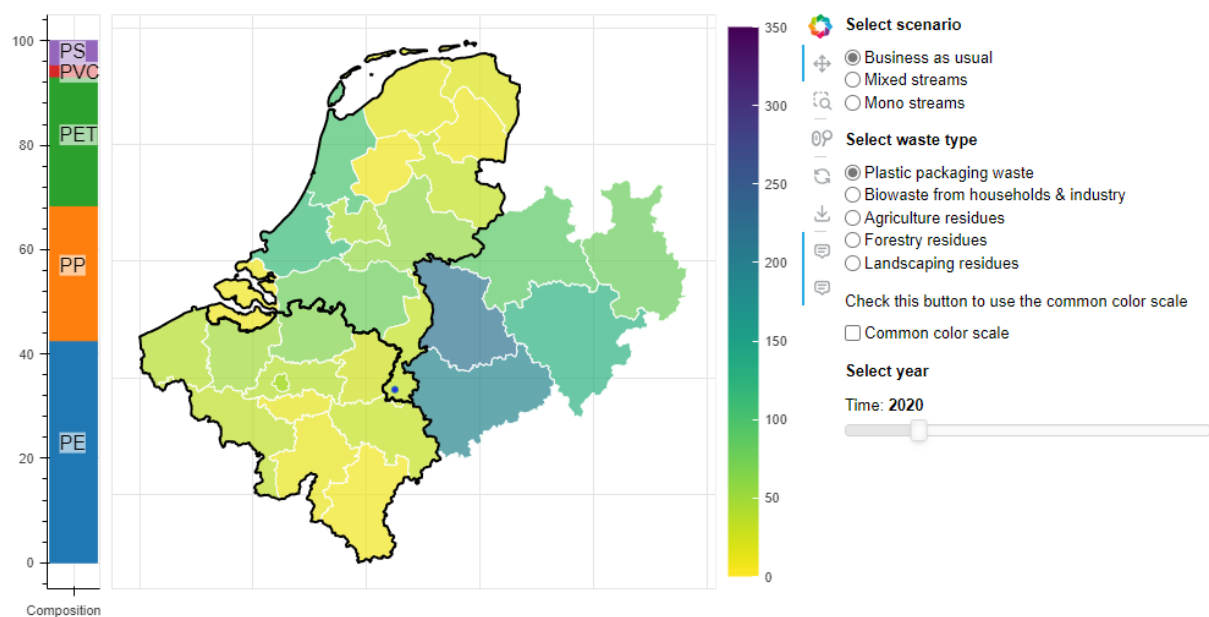


Figure 15: Screenshot of the GIS browser tool

5 Waste projections results

5.1 Introduction

This chapter presents the projections on plastic waste and biowaste and their geographical distribution in the ARRR region as a result of applying the methodology described in the previous chapter.

5.2 Plastic waste

5.2.1 National plastic waste projections

Figure 16 to Figure 18 show the total plastic packaging waste generation projections based on our modeling results, while also showing the historic data from Eurostat. According to our projections, the plastic packaging waste increases by 31% (Belgium), 36% (Netherlands) and 39% (Germany/NRW) until 2060 compared to 2020 values. This increase is largely driven by the moderate GDP growth projections from the OECD (1.13, 1.18% and 0.86% CAGR between 2022 and 2060 for Belgium, the Netherlands and Germany respectively). The relative plastic growth in Germany is higher despite the lower GDP projections, because historically Germany had a stronger growth in plastic packaging waste per GDP/cap.

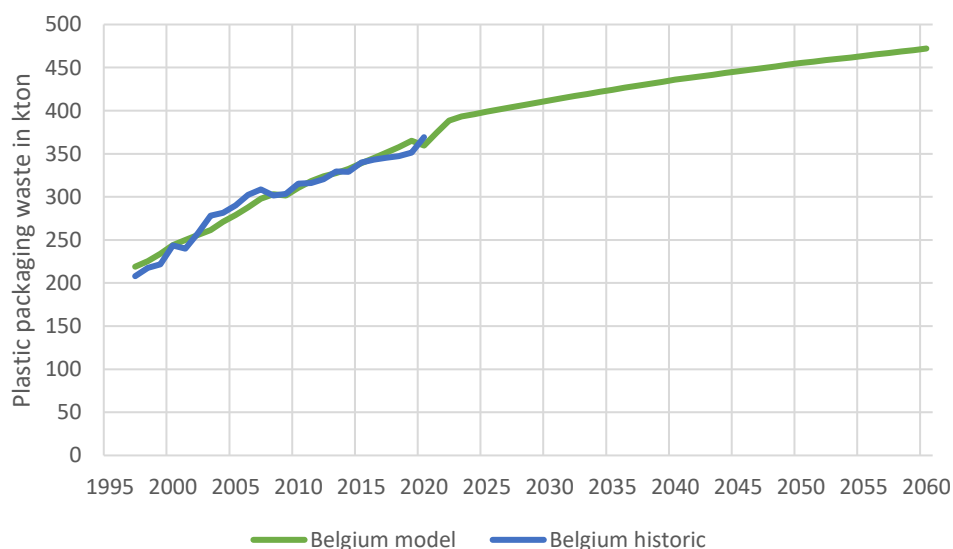


Figure 16: Plastic packaging waste projection for Belgium

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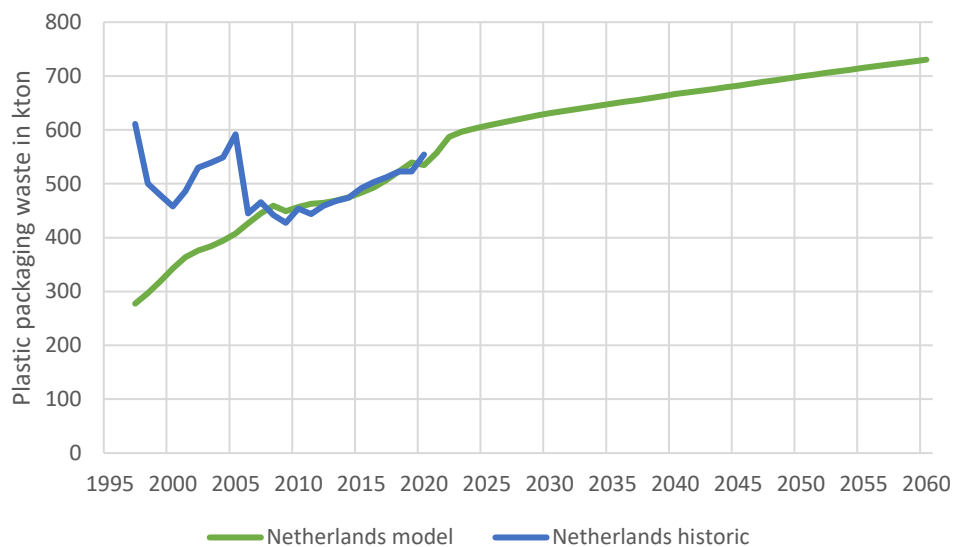


Figure 17: Plastic packaging waste projection for the Netherlands

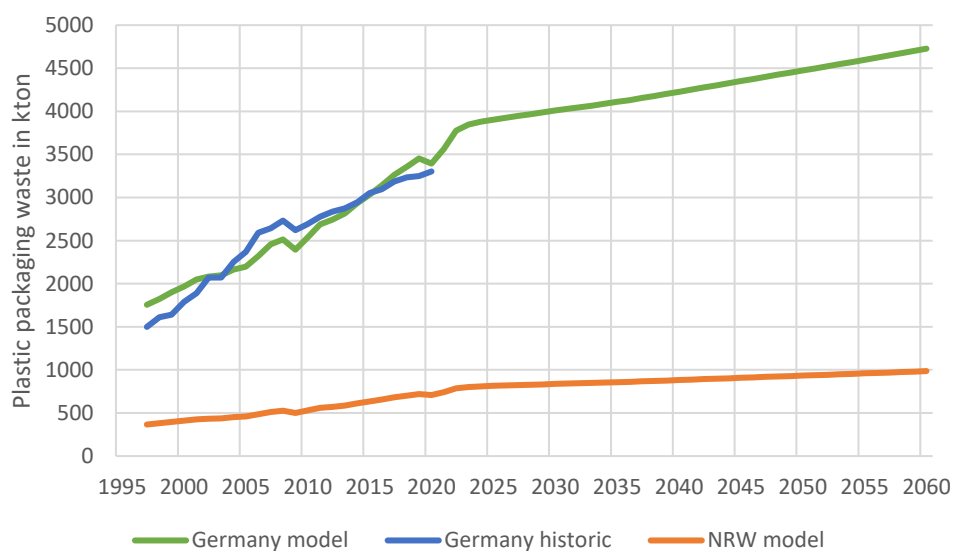


Figure 18: Plastic packaging projection for Germany and NRW

For plastic packaging waste generation in the ARRA region (NL, BE, NRW) the total was around 1602 kton in 2020 and increases by 37% to 2189 kton by 2060 according to our projections. Assuming an average calorific value of plastics of 35 GJ/t (Stegmann et al. 2022), this equals 56 PJ in 2020 and 77 PJ in 2060.

5.2.2 Plastic waste compositions

Not only the absolute amounts of waste potential are important, but also their composition and quality. For that, hardly scenarios are available. The SYSCHEMIQ team has two main sources of data available, i.e., (1) the current country specific plastic waste composition data of the KPMG study (KPMG 2023) and (2) the Netherlands' current and future scenario specific plastic waste composition data of

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the InReP scenarios (Blanksma, Vink, and Bruijnes 2022; Harmelen et al. 2022), see chapter 3.2.1.

The expected future plastic composition in the BAU, mixed plastic and mono-plastic scenario can be based upon the scenarios from the InReP project (Blanksma, Vink, and Bruijnes 2022; Harmelen et al. 2022), developed for the Dutch Ministry of Infrastructure and Water management. However, these results, generated with the PURE model on plastic waste collection and sorting of Wageningen Food and Biobased Research (WFBR), are confidential. A request for use within SYSCHEMIQ has been filed. In case these results do not become available for SYSCHEMIQ, we will make an expert estimation on the development of plastic waste composition in the direction of mixed plastics or monoplastics, where in the mixed plastic scenario, almost all PE plastics end up in a mixed plastic stream and only PET remains separate. In the mono-plastic scenario, the mixed stream will be relatively small while the mono-streams for PE, PP, PET and film increase. For our assessment, we assume that all three countries of the ARRRRA region are transitioning towards these future packaging compositions of the mixed and mono-plastic scenarios by 2050, after which the composition is kept constant.

5.3 Biowaste

Figure 19 shows the biomass waste and residues streams for Belgium, NRW and the Netherlands. Forestry residues are the biggest biomass residue source according to our data selection from Elbersen et al. (2016) (see chapter 4.2). The residues stand in direct relation with the forest areas and forestry industry, which makes them a substantial resource in NRW and Belgium, but less so in the Netherlands. For Belgium and the Netherlands the forestry residues increase by around 20% between 2020 until 2060, while the residues in NRW stay largely constant in the same period. These projections are based on conservative demand growth for stemwood, the national forest management plans, and sustainability constraints for the removal of residues, which considers spatially explicit information on slope, soil type and conservation/protected areas (Elbersen et al. 2016).

Agricultural residues are a relatively constant flow, experiencing an 8% and 15% decrease in Belgium and NRW until 2060, and a 17% increase in the Netherlands. Most straw is coming from cereals, for which Elbersen et al. (2016) expect a decline, which is barely compensated by the slight increase in straw from other crops.

Landscaping residues seems to be more substantial than agriculture residues and biowaste streams from households and industry. They increase by 31%, 64% and 71% in Belgium, the Netherlands and NRW, respectively, between 2020 and 2060.

Biowaste from households and industry (separately collected vegetal waste) are the smallest biowaste- and residue flow in the ARRRRA region. However, they show the strongest growth according to Elbersen et al. (2016) and our extrapolation, increasing by 139%, 168% and 178% in Belgium, NRW and the Netherlands respectively until 2060. This is driven by increasing GDP and population and an assumed increased separation of (bio) waste streams in the EU countries (Elbersen et al. 2016).

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For the ARRRA region in total, the forestry residues increase by 12% from 5.491 kton in 2020 to 6136 kton in 2060, the agriculture residues decrease by 9% from 895 kton to 812 kton, the landscaping residues increase by 48% from 1415 to 2097 kton, and the Household & industry biowaste increase by 160% from 436 kton to 1135 kton.

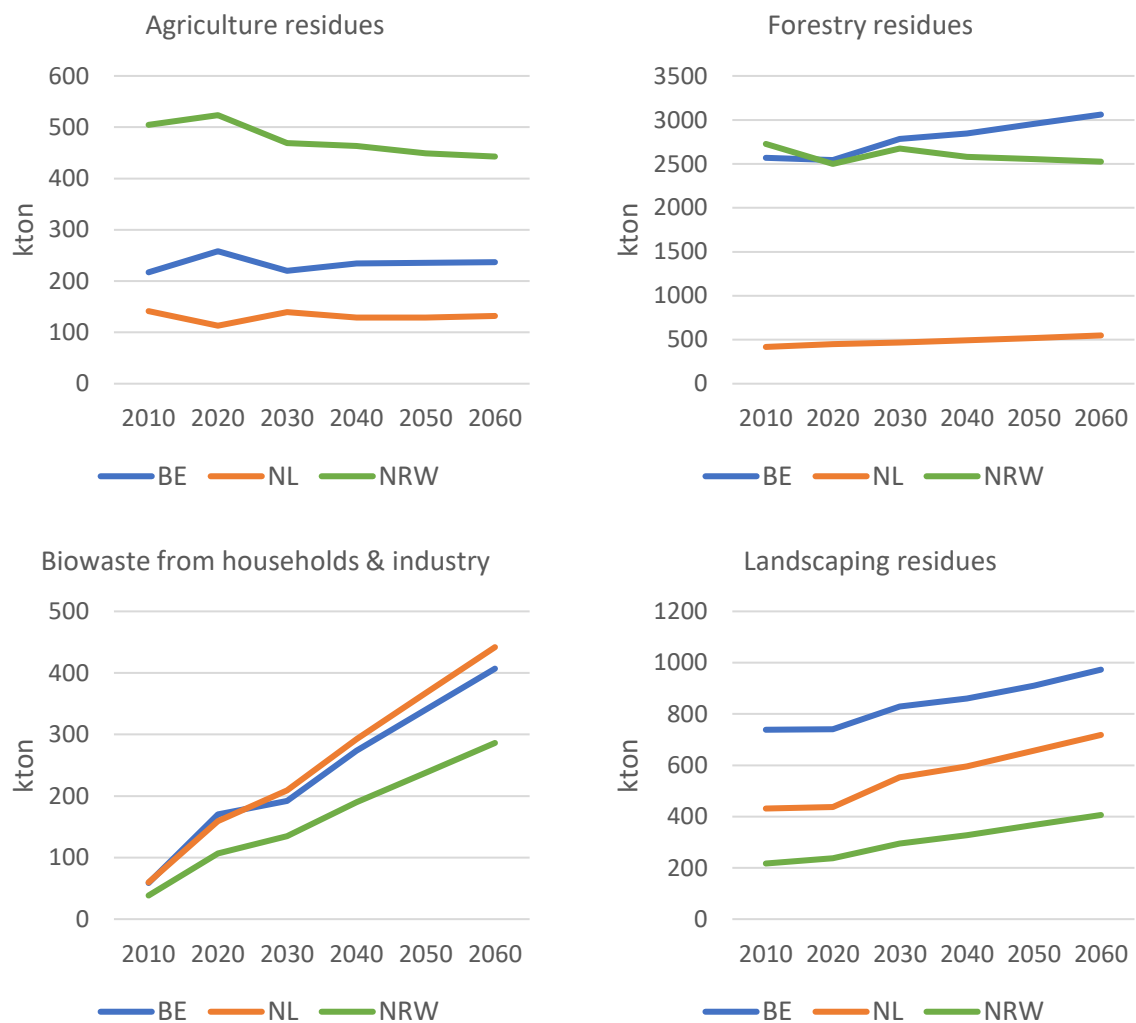


Figure 19: Projections of biomass wastes and residues

Hence, a total of 8.236 kton biomass waste and residues were available in the ARRRA region in 2020, increasing by 24% to 10.180 kton in 2060. Using the lower heating values of Elbersen et al. (2016) we estimate that this equals an energetic biomass wastes & residue potential of 141 PJ in 2020 and 175 PJ in 2060.

5.4 Spatial results for ARRRR NUTS2 regions

Figure 20 shows the regional distribution (NUTS2 level) of plastic packaging waste in the ARRRR region for a business as usual scenario in 2020 and 2060. The waste distribution follows the population density and economic performance of a region (GDP), leading to substantial differences in waste generation. Most waste is generated in North Rhine Westphalia, in particular in the Dusseldorf and Cologne NUTS2 areas.

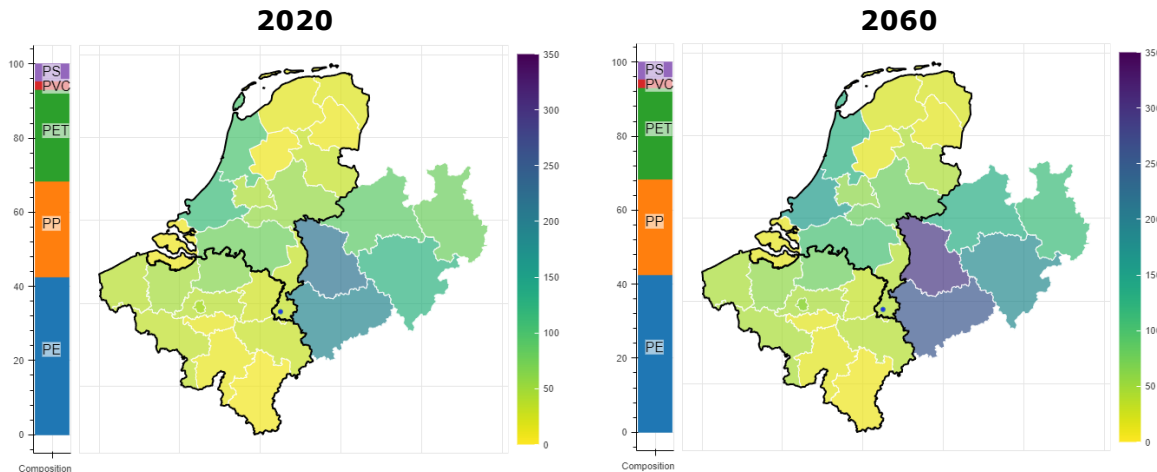
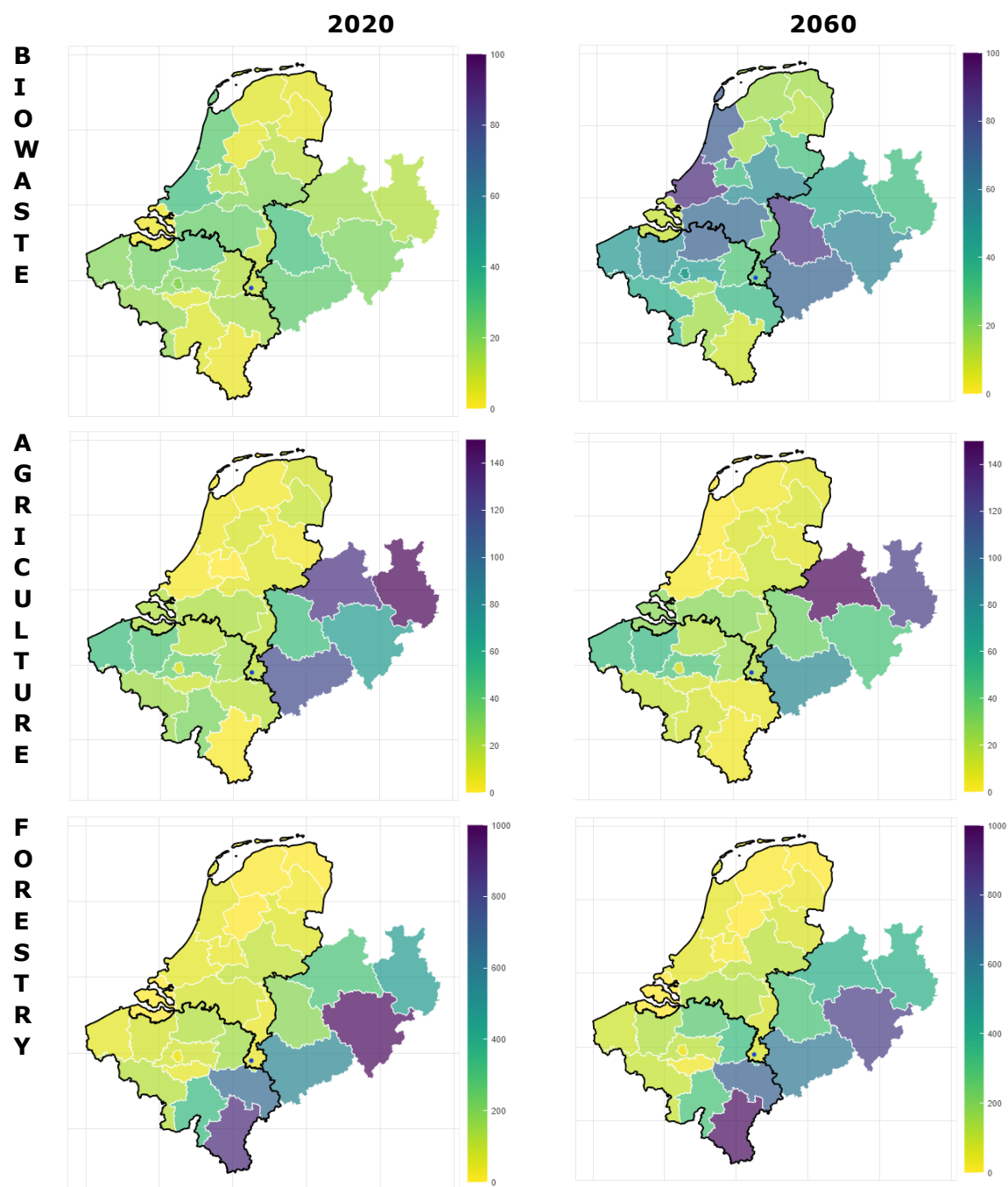


Figure 20: The regional distribution of plastic packaging waste in 2020 and 2060

Figure 21 shows the spatial distribution of the different biomass waste and residues streams. Here even more differences between the regions can be observed. For agriculture and forestry residues NRW is the biggest provider, followed by Belgium and the Netherlands. For biowaste from households and industry the order is the opposite.

The biowaste from households and industry are lowest in North-eastern Netherlands and south-eastern Belgium and highest in the NUTS2 regions South Holland and Dusseldorf. Agricultural residues are strongest in the Dusseldorf NUTS2 area followed by Detmold. In Belgium, West and east Flanders are the dominant regions. Forestry residues are comparably small in the Dutch regions. They are predominantly coming from NRW and the south-eastern Belgium regions, in particular from Arnsberg, Cologne and the Belgium Luxembourg region. Similarly, landscaping residues are mostly in NRW and south-eastern Belgium.

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D7.1 Scenarios for plastic waste generation

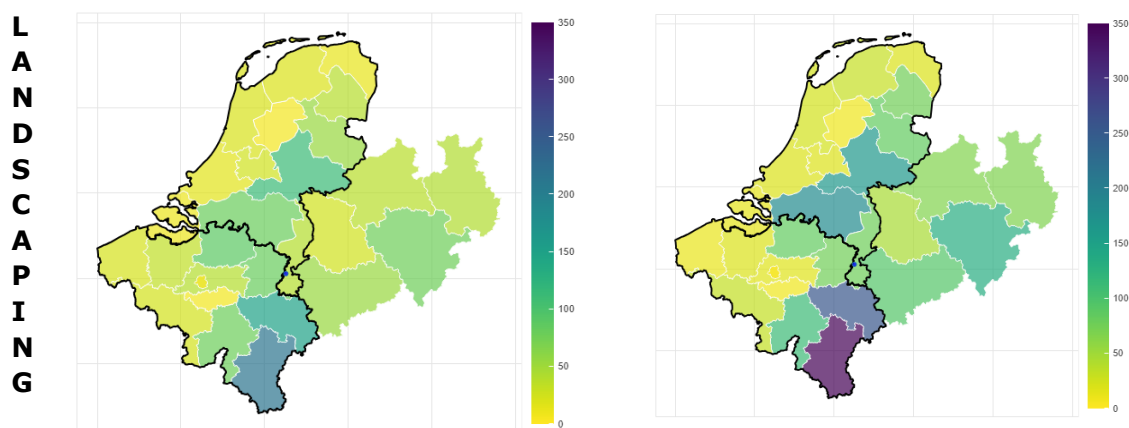


Figure 21: The spatial distribution of biowaste streams

6 Conclusions & next steps

6.1 Methodology

We built a consistent set of foreground and background scenarios to explore and test the plastic model framework designed for SYSCHEMIQ. This was necessary since such a broad and complex scenario data set ranging from GDP and population projections, plastic waste projections on volume and composition, plastic recycling technology options, energy and commodity prices and policy targets and measures with respect to climate and CE is not available, to our knowledge.

Hence, we linked background scenario data on the global economy and energy system (IMAGE / TIMER) and connected these to simple foreground scenarios developed ourselves on waste quantities (by developing a GDP/cap correlation model) and qualities (based upon InReP data) and made these country specific. However, future compositions for industry and office waste are still unknown. Furthermore, we regionalized these to NUTS2 level by using regional population projections (EUROSTAT) and put these in a newly developed GIS visualization tool. For this tool, we did not only assess waste projections but also included biowaste data (EC Outlook of spatial biomass value chains in EU28) and applied a simple linear extrapolation to 2060. Finally, energy and commodity price projections have to be translated into polymer price projections.

These data sets are the backbone of making scenario calculations for three simple foreground scenarios, being Baseline (Current plastic mix), a Mixed plastic policy and a Monoplastic policy scenario. These are combined with two global background scenarios on climate, based upon Shared Socioeconomic Pathway 2 – Middle of the road by IMAGE / TIMER, viz. a 3.5 degree climate scenario (baseline or no climate policy) and a 1.5 degree scenario (reaching Paris agreement).

Still not well developed are the policy measure packages but these will be a major point of attention in the next project years. Coherent policy packages are crucial in both the real world as well as the model framework since circular transitions do not simply 'just' happen. Policy measures are needed to guide, support, stimulate or even enforce certain societal changes for these to happen. A first crude set of policy measure packages has been designed, but it will be very interesting to see how model responses are due to these policy interventions. Here we are entering the interface between scenario thinking and intervention thinking. Moreover, cooperation with WP 1 will be crucial to study for the Quick scan policy responses.

In total, this scenario set of data should be sufficient for making a Quick scan in order to learn about the model framework and the plastic system developments, as a prelude for evaluating a broader set of possible developments within SYSCHEMIQ at the end of the project in a final assessment.

Regarding the GIS tool, we conclude that it is both challenging and enlightening to have NUTS2 level waste data available. The NUTS2 data so far are not highly advanced. However, first steps in showing spatially explicit waste projections as potential resources are highly relevant and are likely to support inclusion of transport

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networks and optimization of plant locations, two aspects that are relevant for the plastics systems of the near future.

6.2 Results

Our studies project that plastic packaging waste generation in the ARRRR region (NL, BE, NRW) will increase by 37% from 1602 kton in 2020 to 2189 kton in 2060. Moreover, a total of 8.236 kton biomass waste and residues were available in the ARRRR region in 2020, increasing by 24% to 10.180 kton in 2060. Biowaste potentials seem substantially larger than plastic waste potentials, depending on the region. Regional waste differences are substantial, since plastic waste densities vary between NUTS2 regions with a factor 10 in the current situation and will increase to a factor 15 in 2060. For biowaste, these variations are even much larger. Hence, location is relevant.

The combined 2020 plastic and biowaste flows are equivalent to around 197 PJ (56 PJ plastic waste and 141 PJ biowaste). In 2019 the Dutch chemical sector consumed 805 PJ of energy and feedstock (excluding refineries) (Oliveira and van Dril 2021), meaning that the **ARRRR** waste streams corresponds to ca. 24% of the **Dutch** demand. Around half of the total energy inputs into the chemical sector are consumed as feedstocks (IEA 2018), which would equal 402.5 PJ for the Dutch chemical sector. Hence, almost half of the chemical feedstocks in the Netherlands amounts to the waste and residue flows in the total ARRRR region that were assessed in this report.

Moreover, by looking into further plastic waste streams and biowaste streams, the resource potential could be larger. Nevertheless, in the future also other sectors (e.g., the energy and building sector) will be looking into waste as a resource, leading to increased competition for such waste streams. Hence, also other feedstock alternatives need to be investigated (primary biomass, carbon capture & utilization) or chemical and plastic demand reduced (e.g., via reuse, redesign and other higher circular strategies). The SYSCHEMIQ project aims to shed some light on the impact of such strategies.

Plastic waste mixes (in terms of polymers) are country specific and will change over time as a result of policy. The quick scan will show the impact of such changes in material composition with a preliminary scenario analysis and lay the basis for further refinement until the final assessment within the SYSCHEMIQ project.

The analysis of the background scenarios of the future energy system showed that price developments are relatively moderate compared to current fluctuations, which is logical since models assume stable market developments. Any profitability calculation is counting on consistent energy and commodity prices, which is particularly a challenge for plastics. This needs to be addressed in a sensitivity analysis.

In the 1.5 degree scenario fossil fuel prices drastically increase, which encourages a switch to renewable electricity and waste and biomass as a resource. This is due to the high price of CO₂ emissions in this ambitious climate mitigation scenario.

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Emissions from electricity production reduce, while the prices increase during the transition phase before decreasing again eventually.

The selected background scenarios show two extremes (no climate policy, 1.5 degree target) which allows for exploring the potential ranges of results in the model. In the next steps additional scenarios could be explored if deemed interesting, e.g. on plastic waste volume and on pricing.

6.3 Next steps

The following next steps will be taken within WP7 Society and business impact assessment:

- Implement scenarios in the PRISM & CIMS models
- Improve material composition assumptions, making them specific for Belgium & Germany.
- Conduct a first quick scan with the models using the scenario data of this report.
- Afterwards prepare more and more refined scenarios, based on lessons learnt and work from other work packages (e.g., WP1 on governance and WP6 on thermos-chemical recycling)

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Annex 1

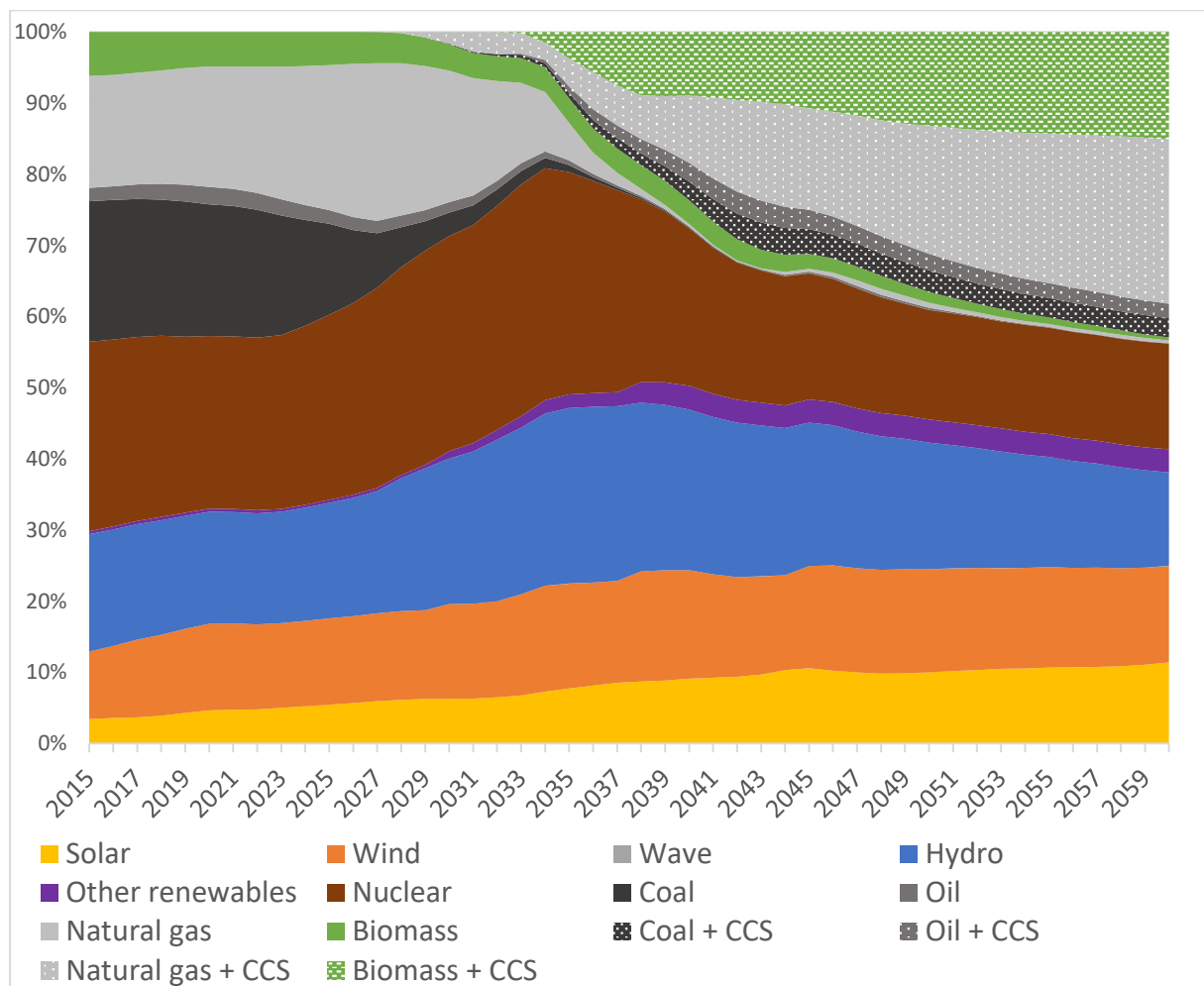


Figure 22: Electricity shares by production technology in Western Europe for the SSP2 1.5 degree scenario