THE CARBON MANAGERS

Modelling possible pathways for the EU chemical sector's transition towards climate-neutrality and circularity with iC2050

cefic

Section 1

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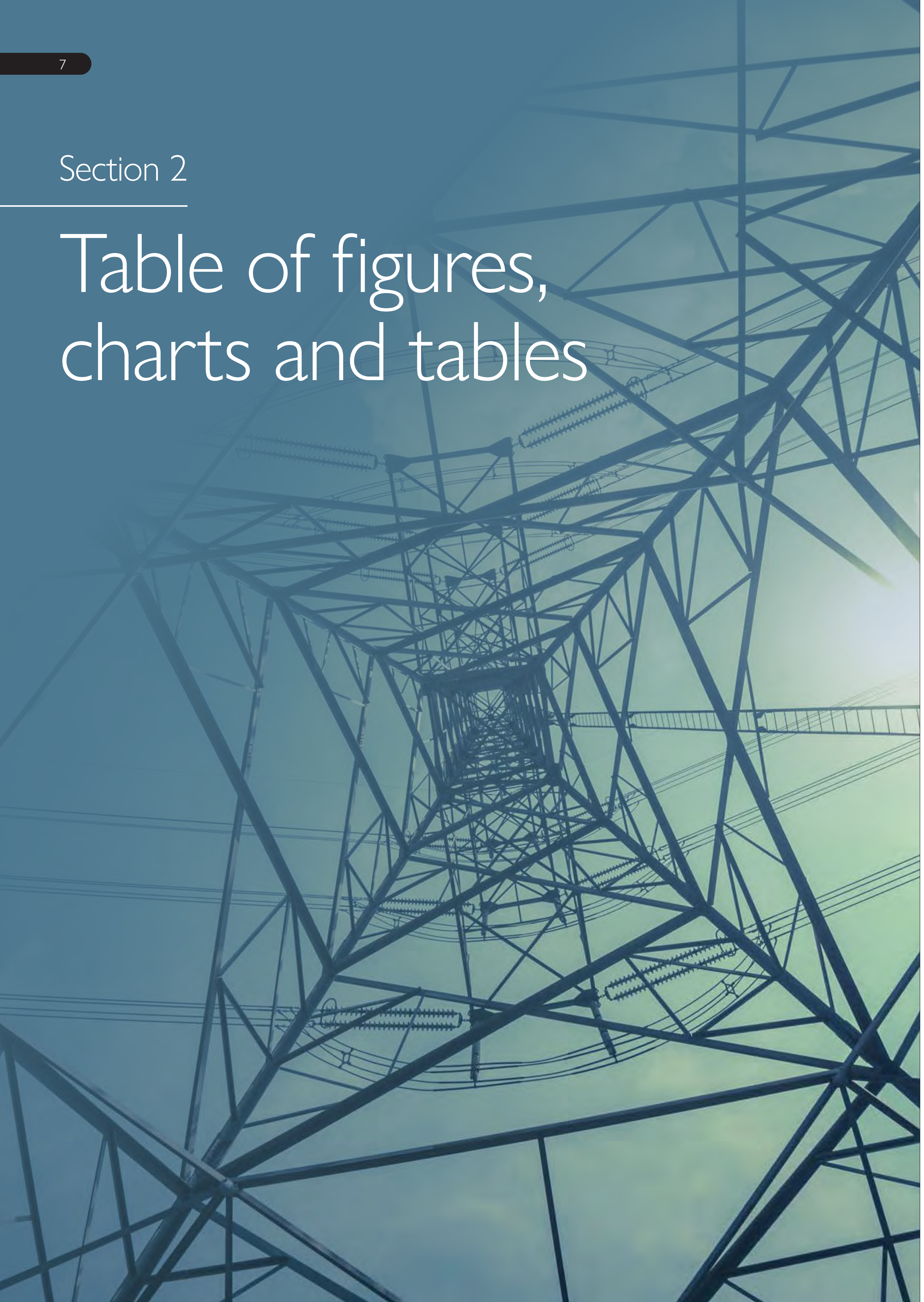

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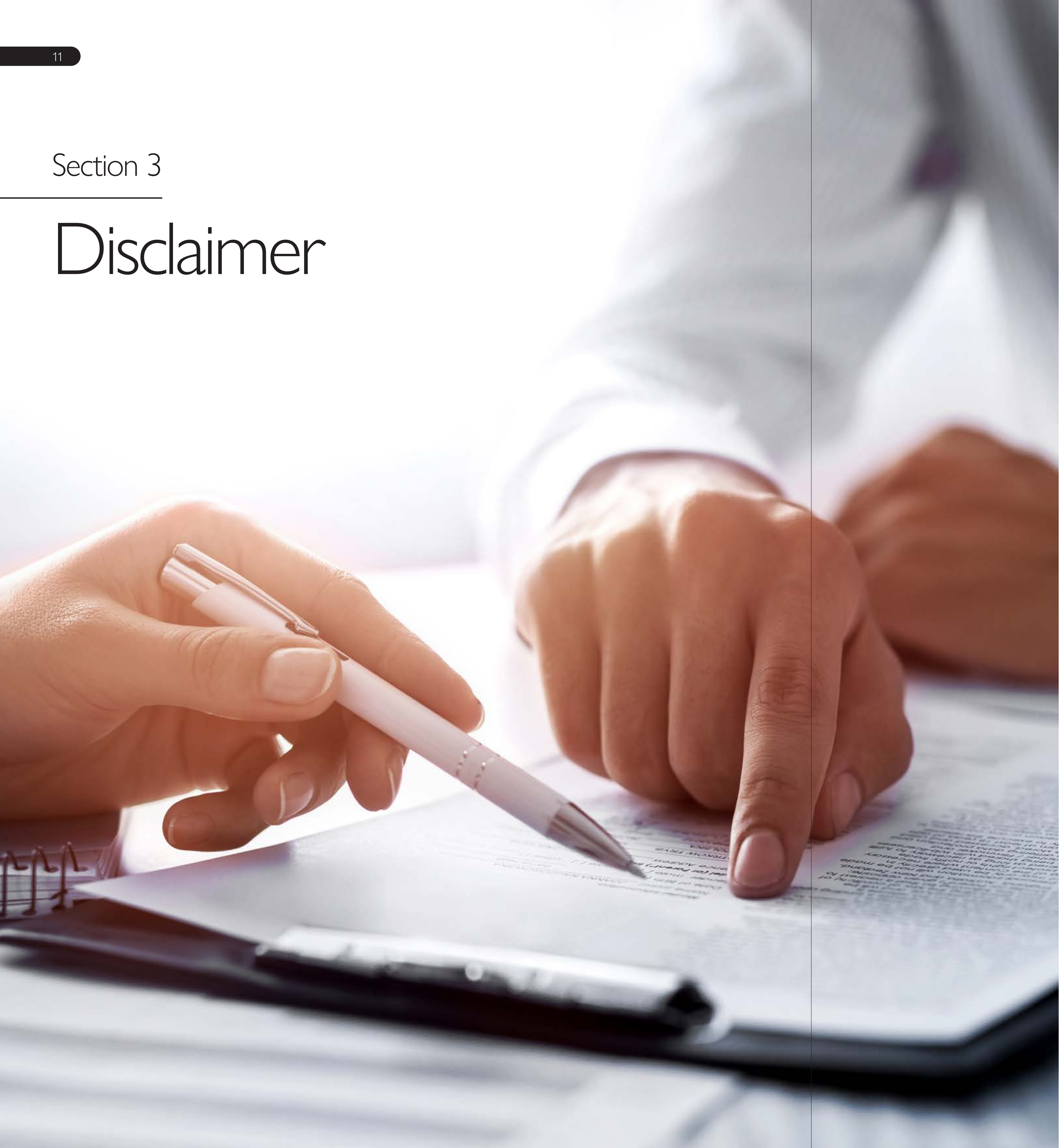

This report was prepared by Cefic[1], the European Chemical Industry Council, with the support of its iC2050 model. Views and assumptions expressed in this report do not necessarily reflect the official position or opinion of Cefic or its members.

The iC2050 modelling tool enables stakeholders to visualise a wide number of potential scenarios towards climate-neutrality by 2050 based on a simplified set of input assumptions and output parameters. The tool is not designed nor intended to forecast future demand or volumes of the sector.

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Section 4

Foreword by the Cefic President

In an era of unprecedented change, EU chemical companies find themselves at the forefront of a rapid transformation. The ambition is clear: become climate-neutral and circular by 2050. The European Scientific Advisory Board on Climate Change underscores the urgency of the situation, recommending net emissions reductions of 90-95% by 2040 compared to 1990 levels.

Our industry faces monumental expectations from every corner: from investors, consumers, regulators, and civil society. To ride this wave, chemical companies and the sector at large need to implement robust transformation plans.

Cefic has spearheaded numerous initiatives to fortify the sector in this endeavour. It initiated an extensive dialogue with all stakeholders, to mark the first steps of the journey. The Mid-Century Vision report titled 'Molecule Managers' in 2019 set the stage for a profound conversation about the future of the chemical industry and its pivotal role in constructing a prosperous and sustainable Europe by 2050. Building on this foundation, Cefic took part in the elaboration of the Transition Pathway for the chemical sector by the European Commission in 2023.

The iC2050 model is at the heart of our efforts. It is a powerful tool meticulously designed to reflect the complexity of chemical value chains and it allows us to explore and quantify the implications of achieving climate-neutrality and circularity. This model serves as a compass, aiding decision-makers both within and beyond the industry to comprehend, and objectively evaluate the magnitude of change. iC2050 is not a crystal ball predicting the future; it is a mechanism to understand the consequences of our actions — or inaction — by showing their natural outcomes. It unveils the intricate connections between economic, technological, and societal facets of this transformative journey.
When it comes to the role that carbon plays within industry, the chemical sector is clear about one thing: carbon is and will remain at the very heart of many of our processes. It is an essential element of many chemicals, as it is for most products society is using. Adopting a holistic value-chain approach, iC2050 illustrates the chemical industry's role as a "carbon manager" and an indispensable contributor to reinstating sustainable carbon cycles through heightened resource circularity.

As you delve into this report, I hope you will appreciate the insights it offers and embrace the profound impact it promises. Enjoy the reading!

Section 5

Executive summary

The **EU Climate Law,** which charts Europe's journey towards climate-neutrality, will be highly transformative for the chemical sector, including its wider ecosystem and value chains. The sector faces the dual challenge of **reducing greenhouse gas (GHG) emissions** and **transitioning towards circularity.** To stay within planetary limits and lessen its impact on climate and resources, the chemical industry must shift from a linear model to a circular one. There are **three main circular carbon sources** to consider: biomass, recycled waste, and carbon dioxide (CO_2) captured from emissions or directly from the air. Each source comes with its own set of challenges, such as limited supply, higher costs, or extensive infrastructure requirements.

The **iC2050 model** is a unique tool designed to sketch and demonstrate feasible pathways towards a climate-neutral and circular chemical industry. It generates pathways to aid in pinpointing cost-effective strategies for reducing emissions and informs chemical companies' strategies by placing them in a wider sectoral context. Its objective function is to minimise the Net Present Cost (NPC) of production in the chemical industry while meeting the GHG abatement and sustainable carbon targets. Based on projections of future demand for chemical products up to 2050, and a description of the future operating conditions for the sector (defined by the user), the model computes the corresponding GHG abatement trajectory. The scenarios and sensitivities presented in the report are developed using various data sources and assumptions, collected through surveys, workshops, and bilateral discussions with experts. The model operates under the assumption of perfect foresight, ensuring optimal investment decisions, and calculates costs using a 2019 Euro ($€_{2019}$) value. The model's framework includes an objective function, sets, parameters, decision variables, and constraints, all integrated within GAMS (General Algebraic Modelling System).

2019 is the starting point for all scenarios. During that year, the European chemical industry produced 281 Million tons (Mtons) of chemicals and the sector's total GHG emissions were around 329Mtons of CO_2 equivalent ($CO_{2\text{-eq}}$). Crackers play a central role, producing essential chemical building blocks while consuming most of the sector's feedstock.

The "Base Case" scenario

As a first step for our research, a "Base Case" scenario has been developed to serve as a benchmark for examining the European Union (EU) chemical sector's transition to climate-neutrality. This "Base Case" scenario is a "snapshot representation" based on current publicly available information and existing EU regulations. The "Base Case" scenario serves as a **benchmark for our sensitivity analyses** and to examine how different framework conditions will affect the EU chemical sector's transition to climate-neutrality. It should not be confused with a "Business as Usual" (BAU) scenario and should be understood as a "snapshot representation" of future operating conditions for the chemical sector, based on existing policies and **information publicly available** today. This scenario adopts a **neutral view** and relies on existing EU regulation and adopted policies, as the main source of information. As part of our data collection exercise, we have also engaged ICIS, a reputable source of market and pricing data for the chemical sector, to develop a customised demand scenario that reflects how climate targets could affect the EU27 demand for chemicals.

As a default approach in this report, the climate-neutrality target applies to **all emissions in scope.** But the results of the "Base Case" scenario, which was also conducted for scope 1 direct emission only, show that the deployment of abatement solutions and corresponding resources highly depend on the scope of emissions that need to be abated, even if the initial set of assumptions remains the same. Even when encompassing all emissions, the pace of reductions varies between different emission scopes depending on the availability of abatement solutions. The majority of residual unabated emissions in 2050 fall under scope 3, while the rest are scope 1 emissions, which remain uncaptured emissions as the capture rate is below 100%. To reach climate-neutrality, residual emissions by 2050 should therefore be compensated by **negative emissions.** Under the "Base Case" scenario, in 2050, more than 50Mtons of $CO_{2\text{-eq}}$ are compensated by biogenic emissions that are captured and stored into geological storage or chemical products.

In order to reach the climate objectives, the model taps into all main categories of solution for abating direct GHG emissions: switching to **alternative processes and production routes,** changing the **heat source,** and **capturing CO_2.** The production capacity deployment for alternative technologies across the modelling shows that (partial) electrification of the steam cracking processes also emerges as a key technology to abate direct emissions from traditional steam cracking.

The total amount of **feedstock** consumed by the chemical industry increases by 15% by total mass of feedstock compared to 2019, driven by demand growth. By 2050, the share of bio-based feedstock increases above 40% of total consumption, while the share of fossil feedstock decreases to around 35%. Feedstock from chemical recycling of polymers emerges as one of the solutions to abate end-of-life emissions and as an alternative source of feedstock. It represents 14.6% of the total feedstock consumption in 2050.

The total amount of **captured CO_2,** both from concentrated and unconcentrated sources, increases to reach almost 35Mtons in 2050. Most of it is stored into geological storage (Carbon Capture and Storage — CCS), while a smaller share is used as alternative feedstock in combination with hydrogen.

To determine whether the chemical sector becomes climate-neutral across the entire modelling scope, iC2050 needs to identify whether the embedded carbon within products is "kept within the loop" and re-circulated, or whether it is emitted as CO_2 into the atmosphere. **Chemical recycling** allows reducing emissions from polymer incineration, while providing recycled feedstock and reducing the consumption of virgin raw materials. In the mid-20s, it is deployed and rapidly scaled up, covering 45.7% of the total volume of polymers by 2050.

On the cost side, the deployment of solutions for reaching the climate and circularity objectives results in an NPC of €2.18 Trillion, divided between capital and operational expenses. Massive **capital investments** start immediately in the period, increasing exponentially. They add up to a total of 318 Billion € (Bio€) over the entire period. The model also shows the difficulty and cost of abating residual emissions just before 2050. **Operational costs** related to the purchase of alternative materials on the market also increase very rapidly, but slow down around 2040. Total operational costs add up to 1,863 Bio€.

The impact of policies

Based on the results of the "Base Case" scenario, the report subsequently explores the impact of policies, assessing their potential impact on the chemical sector's abatement pathway.

In its Impact Assessment supporting the Communication on a **2040 Climate target,** the European Commission considers three different levels of ambition. These ambitions levels have been transposed to the chemical industry, showing their impact on the abatement pathway of the sector. Reducing the 2040 level of ambition for the chemical sector to 81% results in a more linear trajectory compared to the 88% emission reduction target. Conversely, increasing the 2040 level of ambition to 94% requires frontloading emission abatements to meet the reduction objective, resulting in a smoother abatement curve after 2040.

Implementing a more aggressive intermediate target necessitates earlier investments in abatement solutions. Most spending occurs between 2030 and 2040, with higher levels of ambition resulting in significantly higher capital investments and NPC compared to other scenarios, since less mature abatement solutions need to be deployed earlier at a higher cost.

The "Base Case" scenario includes a 20% target on the share of sustainable non-fossil carbon embedded in products, in line with the aspirational objective of the European Commission's communication on **Sustainable Carbon Cycles[2].** In its draft guidance for the chemical sector, the Science Based Targets initiative (SBTi) proposes minimum and recommended alternative feedstock targets. Combining the recommended targets with the "Base Case" assumptions does not yield a feasible solution, necessitating the release of certain constraints on biomass availability, carbon capture and chemical recycling development pace.

The above adjustments influence the balance between residual emissions and removals. The increasing role of biomass results in higher volumes of carbon removals, which increases the amount of residual emissions that can still be emitted in 2050.

The last sensitivity analysis ("RED H_2 Targets") addresses the Renewable Energy Directive (RED), which sets targets for renewable fuels of non-biological origin (RFNBOs), mandating a minimum share of hydrogen from RFNBOs in the industry. The targets are set at 42% in 2030 and 60% in 2035 and they significantly impact production costs between 2020 and 2040, with major investments needed to ramp up electrolysers's capacity. To achieve a feasible solution and satisfy the demand emerging from electrolysis, the constraint on yearly availability of electricity has been increased from 300TWh to 1,000TWh.

The **comparison of policy scenarios** results show an interesting mirror effect between the high 2040 level of ambition for direct emissions and the scenario enforcing a renewable H_2 target. The $S3^{iC2050}$ scenario, although resulting in the most aggressive direct emissions reduction for 2040, has the highest amount of residual direct emissions in 2050. It also has the highest amount of carbon removals and is therefore the scenario that relies the most on biomass. The "RED H_2 Targets" scenario on the other hand, has the lowest amount of direct residual emissions in 2050, as well as the lowest volumes of carbon removals. Both scenarios are also at the extremes when it comes to energy consumption, with the $S3^{iC2050}$ scenario resulting in the lowest FED while the "RED H_2 Targets" scenario has the highest. However they both push the boundaries of the sector's capabilities to the maximum and are therefore the costliest.

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[2] European Commission. (2021). Sustainable Carbon Cycles. 26c00a03-41b0-4d35-b670-fca56d0e5fd2_en (europa.eu)

What if?

In order to complement our analysis, we have "challenged" the "Base Case" scenario, with a series of **"what if" and "what if not" sensitivities,** to explore other hypothetical futures. These sensitivities focus on four categories of abatement solutions: electrification, biomass, recycling, and carbon capture.

In the "Base Case" scenario, electricity is assumed to have limited availability within the chemical industry. For **electrification,** we looked at the impact of higher or lower availability and prices. Constraining access to electricity and increasing its price have a clear negative effect on the industry's abatement curve.

The availability of **sustainable biomass** is another key factor impacting the industry's emission trajectory, limiting or increasing the role of negative emissions. Fossil-based feedstock stays the main source of carbon feedstock when severely constraining access to biomass. While captured CO_2 and recycled feedstock play significant roles, they are unable to compensate for the reduced share of biomass. To achieve a feasible solution with restricted access to bio-based feedstock, the yearly availability of electricity has been increased to 1,000TWh and the access to biomethane as a fuel for heat generation has been increased.

The impacts of increasing or decreasing enabling conditions for **recycling** are explored, with assumptions on mechanical recycling volumes and chemical recycling technologies varying across scenarios, highlighting the potential of both mechanical and chemical recycling in reducing reliance on virgin raw materials and minimising carbon emissions. By comparing scenarios with differing levels of recycling technology deployment and policy support, the analysis demonstrates how enhanced recycling efforts could significantly increase the share of circular carbon.

Last but not least, the development and deployment of solutions related to **carbon capture,** as well as the surrounding infrastructure for transport and storage, significantly shape the sector's abatement pathway. Having more solutions available reduces the pressure to substitute fossil carbon sources. In a constrained scenario, the chemical sector needs to show resilience by adapting its fuel mix and deploying alternative technologies to manage emissions upstream.

When comparing all the above sensitivities, we see that limiting access to biomass significantly reduces the potential for removals and therefore results in lower gross residual emissions but it is also the costliest route. Securing access to electricity at competitive prices results as the most efficient lever to reduce the costs of achieving the targets. It also reduces the reliance on negative emissions to reach climate-neutrality. The reliance on bio-based technologies and bio-based feedstock is the most elastic and sensitive to changes in the assumptions, therefore showing by far the biggest range of uncertainty. On the contrary, scenario results on the electrification of crackers remain pretty stable across scenarios.

Main conclusions

A number of technological pathways like electrification, bio-based routes, chemical recycling or carbon capture emerge from our entire analysis, as backbone solutions for reaching the climate neutrality and circularity ambitions. Negative emissions are also required in all scenarios. How much each solution contributes to the end-result remains primarily **a function of availability and relative cost.** The chemical industry's pathway to climate-neutrality and circularity is influenced by numerous factors, both within and beyond the control of chemical companies, across the value chain. This creates significant uncertainty around the mix of solutions and costs needed for the transition, highlighting the **need for access to a wide range of options.** Restricting access to certain technologies, energy, or feedstock sources increases reliance on remaining options, putting at risk the achievement of climate and circularity targets. For example, limited access to electricity could jeopardise climate-neutrality goals or lead to overreliance on biomass and unrealistic carbon capture requirements. Additionally, restricted access to alternative resources or technologies raises costs, including capital costs, as it prevents the industry from exploring the lowest-cost pathways.

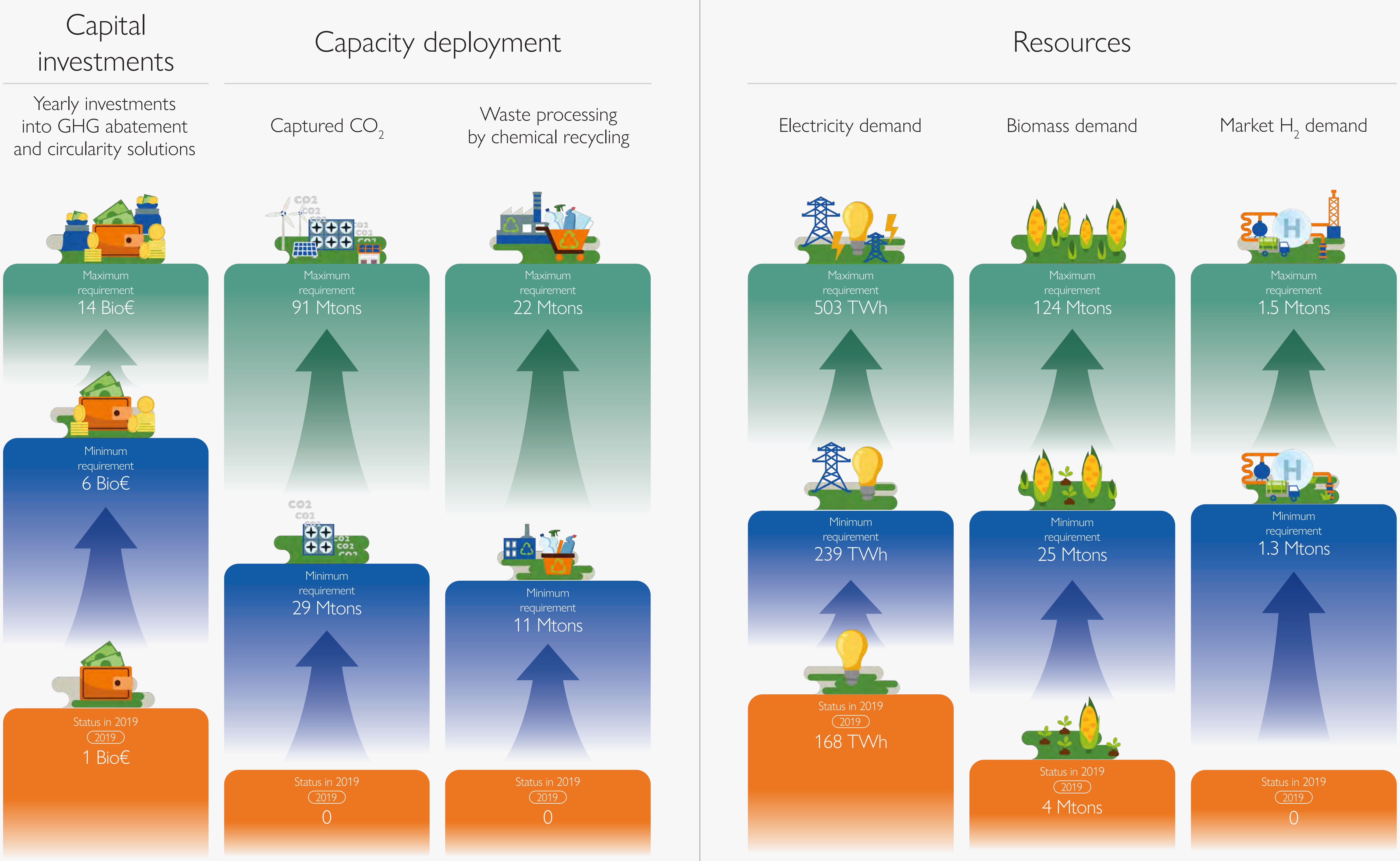
Figure 1 shows the differential between current industry conditions, and where the industry needs to be in order to reach its climate and circularity objectives. For each element the figure indicates both a minimum and a maximum requirement, to reflect the uncertainty based on the scenarios described in this report.

Despite process electrification, the chemical industry remains **molecule-based,** with carbon playing a central role. **Access to biomass** is essential to replace fossil molecules, as it is the easiest and most economically attractive feedstock alternative, requiring minimal adaptation to existing processes. However, biomass availability is finite, especially when adhering to sustainability obligations. Geopolitical developments, such as those related to Ukraine, will impact the EU's ability to secure green molecules. The chemical industry will face competition from other sectors, necessitating bold action from EU decision-makers. Crop yields across the EU must increase to their maximum, and if demand cannot be met, resources should be prioritised for applications offering the best climate and environmental benefits.

The competitiveness of the chemical industry is not the focus of this report, as the model does not bring down production as a result of growing production costs. In reality, failing to create the necessary enabling conditions for the chemical sector's transition will not only weaken climate action but also potentially lead to a **deterioration of the EU's economic fabric.** Investments in the transition will have to be financed by higher revenues, or investments will not occur in Europe. Therefore, **increasing demand** for net-zero, low-carbon, and circular products is also crucial.

Figure 1

Key indicators of the transition



Section 6

The iC2050 project

Section 6.1

Context

The **EU Climate Law,** which charts Europe's journey towards climate-neutrality will be highly transformative for the chemical sector, which in turn, has a strategic role in the European economy. **Chemicals are essential to modern life:** they are at the heart of Europe's major value chains, including pharmaceuticals, electronics, batteries for electric vehicles, and construction materials. The chemical sector's transformation, which may be needed to contribute to climate change mitigation, will therefore have effects that extend **beyond its own perimeter.**

The **contribution of various sectors of the economy to the climate-neutrality objective,** while not predetermined, has been rigorously evaluated and scrutinised to inform EU policy decisions. With only 26 years until the 2050 deadline, it is evident that certain industries need to lead the way to balance those that are harder to abate and are anticipated to still be net emitters by 2050. This underscores the need for a transparent dialogue on sector-specific transition strategies. Important questions arise: which industries should be promoted as frontrunners? What essential support structures are necessary? How will the EU efficiently distribute resources until the infrastructure for clean energy and feedstock production is significantly expanded?

The chemical industry faces an additional significant challenge: **transitioning towards circularity.** To stay within planetary boundaries and lessen its impact on climate and resources, the industry must shift from its traditional linear model to a circular one. There are **three main circular carbon sources** for the chemical industry to consider: biomass, recycled waste, and carbon dioxide (CO_2) that is captured from pipe emissions or directly from air. Each, however, comes with its own set of challenges. **Biomass** is limited in supply and generally comes at a higher cost than fossil-based supply. **Waste recycling** and **CCU** require extensive infrastructure and investment. **Direct Air Capture** is too expensive and might not benefit the climate due to the very high energy demand of capturing CO_2 molecules that are diluted in the atmosphere (versus industrial emissions, where they are more concentrated). These alternative carbon sources generally have a **lower energy density** than fossil fuels, which may need to be complemented with an additional energy source (e.g., hydrogen). Therefore, it is crucial to thoroughly evaluate their availability and the potential competition for these resources from other industries to accurately determine the feasibility of replacing fossil carbon.

In delineating the industry's climate transition, it is important to clearly articulate our objectives to foster clarity and alignment. The main, if not only, environmental objective of the iC2050 model is to reduce GHG emissions. Therefore, this report only looks at the impact of circularity **in the context of climate change.**

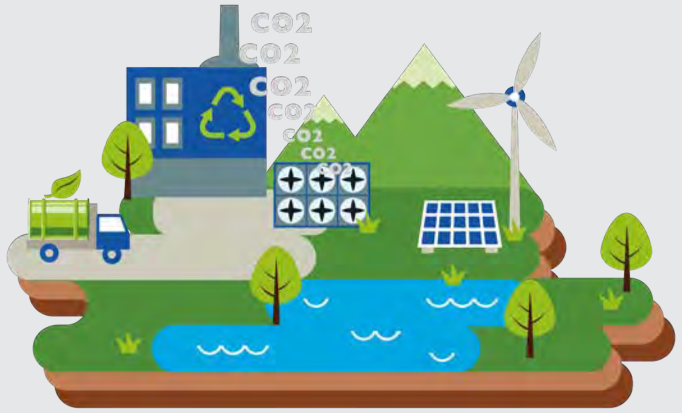
Three related but different concepts:

Figure 2

The role of carbon in climate and sustainability objectives

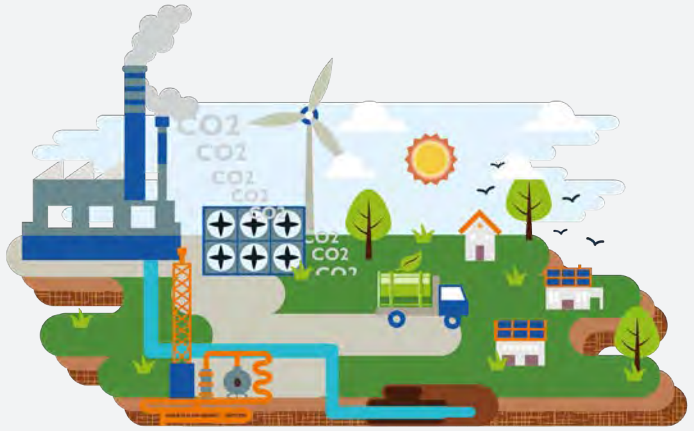
Decarbonisation

Carbon is a basic and essential element on Earth, it is at the source of life and organic chemistry. It is an essential element of many chemicals, like it is for most products society is using. From a climate perspective, the use of carbon sources is only problematic when combined with combustion (notably for energy production), leading to emissions into the atmosphere, in the form of CO_2.



Fossil or non-fossil carbon

Fossil carbon refers to carbon that is derived from fossil materials, such as coal, oil, and natural gas. These fuels are formed from the remains of ancient plants and animals that have been subjected to high pressure and temperature over millions of years. Today, fossil carbon fuels are the primary source of energy worldwide, contributing significantly to global economies. They provide a consistent and reliable source of energy, supporting continuous power generation and industrial operations. However, fossil carbon reserves are limited and non-renewable. Reliance on fossil fuels and feedstock also has other types of environmental, as well as geopolitical impacts.



Climate-neutrality

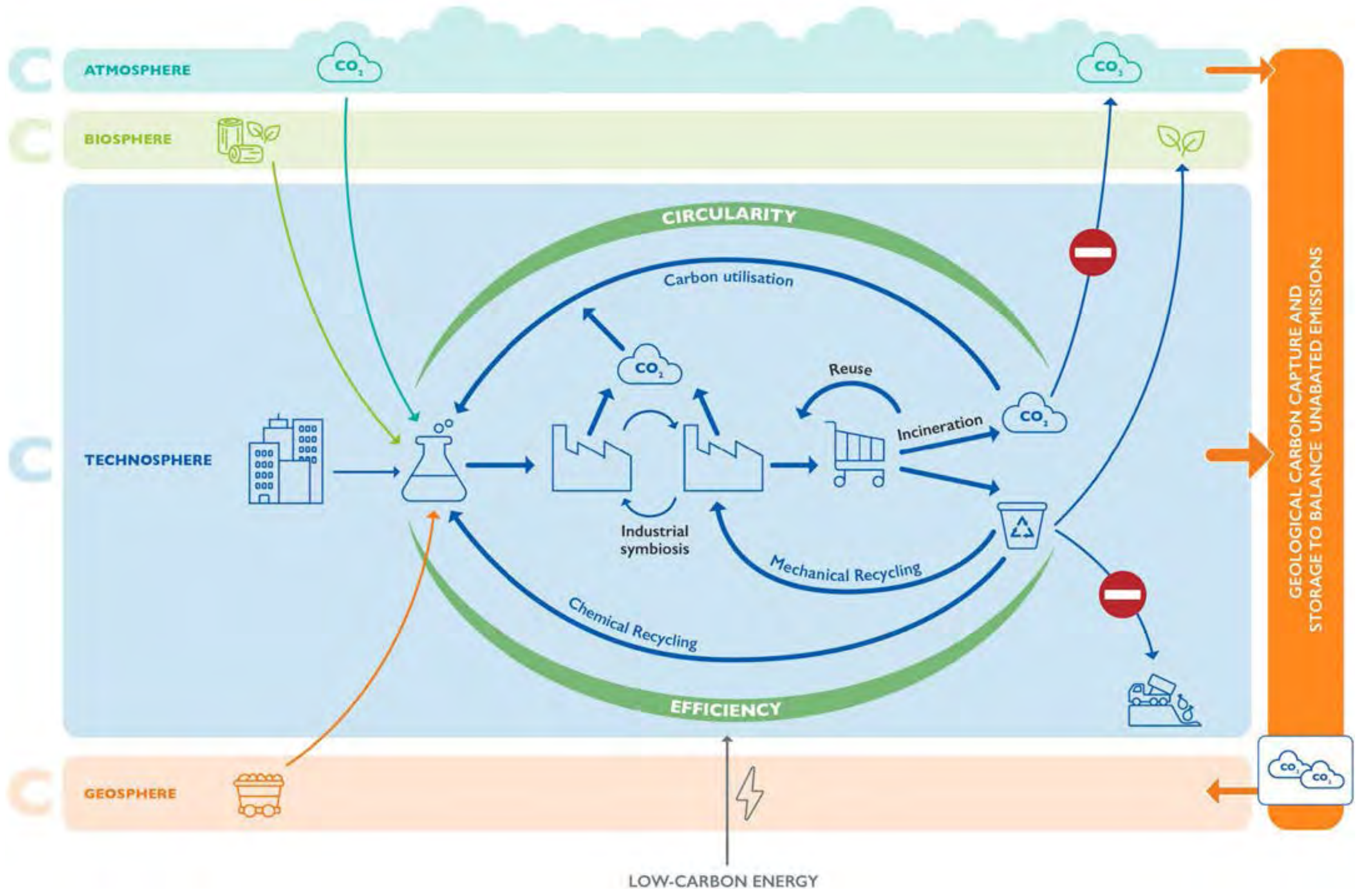
Climate-neutrality, as defined by the EU climate law, refers to the state in which the net greenhouse gas emissions released into the atmosphere are balanced by the amount of greenhouse gases removed from the atmosphere. This is a central goal in the EU's efforts to mitigate climate change and limit global warming to well below 2 degrees Celsius compared to pre-industrial levels, as outlined in the Paris Agreement. Fossil carbon can still be in circulation in a climate-neutral economy: long-term carbon storage avoids that the excess of carbon is emitted.

In the pursuit of the Paris Agreement's goals and in evaluating advancements, it is necessary to consider both the current levels of atmospheric CO_2 and the potential increase stemming from feedstock and energy choices. Rising atmospheric CO_2 concentrations contribute to global temperature increases. Therefore, it is essential to confine **cumulative emissions within a predetermined budget** by reducing global annual emissions to net-zero by mid-century.

The chemical sector requires carbon-based molecules as a raw material for its products and will continue to do so in the future. By contributing to sustainable carbon cycles, the chemical industry can function as a **"Carbon Manager"**, initially reducing and subsequently neutralising its impact on climate along the entire value chain, while consistently delivering societal benefits.

Figure 3

Sustainable carbon life cycle[3]



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[3] Disclaimer: In Sustainable Carbon Cycles, most of the carbon used in production stays within the economy. The carbon goes through various transformations in the chemical value chain. Some of it is burned as fuel during production or incinerated at the end of a product's life. The CO_2 released during these processes is captured and reused as raw material through CCU. Products containing carbon are kept in the cycle through reuse and recycling, either mechanically or chemically, as much as possible.

Biodegradable products can also be recycled or processed through composting or fermentation, returning their components to the biosphere. Minimising landfill use helps keep carbon in the loop. Capturing CO_2 and storing it underground can offset unavoidable emissions. Carbon captured directly from the air can be used as additional raw material, helping to reduce atmospheric carbon to levels that meet the Paris Agreement goals. Any extra carbon needed can be extracted from underground (fossil carbon) but should be balanced by an equal amount of carbon removal. To positively impact climate change, all processes should use low-carbon energy.

Section 6.2

Objectives

The iC2050 model is a unique tool. It has been calibrated and tailored specifically to the EU chemical sector in order to sketch and demonstrate a variety of feasible pathways towards a climate-neutral and circular chemical industry. These pathways are generated based on a **set of assumptions** regarding factors that collectively shape the future operational landscape for the chemical industry up to 2050. The specifics of these assumptions are detailed in the section "Categories of input parameters" (see also Annex 1).

Using these assumptions, the model generates pathways that can aid in pinpointing the most **cost-effective** strategies for reducing emissions. It informs chemical companies individual strategies and helps them navigate the transition, by allowing them to put their own companies' strategy into a wider sectoral context. Additionally, the model and its scenarios serve as a foundation for discussing with all stakeholders about the potential **implications of decisions** that will impact the future of the chemical industry, both in corporate and public spheres. We know the "what" — the climate goals, but we still do not have all the answers as to how to get there. The iC2050 and this report are another step towards defining this "how".

In this report, we articulate a primary **"Base Case" scenario** followed by a series of sensitivity analyses looking at different levels of ambition or enabling frameworks. It is essential to recognise the **inherent uncertainties of these scenarios,** as forecasting the future is fraught with challenges, and unforeseen events or groundbreaking innovations could significantly deviate the course towards 2050. Nonetheless, they provide valuable insight into the **intricate interplay between various facets of the transition** and underscore the critical importance of certain factors. Our intent is not to debate the attainability of climate-neutrality, but to leverage the model to **spotlight potential hurdles** if the prerequisites for the industry's transformation are absent.

The impact of the chemical sector can be felt both directly and indirectly, with GHG emissions occurring across its **entire value chain.** Upstream activities such as raw material extraction and processing are significant sources of emissions, while downstream, the disposal of products derived from organic chemistry can release substantial amounts of carbon into the atmosphere unless recycled. Therefore, our analysis of climate-neutrality **spans multiple scopes,** with a focus on the primary sources of indirect emissions and segments of the value chain, where the chemical industry holds the biggest potential to deploy emission reduction measures.

Climate policy is often discussed alongside **energy policy.** The EU has established a comprehensive policy framework and a clear vision for transitioning the energy and transport sectors. In 2019, the chemical sector consumed approximately 2,100 PJ of energy. Our bottom-up calculations indicate that **non-energy fuel consumption** (i.e. feedstock) exceeded 5,300 PJ. According to other sources[4], fossil resources as chemical feedstock add up to 10.4% of all fossil carbon consumption in the EU. This report therefore aims to highlight what we consider the **hidden aspect of fuel supply: the role of carbon-based feedstock.** As the EU now intends to intensify its efforts on transition of energy-intensive industries, addressing this challenge will be essential. The iC2050 model allows us to study the impact of substituting fossil-based carbon with sustainable and circular sources, as well as the essential volumes needed for this shift. It tracks the industry's **carbon flows,** whether incorporated in products, released, or sequestered and stored.

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[4] Kähler, F., Porc, O. and Carus, M. (2023). RCI Carbon Flows Report: Compilation of supply and demand of fossil and renewable carbon on a global and European level. Renewable Carbon Initiative, RCI's scientific background report: "RCI carbon flows report – Compilation of supply and demand of fossil and renewable carbon on a global and European level" (Oct. 2023) | Renewable Carbon Publications (renewable-carbon.eu)

Section 6.3

Expert review & stakeholder consultation

We have developed the scenarios and sensitivities presented in this report by using various sources of data and assumptions, which we have detailed in the section "Assumptions in the "Base Case" scenario", in Annex 3, Annex 4 and Annex 5. We have collected these assumptions through **surveys and workshops** with experts from **chemical companies and trade federations,** supplemented by bilateral discussions for more in-depth insights.

The chemical sector does not exist in isolation from the rest of society. Therefore, we have sought feedback from our **key stakeholders** and the **research community** working on Industrial Transformation, through a webinar and a consultation survey. Throughout the consultation process, we have prioritised **publicly available information and official sources,** to ensure that our scenarios are based on a robust set of assumptions.

Section 7

Technical description of the iC2050 model

The iC2050 model, which was developed by Deloitte for Cefic, is a **linear optimisation** model constructed to explore potential routes towards a climate-neutral and circular chemical sector. The objective function is to minimise the NPC of chemical production, while fullfilling the GHG abatement and circularity constraints. Based on projections of future demand for chemical products up to 2050 and a description of the future operating conditions for the sector (defined by the user), the model computes the corresponding GHG abatement trajectory. Additionally, it equips users with insights to tackle pivotal queries, such as:

- The **mix of technologies** that could enable the industry to attain climate-neutrality by 2050.
- The **energy and raw material sources** that would be utilised in chemical production.
- The contribution of **circular practices,** including recycling, utilisation of CO_2 as a raw material, and the employment of biomass.
- The potential impact of **CCS and CCU.**

The model adopts a **value chain perspective,** encompassing multiple commodities. It is designed to incorporate a variety of production pathways, acknowledging the intricate interdependencies among diverse products and processes.

Operating on the assumption of **perfect foresight,** the model presumes that decision-makers possess complete, uncertainty-free knowledge of future conditions, enabling them to make optimal investment choices. This approach implies that the model's internal decision-maker is aware of all potential outcomes of any decision within the model's timeline, thus facilitating the most efficient decisions based on this knowledge.

The model calculates the **present value of capital and operational expenses** (CAPEX and OPEX respectively) for chemical production, heat generation, and carbon capture technologies using an exogenous discount rate set to the year 2019. To ensure that yearly costs are comparable taking into account inflation, the real value of Euro is used as the unit to report costs and prices in **2019 Euro** ($€_{2019}$) throughout the model. This approach ensures that costs, which are that are reported for different years in the modelling period, are based on the same currency.

The model is written in **GAMS**[5] and solved using the CPLEX solver.[6] As an optimisation model, it comprises several core components:

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[5] GAMS® Documentation Center

[6] What is CPLEX? - IBM Documentation

Objective function

The objective function is the main goal in optimisation problems. For iC2050, the objective is to minimise the NPC for the chemical industry. It accounts for capital and operational expenses, excluding research and development, transportation, logistics, and additional infrastructure spending.

Sets

Sets refer to collections of items that are categorised together because they share similar properties. For example, sets might include the various years showcased, or the different products featured.

Parameters

Parameters refer to external elements (exogenous factors) that impact the results of the model. They are established across specific sets. Parameters include, for instance, the availability of resources and the capital expenses associated with technologies.

Decision variables

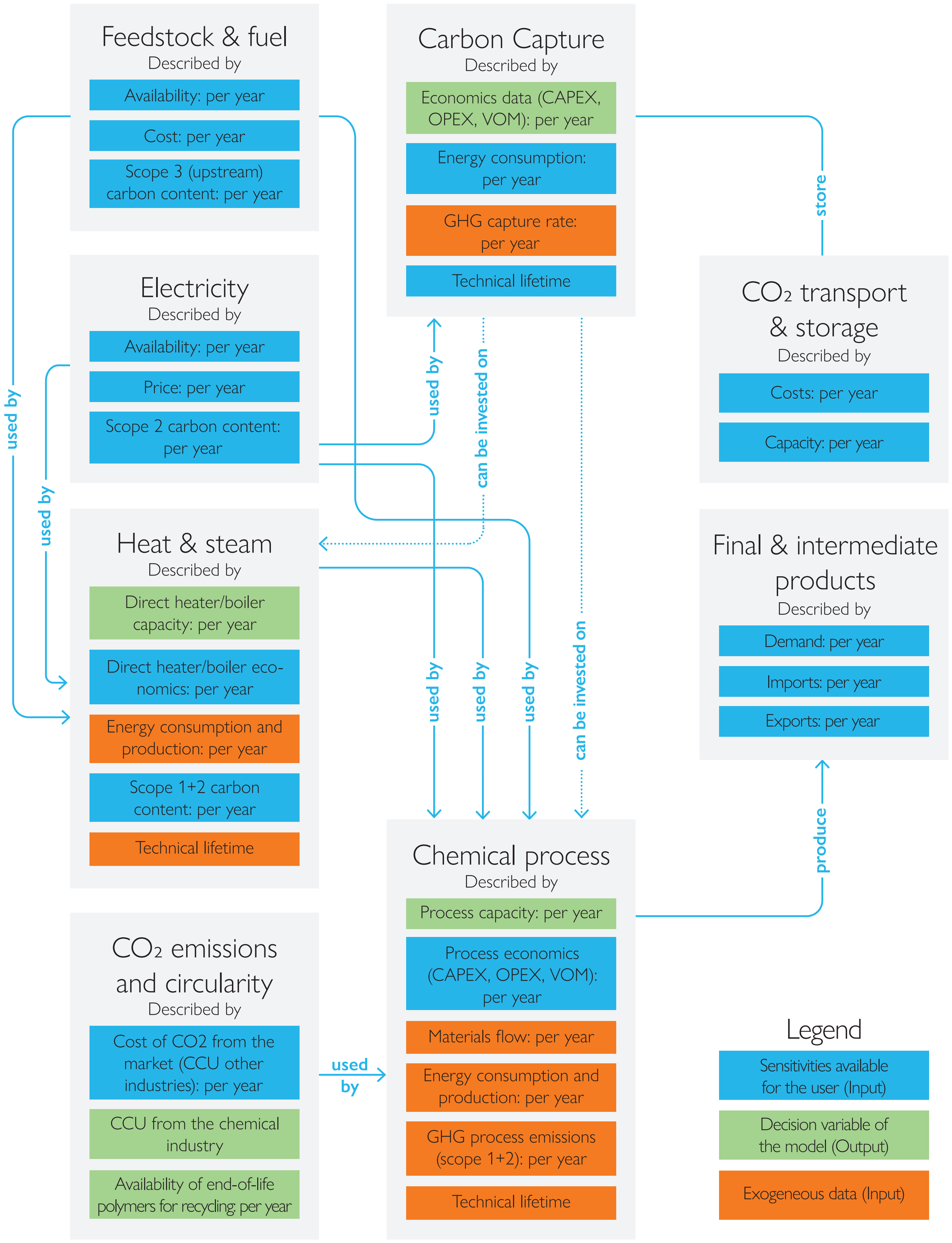
Decision variables are those manipulated by the model to find the optimal solution. Examples include newly installed capacities and emissions.

Constraints

Constraints are mathematical equations that involve the decision variables and parameters. They represent the physical, technological, and policy limitations that restrict the range of possible solutions for the decision variables. For example, one of the constraints is the climate-neutrality goal in 2050.

Figure 4

Interacting modules of the iC2050 model



Section 7.1

Modelling scope

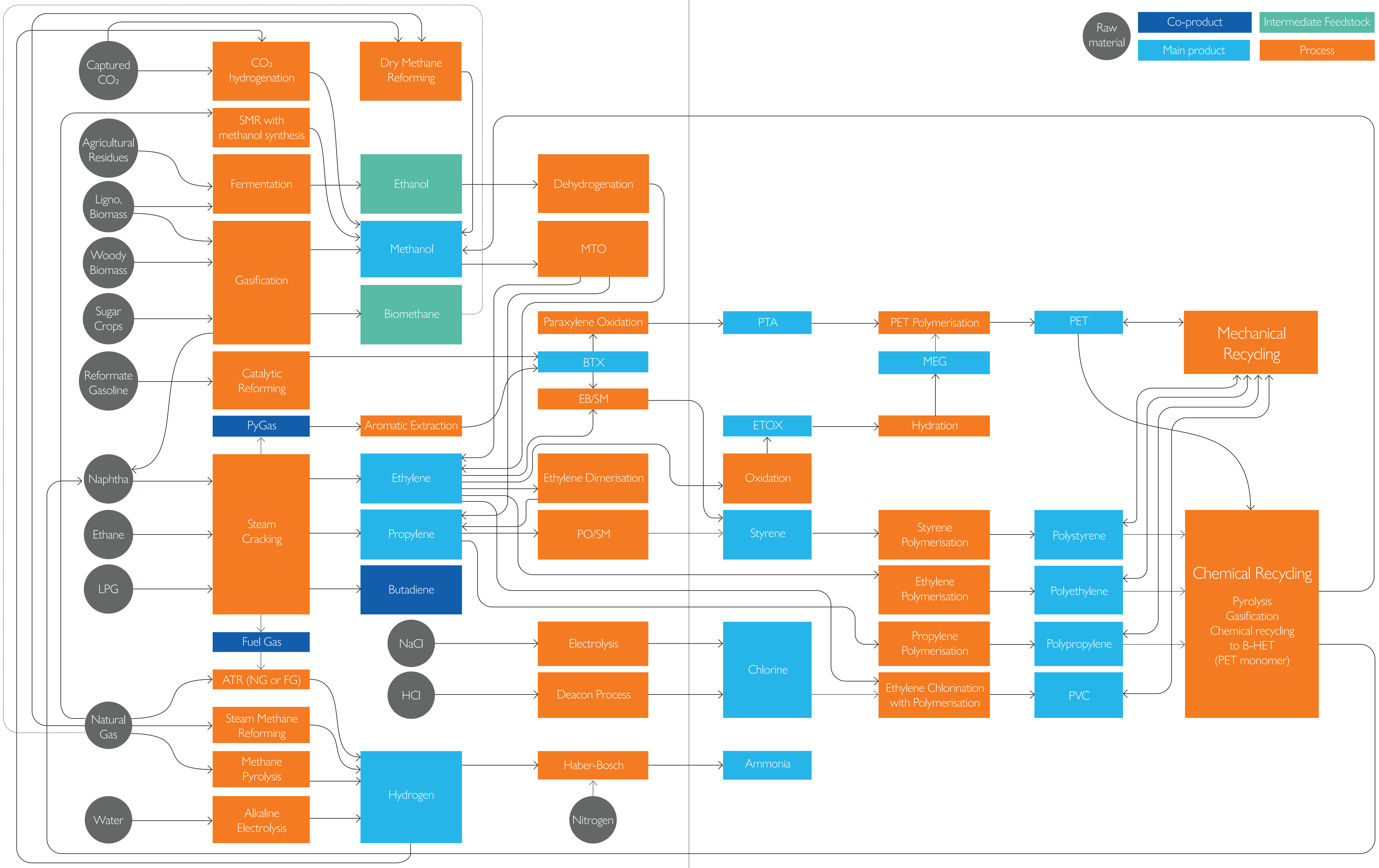
Product scope

The iC2050 model depicts the production processes of **18 chemical products** and their interconnections in a detailed manner. **Other chemicals** are represented in a simplified aggregated way.

Many processes in the model require several inputs to produce one chemical, which can be either a final product or an intermediate material. When the inputs originate from different carbon sources, the model calculates the amount of carbon in the outputs based on the chemical reaction's stoichiometric coefficients. This method allows setting and tracking non-fossil sustainable carbon targets for the products in the model, or following the carbon amounts by their source within each product.

Figure 5

Product scope of the iC2050 model



Product scope for detailed modelling

18 chemicals are modelled in detail. They are listed in Table 1.

Together, these products represent the essential organic and inorganic base chemicals, intermediates for the chemical industry, and key commodity polymers. They are also crucial for achieving climate-neutrality, as they account for a **large share of the industry's emissions** (64% of scope 1, 2, and 3 upstream emissions in 2019) and **energy use** (49% of the final energy consumption in the chemical industry in 2019).

Additional criteria that have informed the selection of these chemicals are:

- their significance for the circular economy objectives.
- the availability of climate-neutral pathways based on emerging technologies.
- a balance between model comprehensiveness and complexity, ensuring optimal coverage without excessive intricacy.

Table 1

The 18 chemicals modelled in the iC2050 model

Inorganics

Products	Ammonia	Hydrogen	Chlorine
Description	Ammonia is the second most produced chemical worldwide. It is obtained from the reaction of hydrogen and nitrogen. Since the beginning of the 20th century, 99% of ammonia production relies upon the Haber-Bosch process. The classical Haber-Bosch process uses CH_4 (methane) to remove O_2 for air to produce N_2 and provide H_2 via reforming.	Hydrogen can be obtained from different processes. Inside the iC2050 model, different processes are modelled: Steam Methane Reforming (SMR) and Auto Thermal Reforming (ATR) are the most widespread production technologies. They can produce either "grey" hydrogen if the excess CO_2 produced is released in the atmosphere, or "blue" hydrogen if a carbon capture and storage mechanism is in place. Electrolysis using electricity to split water into hydrogen and oxygen Methane pyrolysis, which is under development stage, produces hydrogen and solid carbon	Worldwide, electrolysis has been the favoured chlorine production process — the so-called chlor-alkali process. During the 20th century, three main chlorine production technologies were developed: membrane, diaphragm and mercury[7]. All three rely on electrolysis and caustic soda and hydrogen are the common coproducts. More recently, an alternative chlor-alkali process was developed, called the Oxygen-Depolarized Cathode (ODC) technology. This technology is only used where there is no use for hydrogen as this process only produces chlorine and caustic soda. Today, this process represents only 0.8% of the total EU chlorine production.

Organics

Products	Ethylene	Propylene	Benzene & Xylene	Toluene	Methanol
Description	In Europe, ethylene is generally produced via steam cracking, a process where saturated hydrocarbons are broken down into smaller unsaturated hydrocarbons. The feedstock used for steam cracking processes is composed of naphtha, ethane, propane or butane. These feedstocks are thermally cracked with steam in furnaces. Cracking severity (i.e. the process temperature) is adjusted accordingly to maximise the preferred product production.	Propylene is produced through steam crackers (cf. ethylene), Fluid Catalytic Cracking (FCC) and on-purpose routes (Propane Dehydration and Metathesis). FCC is a process widely used in petroleum refineries to convert long alkanes into more valuable gasoline, alkenes gases and other products.	Benzene is mainly produced from pyrolysis gasoline produced in the steam cracker, and through continuous catalytic reforming (CCR). Xylene is produced mainly from CCR. Benzene and xylene can also be produced from methanol via Methanol-To-Aromatics (MTA) processes.	Toluene is produced through two main processes: catalytic reforming and aromatic extraction from pyrolysis gasoline (pygas) co-produced in the steam cracker. Toluene can be produced through hydrogenation of pygas that is produced during steam cracking.	Methanol is mostly produced via natural gas steam reforming but can also be produced from coal (mostly in China). Natural gas is transformed into Synthesis Gas (syngas). Then, it is converted into crude methanol and thereafter distilled to increase its purity. Carbon dioxide hydrogenation and dry methane reforming are emerging technologies that utilise CO_2 for methanol production.

Intermediates

Products	Styrene	Ethylene Oxyde	Mono-ethylene glycol (MEG)	Purified Terephthalic Acid (PTA)
Description	Around 60% of styrene is produced by the dehydrogenation of ethylbenzene. Ethylbenzene, which is produced from ethylene and benzene, is used almost exclusively to manufacture styrene.	Ethylene oxide is obtained via ethylene partial oxidation. In the model, ethylene oxide is mainly used to produce ethylene glycols, which is then used to produce Mono-Ethylene Glycol (MEG), which is then turned into polyethylene terephthalate (PET).	Ethylene glycol is produced from ethylene, via the intermediate ethylene oxide. Ethylene oxide reacts with water to produce ethylene glycol. MEG is used to produce PET.	In the Amoco process, which is widely adopted worldwide, terephthalic acid is produced by catalytic oxidation of paraxylene.

Polymers

Products	Polyethylene (PE)	Polypropylene (PP)	Polystyrene (PS)	Polyethylene Terephthalate (PET)	Polyvinyl Chloride (PVC)
Description	Ethylene is a stable molecule that only polymerises in contact with catalysts. The conversion is very exothermic. Coordination polymerisation is the most common technology, which means that metal chlorides or metal oxides are used. Polyethylene can be produced by radical polymerisation, but this route is of limited use and usually requires high pressures.	Polypropylene is produced by the chain polymerisation of propylene.	There are three types of processes generally used to produce polystyrene: suspension, solution and mass (bulk) polymerisation of styrene.	Polyethylene Terephthalate (PET) is produced by polymerization of MEG and PTA.	Suspension polymerisation is the most common PVC production process. This is because the resins produced are versatile and suitable for a wide range of applications.

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[7] The mercury technology was phased-out by the end of 2017.

Aggregated modelling for the “Rest of industry”

The remaining 36% of emissions and 51% of energy demand are modelled in an **aggregated manner** within two categories:

- “REST” which represents all chemical industry value chains derived from base chemicals and which are situated downstream of the 18 products modelled in detail; products include mostly second and third tier intermediates in the chemical industry, which means that little to no direct use of fossil feedstock occurs;
- “REST Bio” which represents all value chains that source biomass directly (e.g. production of ethanol by fermentation), without any base chemical as intermediate feedstock.

While covering thousands of different chemical products, “REST” and “REST Bio” are considered by the model as **single products.** The “REST” and “REST Bio” aggregates constitute the remaining emissions and energy consumption, which are not covered by the 18 chemicals modelled in detail. The model can invest in alternative heat supply technologies to meet the heat and steam demand for the aggregated rest products. CO_2 capture can be deployed to capture the direct emissions from the “REST” product as one of the possible abatement solutions.

Timeframe and geographical scope

The model covers the **period from 2019 to 2050.** The year 2019 is based on historical data for demand and supply, while the model optimises the investment decisions for the following years. The model inputs also rely on historical data for production volumes and mechanical recycling until 2023.

The model treats the **EU27 countries** as a single region, with an aggregated demand for chemical products. It also assumes that the chemical industry operates as a **single production entity.**

Emission Scope

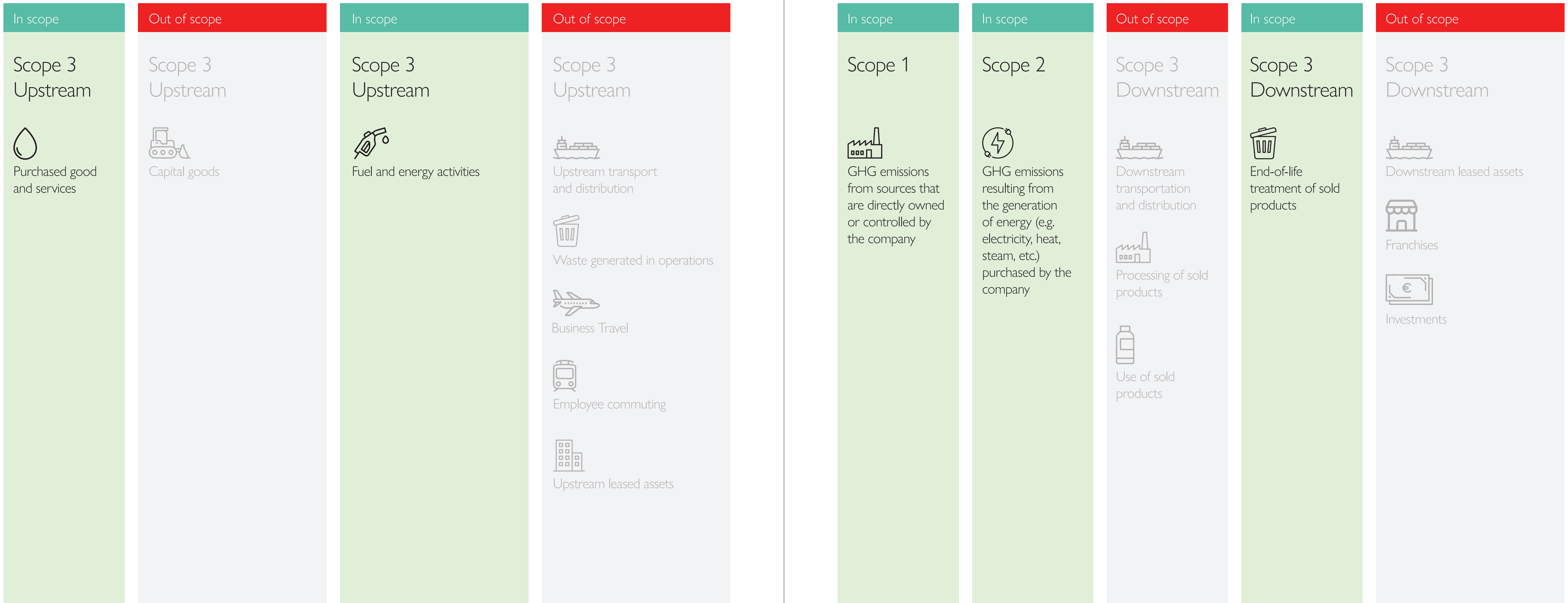
The European economy is moving towards climate-neutrality in 2050 as planned in the Climate Law but the contribution of the EU chemical industry to the climate-neutrality objective is still to be determined. In iC2050, the 2050 climate-neutrality target is modelled as a strict constraint that requires that the net emissions in the year 2050 under the chosen emission scopes should be no more than zero.

The iC2050 model can account for different emission scopes for climate-neutrality. The different emission scopes that are included in iC2050 are shown in Figure 6.

By default and unless specified otherwise, the climate-neutrality constraint applies to **all emissions falling in the scope of the model.** However, we also show some results for the "Base Case" scenario where the constraint only covers scope 1 direct emissions.

Figure 6

Emissions scopes and remit of the model



In scope	Out of scope	In scope	Out of scope	In scope	In scope	Out of scope	In scope	Out of scope
Scope 3 Upstream	Scope 3 Upstream	Scope 3 Upstream	Scope 3 Upstream	Scope 1	Scope 2	Scope 3 Downstream	Scope 3 Downstream	Scope 3 Downstream
Purchased good and services	Capital goods	Fuel and energy activities	Upstream transport and distribution Waste generated in operations Business Travel Employee commuting Upstream leased assets	GHG emissions from sources that are directly owned or controlled by the company	GHG emissions resulting from the generation of energy (e.g. electricity, heat, steam, etc.) purchased by the company	Downstream transportation and distribution Processing of sold products Use of sold products	End-of-life treatment of sold products	Downstream leased assets Franchises Investments

Section 7.2

Categories of input parameters

A scenario is defined within the iC2050 model in the form of combination of different assumptions. The iC2050 model uses various data inputs to represent how the EU27 economy, technology, and policy could evolve up to 2050 and achieve climate-neutrality. The model is a tool to explore different possible pathways toward this goal. Each pathway is based on a future narrative that shapes the input assumptions. The combination of assumptions is **unique for each pathway** and covers different aspects of technology, policy, and resource availability, as shown in Figure 7.

The demand, imports, and exports data, which are defined outside the model, determine the required **production volumes** of chemicals. The model may increase the production of intermediate chemicals internally, depending on the enabling conditions, to use them as feedstock for alternative technologies. However, it is important to consider that **the model cannot reduce production volumes to meet climate objectives.** In reality, this can only be secured through robust carbon leakage protection.

The **production technologies** that supply the chemicals have economic and technological parameters that describe their characteristics.

Figure 7

Overview of input parameters underlying the iC2050 scenarios

Production volumes
Domestic demand
Imports
Exports

Technology Costs
Capital costs
Operational costs
Renovation costs

Resources
Availability
Price
GHG intensity
Embedded carbon content

Technical Data
Lifetime
Yields (Inputs/Outputs)
GHG/Energy intensity
Utilization factors

End-of-Life Data
Share of managed waste
Share of mechanical recycling
Share of polymers by usage
Polymer lifetime

Policy
Carbon price
Emission cap
Minimum share of sustainable carbon in products

The model utilises publicly accessible data alongside production volume forecasts from ICIS (See Section "Volumes resulting from the analysis" for more details). No proprietary corporate data is included in our scenarios. A comprehensive outline of all input variables can be found in Annex 1.

Section 7.3

End-of-life modelling for polymers

The chemical industry has the capacity to become a carbon sink by harnessing the full potential of circular practices and the use of sustainable biomass[8]. The path taken by a polymer at the end of its lifespan dictates if the trapped carbon will be emitted as CO_2. The disposal methods for these polymers are carefully calibrated within iC2050, considering the range of emissions that fall under the objective of achieving climate-neutrality.

When products reach the end of their useful lifetime, they can be repurposed, used as energy from burning or recycled to make new items. CO_2 emissions from incineration can be sequestered in geological storage locations (CCS) or re-used (CCU).

Enforcing a constraint of climate-neutrality on **end-of-life emissions of polymers** incentivises the model to extract the utmost value from the atoms already present in the supply chain. To refine the model for various solutions, we must establish initial assumptions covering **usage,** product **lifespan, waste collection** efficiency, and the proportions of **mechanical recycling.**

The following routes are defined within the model when products reach the end of their useful life:

- **Mechanical recycling,** which processes plastics waste into secondary raw materials or products without significantly changing the material's chemical structure.
- **Chemical recycling,** which converts plastic waste by changing its chemical structure and turning it back into substances that can be used as raw materials for the manufacturing of plastics or other products.
- **Waste-to-fuel,** which converts waste materials into useable fuel sources.
- **Waste incineration,** which can be combined with energy recovery and/or CCS.
- **Landfilling,** which is the final placement of waste into or onto the land in a controlled way.
- **Uncontrolled leakage,** where waste ends up into the environment.

When a new scenario is designed, each polymer is **assigned to different sectors,** such as packaging or construction, based on their use. Each polymer and use has an **average lifetime** until it becomes obsolete. The model tracks accordingly the time when each polymer produced by the model reaches its end-of-life stage.

As a first step the model determines the **volume of polymers** that are produced within the EU27, according to the scenario's specified demand and trade assumptions. Polymers that are consumed and disposed of in Europe, including imports, are considered within the scope of the model. Polymers that are exported outside of Europe are excluded from the analysis.

As a second step, the model distinguishes between **"managed" and "non-optimised"** end-of-life materials. The collection and management of plastic waste at the end of its life is crucial for preventing uncontrolled leakages into the environment. Optimised treatment of end-of-life polymer streams also increases the chances of recovering the carbon content within those polymers for re-use. The "non-optimised" waste can only be incinerated or landfilled, or it may leak into the environment.

The "managed" waste, however, has several possible pathways such as mechanical and chemical recycling or waste-to-fuel production. The amount of **mechanical recycling** for each polymer and use is based on predefined shares that reflect the different recyclability rates of different polymers.

The final steps of the model is to **optimise the remaining "managed" waste** that is not mechanically recycled: the model chooses the volumes of polymers to be chemically recycled, transformed to fuels or incinerated in combination with carbon capture, based on the climate constraints and cost minimisation objective. The rest is incinerated or put in a landfill but is subject to a cap.

The flow diagram presented in Figure 8 outlines the optimisation options available for polymers, providing a summary of the steps involved in modelling.

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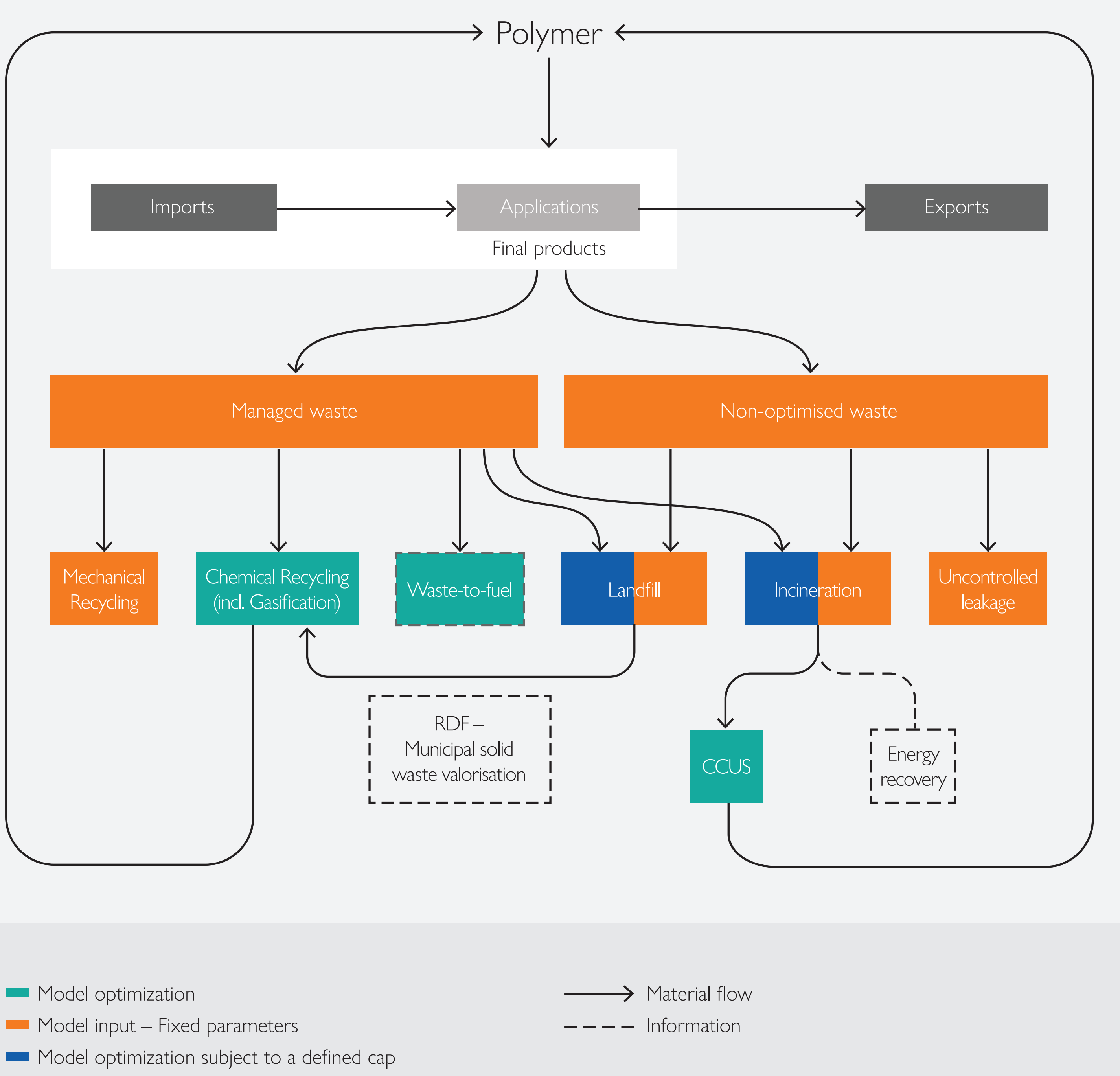
[8] Stegmann P, Daioglou V, Londo M, van Vuuren DP, Junginger M. Plastic futures and their CO_2 emissions. Nature. 2022 Dec;612(7939):272-276. doi: 10.1038/s41586-022-05422-5. Epub 2022 Dec 7. PMID: 36477132.

Figure 8

Waste optimisation routes in the iC2050 model



Section 7.4

Carbon accounting

The model adopts a **sectoral perspective and perimeter** for accounting emissions and measuring progress towards climate-neutrality, looking at interactions with other sectors and the rest of the economy. It tries to reflect the GHG footprint of the European chemical sector in a way that is as close to reality as possible. Due to the purely sectoral approach that only focuses on chemical value chains, the model sometimes deviates from global and EU accounting standards, notably for chemical companies.

To have a real impact on climate change, **carbon removals** need to be durable and long-term (for decades to centuries). While storing biogenic or atmospheric carbon in chemical products may not have an immediate impact on levels of CO$_2$ concentration into the atmosphere, due to the absence of long-term storage, increasing waste recycling will extend the duration of carbon retention within the technosphere. The same applies for the use of CO$_2$ captured in other sectors: while the global and EU's accounting framework would not recognise it as a carbon removal, the sectoral perspective shows that the chemical sector can **absorb CO$_2$ from other sectors** and support their own reduction pathways.

It is important to clarify that this report does not advocate for all bio-based chemicals or chemicals made from captured CO$_2$ to qualify as carbon removals and to receive the corresponding certificates. However, it aims at showcasing the role that chemical products can play in **managing carbon and restoring sustainable carbon cycles.** Whether products stemming from the chemical industry can be regarded as a carbon sink is a debate that is yet to be held. It is clear, though, that without this lever, modelling results would be very different. It would result in much higher investment costs and even more drastic change in the industry's structure, making the achievement of the targets more challenging and uncertain.

Biogenic carbon

We apply different accounting rules for biomass in our modelling approach, depending on its use as fuel or feedstock. Direct emissions from heat processes that use biomass as inputs are **regarded as neutral.** However, when biomass is used as feedstock to produce chemical products, the carbon is stored in the product, for a duration that can range from a few days to several decades. At the end of the use phase, this carbon is considered as either recirculated, captured or released. To account for this uncertainty, we **only recognise a portion of removals** counting towards the climate-neutrality target, as explained in section "Uses and lifetime".

The carbon from biomass that we assume will be permanently stored over the whole period is considered as "removed", neutralising remaining emissions. The part that is likely to be released during the end-of-life phase is treated in the same way as for fuel use and is only recognised as climate-neutral.

Carbon capture and storage or utilisation

CCS is a technology that prevents CO_2 from entering the atmosphere by capturing and storing it. The emission balance of CCS depends on the source of the CO_2. If it comes from biomass, it creates a negative emission, meaning that more CO_2 is removed than emitted. If it comes from for applications that require fuels, the emission balance is **(slightly) positive,** because the CCS process is not 100% efficient and some CO_2 is still emitted.

End-of-life

The model optimises the end-of-life routes for polymer waste, as explained in Section "End-of-life modelling for polymers", taking into account the defined constraints and parameters. The model only considers the emissions from polymer waste that is **produced or imported and consumed** in the EU, and not the polymer products that are exported outside of the EU.

When a polymer is **chemically recycled,** it avoids incineration and thus reduces end-of-life emissions. The emissions associated with the chemical recycling processes are included in scope 1 for the industry.

As there is no widely agreed standard on how to account for such emissions, **landfill** is assumed to have a negligible emission factor, which makes it a preferred option for the model. There a constraint had to be fixed on the amount of waste going to landfill in order to reflect current policy developments.

Summary of the divergences between accounting standards and iC2050

In order to underpin its sectoral approach and to focus the analysis on concrete abatement levers for the chemical industry, iC2050 differs from generally accepted accounting standards. Table 2 summarises the key divergences.

Table 2

Comparison of accounting standards and iC2050 modelling approaches

	Standards	Modelling choices
Carbon removals and biogenic carbon	- When biogenic CO_2 is captured and stored, it should be reported as a removal - Biogenic CO_2 emissions that are captured and used as feedstock for products can be counted as removals only if the captured CO_2 remains stored and does not re-enter the atmosphere	On balance, **the use of biomass for heat generation that results in CO_2 emissions** is accounted as carbon neutral. - When such emissions are **captured and stored (CCS),** they result into negative emission. - A share of **50% of the carbon embedded** in biomass feedstock is accounted **as negative emission** in the model. This is based on the rationale that a share of this biogenic carbon is emitted in the short term, while the rest either remains captured in the product beyond 2050 or is re-circulated. The emitted direct process CO_2 emissions can be captured and stored, hence resulting in further negative emissions.
CCU with carbon emitted by other industries	- According to most standards, carbon usage should be considered as a delayed CO_2 emission and **should not be accounted as negative emission in scope 3 upstream, in any case.** - IEA's standard considers the case where the carbon captured is biogenic, which could justify accounting for a negative emission.	It was decided that, to account for the benefits of capturing and using captured CO_2 from other industries, **the biogenic content of captured emissions would be accounted for as negative emissions.**
End-of-life emissions from imported and exported products	- According to standards that address carbon accounting at the level of an organisation or company, such as the GHG Protocol, **companies should account for the end-of-life emissions of <u>their</u> own production.** - This means that emissions from the **end-of-life of exported European products/polymers should be included,** while emissions from **imported products/polymers should be excluded.**	- Since the model adopts a sector-wide rather than a company-based approach, it was decided that the perimeter where EU chemical companies can control the end-of-life of the products is the **European Union.** - Thus the end life emissions considered are related to products in Europe (emissions from imported polymers/products end-of-life are included while emissions from imported polymers/products end-of-life are excluded).
End-of-life emissions from imported and exported products	According to standards that address carbon accounting at the level of an organisation or company, such as the GHG Protocol, companies should account the end-of-life emissions at the year of production.	- It was decided to account for end-of-life emissions at the end-of the lifetime of a product/polymer. This is the only methodology taking into account the potential evolutions of end-of-life mix over time. - This methodology, while diverging from standards, is aligned with country-wide initiatives.

Section 7.5

Model limitations

Modelling can provide valuable insights, but it also has its limitations. It simplifies and approximates the real world, which is particularly challenging when dealing with a complex and dynamic industry like the chemical sector. The main limitations of the model are discussed in the next section.

Limited product scope

The iC2050 model does not cover all **chemical products** in detail. Therefore, it only includes a limited number of new technologies to abate CO_2 and other GHG emissions in the "Rest of industry".

Moreover, the model considers **other GHG emissions,** but it does not have specific mitigation options for them. Some technologies are expected to lower the amount of Nitrous Oxide (N_2O) from the fertilisers sector and are exogenously assumed. Other GHG emissions change as the model shifts production capacity to technologies with different emission levels. By 2050, in all scenarios, some residual GHG emissions remain, but they are neutralised with carbon removals. The model does not optimise the cost and the best technological mix to abate these emissions, which could create a discrepancy between the model results and reality.

Cost estimates

The model's output does not reflect the actual costs that will likely be incurred in reality. The model is a cost-optimising one, which means it finds the cheapest way to meet products' demand and the climate-neutrality goal by 2050, given certain constraints such as resource availability, etc. Furthermore, the model acts like a **"central planner",** making optimal decisions across value chains and over time, as if it was a single rational and well-informed actor.

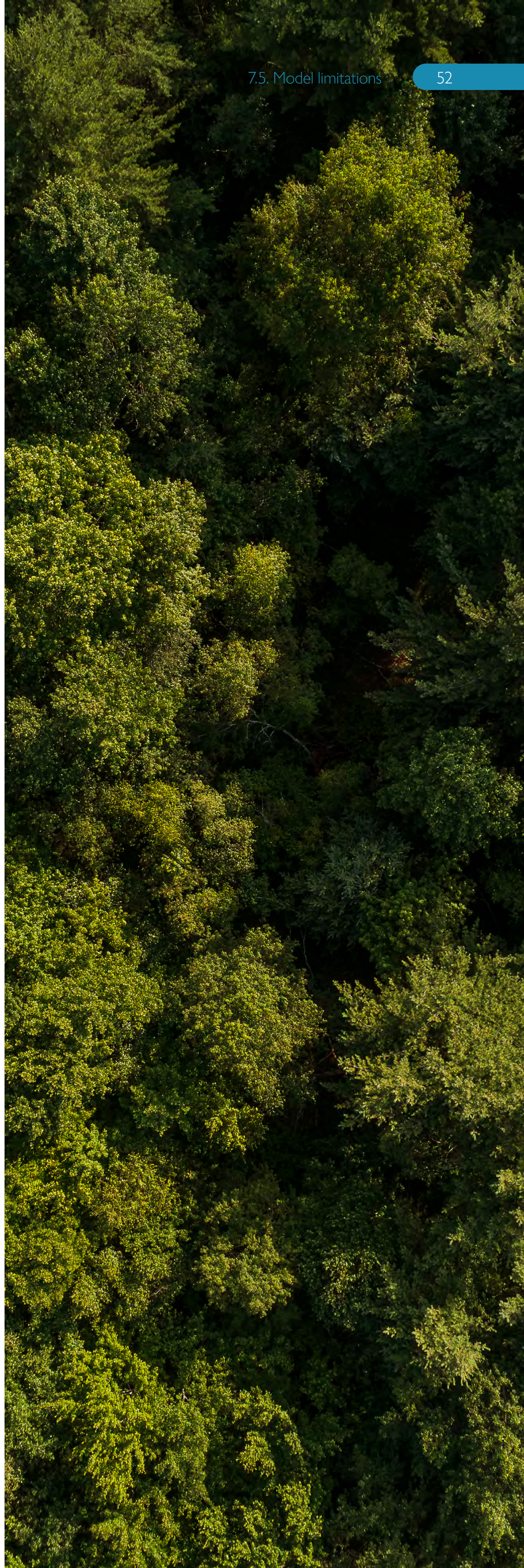
In reality, the transition will involve thousands of economic actors, who make decisions based on regional and local circumstances and their own investment capacities. Therefore, there is a significant gap between the model's theoretical cost and the actual cost of achieving climate-neutrality.

The costs presented in the results are closer to the minimum possible cost that the sector may bear. The difference between this output and reality could be several times higher. Furthermore, the model does not cover the **full costs to society,** including infrastructure (e.g. related to the energy grid or carbon capture), as well as the cost, which is passed through to consumers.

Global competition

The model cannot deviate from the production volumes that are assumed in a certain scenario. This means that climate-neutrality and circularity objectives cannot be achieved by reducing or moving production overseas. As a logical consequence, the model is unable to capture the impact that global competition would have on investment decisions of economic actors.

In our sensitivity analyses, we look at the impact of higher prices for resources. In the model's logic, this leads to less cost-effective abatement pathway. In the real world, uncompetitive prices (e.g. for electricity) versus other producing regions, could **drive low-carbon investments out of Europe,** threatening the achievement of climate target and value creation in the EU.



Section 8

Where do we come from?

Section 8.1

Production

The model uses **2019 as the reference year** for all scenarios. It also respects the actual production volumes data from the historical years 2020, 2021, 2022, 2023 as a constraint for all scenarios.

In 2019, the European chemical industry produced **281Mtons of chemicals[9].** Out of this, the 18 chemicals modelled in detail accounted for 113Mtons, or 40% of the production volume. The most dominant chemicals were ammonia, ethylene, propylene, PE, chlorine and PP[10].

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[9] Source: Eurostat. Total production [ds-056121__custom_12579949]

[10] Source: Cefic. (2021). iC2050 project report – Shining a light on the EU27 chemical sector's journey toward climate-neutrality.

Section 8.2

Emission profile

The sector's total GHG emissions in 2019 were estimated at around **328Mtons of $CO_{2\text{-eq}}$** for all the scopes included in the model. This also covers emissions related to base chemicals imported as chemical feedstock and further processed in the EU27. Figure 9 shows the breakdown by emission scope.

Figure 9

Split of total 2019 emissions by emission scope

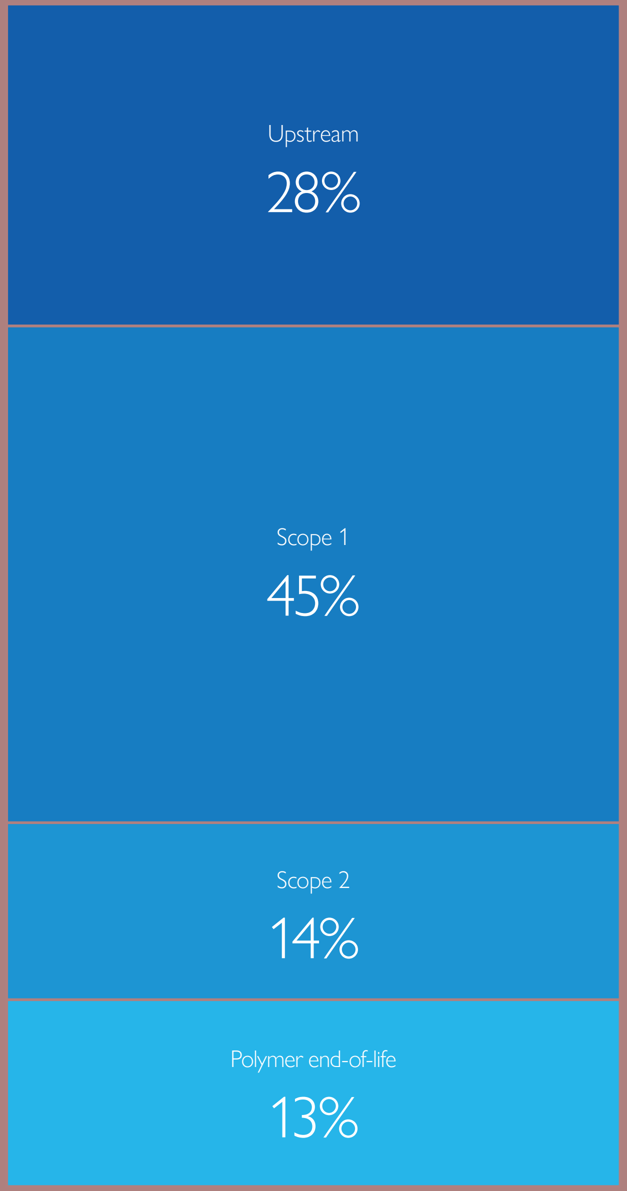


Chart 1 illustrates how the 18 products within the detailed project scope contribute to different proportions of the sector's total emissions, depending on the emission scope. The 18 chemicals that were modelled in detail represent **a substantial share** of the sector's total emissions, amounting to more than 225Mtons of $CO_{2\text{-eq}}$ out of the 328Mtons of $CO_{2\text{-eq}}$, or 69%. The "Rest of industry" emits about 103Mtons of $CO_{2\text{-eq}}$, predominantly from direct sources. This suggests that the chemicals selected for the detailed modelling are relevant for examining the sector's transition to climate-neutrality, but also that the rest of the industry has a key role to play.

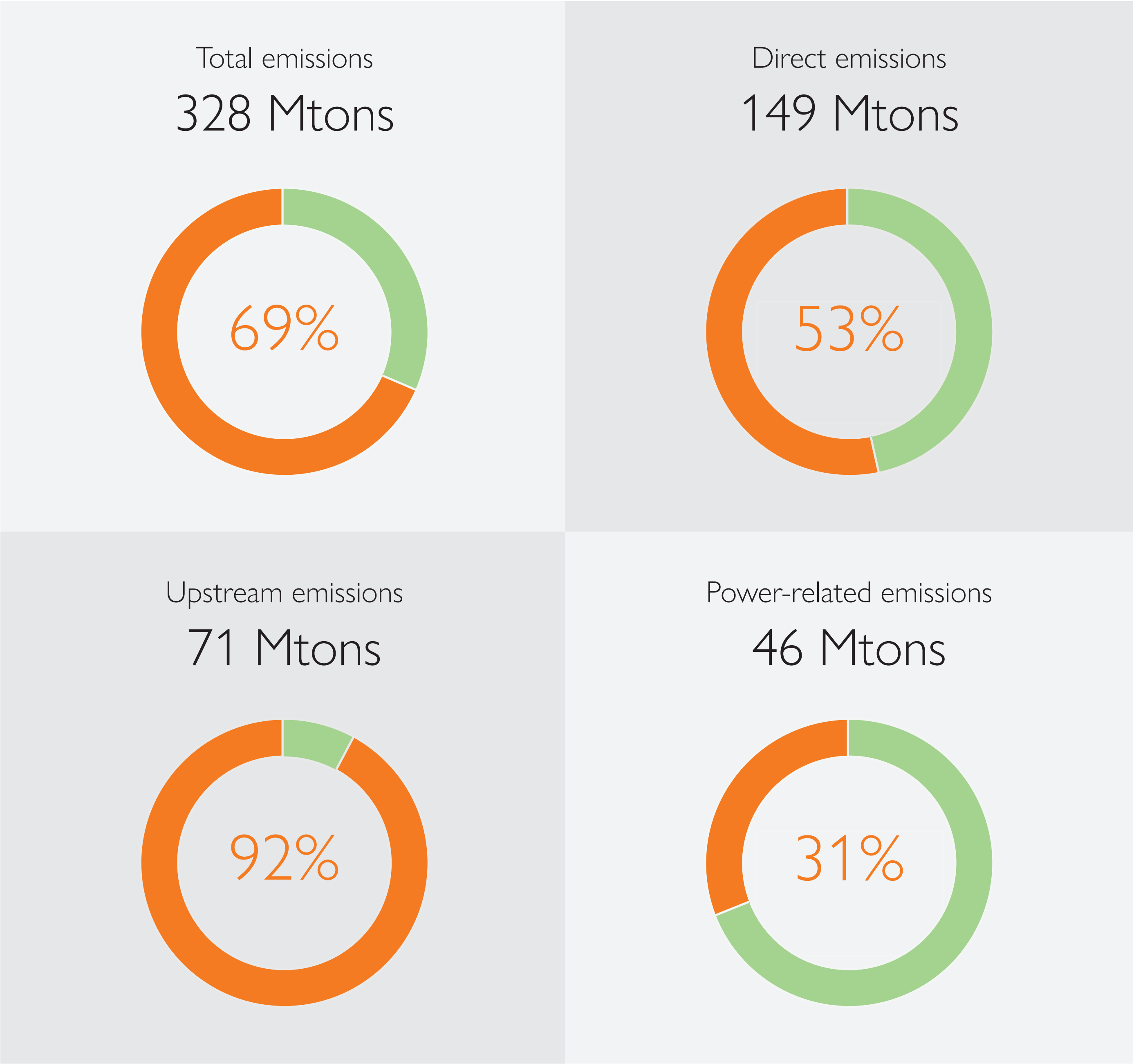
Crackers are a vital technology that produce essential organic chemical building blocks, including the 18 chemical products analysed in detail. These crackers consume most of the feedstock in the sector. Upstream utility-related emissions are largely captured by the 18 products' scope, as they reflect the high fossil energy demand of energy-intensive processes in the sector. Therefore, 92% of **upstream scope 3 emissions** modelled in iC2050 are associated with the 18 selected chemicals. In contrast, **downstream scope 3** emissions are related to downstream production, which is the final stage before reaching the market.

Scope 1 direct emissions, which comprise emissions from both the chemical processes and on-site energy production, were at approximately 149Mtons of $CO_{2\text{-eq}}$ in 2019. The 18 products that we modelled in detail represent about 52% of the sector's direct process emissions and roughly 55% of its utility emissions. The remaining direct emissions from the "Rest of industry" amounted to 69Mtons of $CO_{2\text{-eq}}$, of which 13% were process emissions of non-CO_2 GHGs (nitric acid , fluorochemicals, soda ash, and adipic acid production).

The processes that rely on electricity as an energy source are less energy-intensive and more varied, and they are usually situated downstream in the sector. Therefore, the scope 2 emissions associated with power consumption are only about one third of the total for the 18 chemical products that we examined in detail.

Chart 1

Coverage ratios of the 18-product scope of the industry's emissions in 2019



Apart from CO_2, the 18 chemicals modelled in detail emitted approximately 2Mtons of $CO_{2\text{-eq}}$ of other GHGs in 2019. The "Rest of industry" was responsible for approximately 9Mtons of $CO_{2\text{-eq}}$ of other GHG emitted, i.e 39% of direct process emissions from the "Rest of industry". These emissions are particularly challenging to reduce, because CCS technologies cannot capture them. The main source GHGs were N_2O with 62%, followed by Hydrofluoro Carbon (HFCs) and methane, with 17% and 11% respectively. Altogether, adipic acid, nitric acid and fluorochemicals production were responsible for 79% of all non-CO_2 emissions.

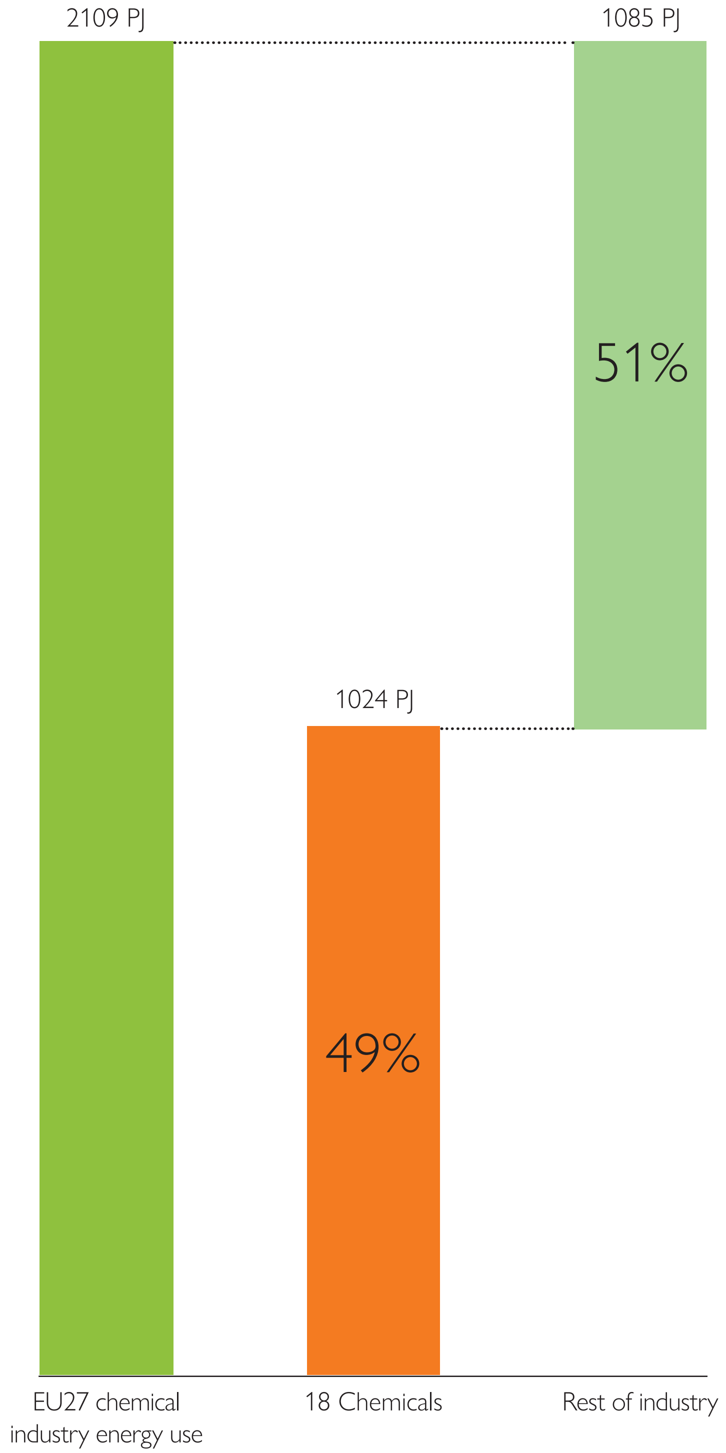
Section 8.3

Energy profile

The energy use of different products partly mirrors their emissions. In 2019, four key chemicals (ethylene, ammonia, chlorine and propylene) accounted for about 75% of the total energy demand for the 18 main chemicals. **Upstream processes** in the chemical sector value chain (such as steam cracking) require much more energy than downstream processes, like polymerisation reactions. The energy use of the "Rest of industry" is estimated at ~1,085 PJ (301 TWh), or 51% of the total EU27 chemical industry energy use[11].

Chart 2

Share of energy consumption for iC2050 products in the EU27 chemical industry in 2019



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[11] Eurostat energy balance, including pharmaceutical industry. The pharmaceutical industry's energy consumption covered within the Eurostat baseline is considered not very significant (about 6%).

Section 8.4

Feedstock mix

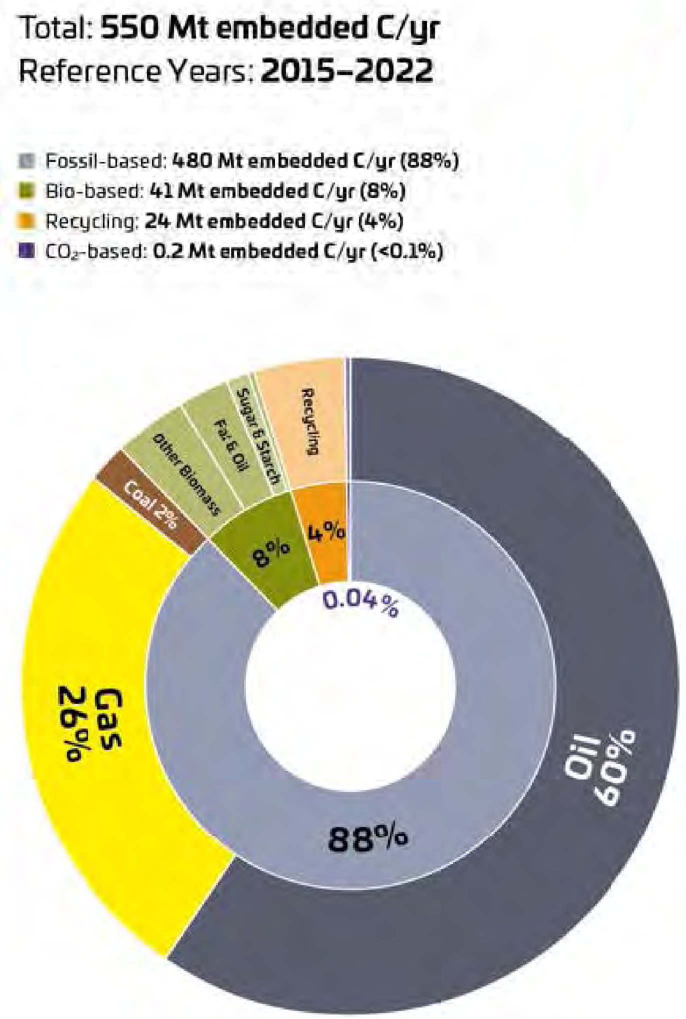
Fossil feedstocks are the main source of carbon for the chemical industry globally. **Circular carbon,** which includes bio-based materials, recycled waste and captured CO_2, accounts for only about 12% of the carbon supply. **Most of the bio-based materials currently in use in the EU27 are covered under "REST Bio", which represents all value chains that source biomass directly.**

This report focuses on **base chemicals or their derivatives,** which depended almost exclusively on fossil feedstocks for their carbon content in 2019. Biogas was used to produce bio methanol, but only in a very small amount, less than 1% of the feedstock demand.

In 2019, **naphtha** was the dominant feedstock, covering almost half of the demand. It is the main input for steam crackers in Europe, which produce most of the 18 chemicals analysed in detail in this study. Steam crackers can also process other feedstocks, such as **natural gas liquids** (for butane, ethane and propane crackers) or **gas oil.** Benzene, toluene and xylene (BTX) are extracted from reformate, which is produced by catalytic reforming of naphtha. Propane is used to produce propylene through propane dehydrogenation and crude oil is used to produce propylene through fluid catalytic cracking.

Chart 3

Global supply for embedded carbon in chemicals and derived materials[12] by Type of Feedstock



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[12] Source: Kähler, F., Porc, O. and Carus, M. (2023). RCI Carbon Flows Report: Compilation of supply and demand of fossil and renewable carbon on a global and European level. Renewable Carbon Initiative, RCI's scientific background report: "RCI carbon flows report – Compilation of supply and demand of fossil and renewable carbon on a global and European level" (Oct. 2023) | Renewable Carbon Publications (renewable-carbon.eu), p. 42

Section 9

Modelling the Future: The "Base Case" scenario

The "Base Case" scenario serves as a **benchmark** for our sensitivity analyses and examines how different framework conditions will affect the EU chemical sector's transition to climate-neutrality. The "Base Case" scenario is a "snapshot representation" of future operating conditions for the chemical sector, based on information that is publicly available today. It should however not be confused with a "Business as Usual" scenario as it is already highly ambitious and implies a major transformation of the sector. It adopts, as much as possible, a **neutral view** and relies on existing EU regulation and adopted policies as the main source of information.

The "Base Case" scenario is not a fixed projection of the future, but rather a snapshot based on the **best available information** today. The chemical sector is subject to rapid technological changes and innovation, which cannot be entirely captured by the model. Therefore, the "Base Case" scenario will inevitably deviate from the actual future conditions. To account for the influence of different EU policies and regulations on the chemical sector's transition, we have complemented the "Base Case" scenario with a set of alternative scenarios. We have also explored a range of "what if (not)?" analyses, which illustrate the potential outcomes of more or less favourable framework conditions for various types of GHG abatement solutions.

Section 9.1

Assumptions in the “Base Case” scenario

End-use demand

We engaged **ICIS**[13]**,** a reputable source of market and pricing data for the chemical sector, to develop a customised demand scenario that reflects how climate targets could affect the EU27 demand for chemicals.

Methodology

The ICIS base case demand scenario is built on an integrated framework, working in a **“bottom up” approach** starting with the end-use demand for petrochemical products. This in turn builds demand for intermediates, base chemicals, feedstocks and eventually crude oil and Natural Gas Liquids (NGLs). All supply & demand forecasts are developed on an annual, country-level basis, with final results being cross-checked against feedstock availability.

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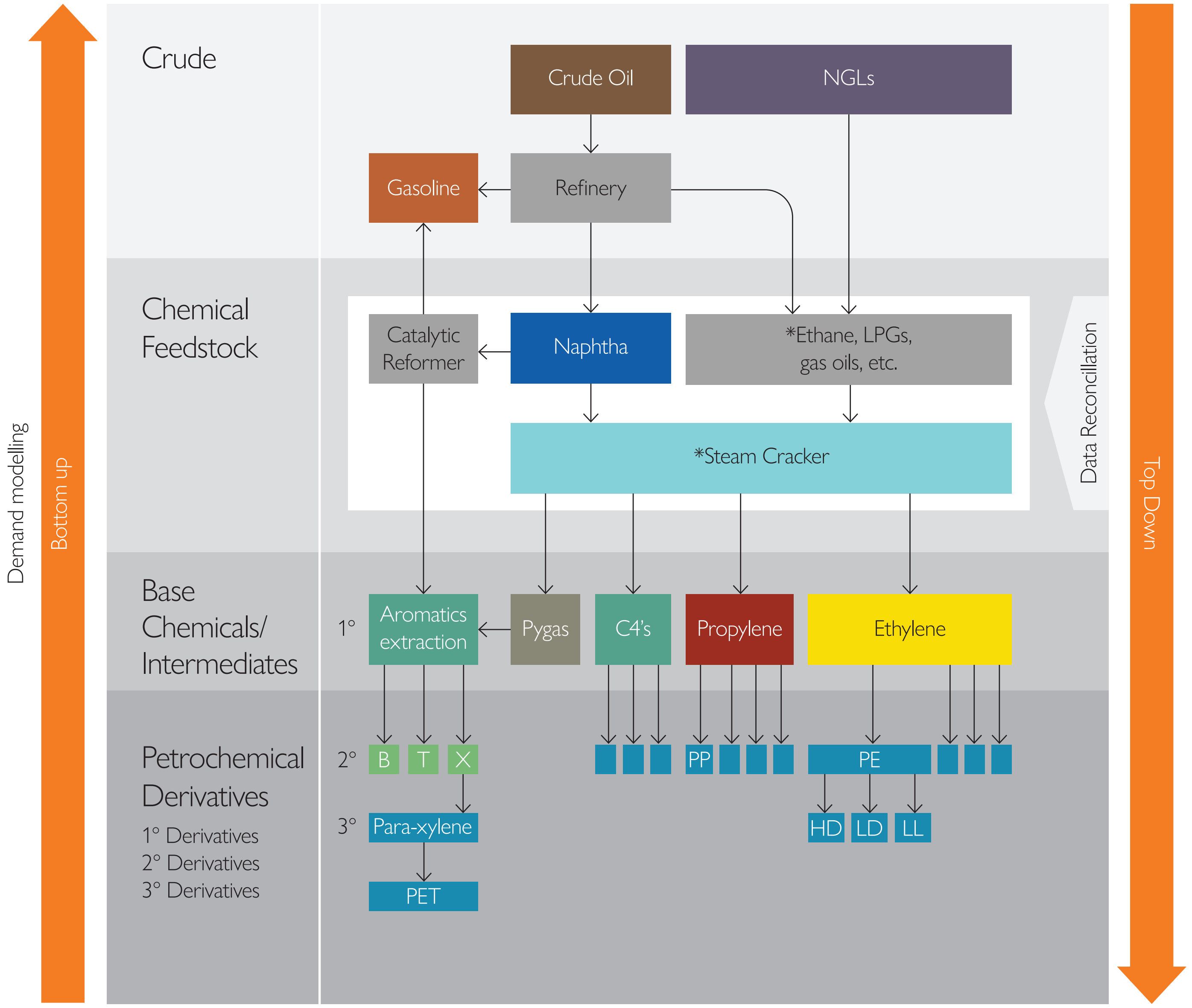
[13] ICIS https://www.icis.com/explore/

Figure 10

ICIS Supply & Demand methodology overview[14]



To forecast the future demand for chemical products, the following main inputs have been taken into account:

- **Macroeconomic trends** such as Gross Domestic Product (GDP), demographics, etc..
- **Evolution of end-use sectors** for each polymer, with an assessment of how different sectors (packaging, construction, automotive, agriculture, etc.) affect current and future demand.
- **Product specific factors** related to shifts in market fundaments (i.e. policy changes).
- **Other ICIS proprietary models** of demand in other sectors that also interface with petrochemicals demand (i.e. transportation sector).

Taking the base case view as a starting point, ICIS then developed a **“Climate-neutrality scenario”** taking into consideration potential impacts of climate targets on the demand for chemicals in the EU27 region. The main factors and trends that inform the analysis are outlined below.

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[14] This a simplified diagram. All other commercially available feedstocks and major processing technologies are considered in the model.

Macro-economic developments

The analysis is based on the general assumption that the EU27 population is expected to peak within this decade, whilst GDP is expected to show slow growth.

Regarding **demographic** trends:

- The population of the EU27 is projected to reach its peak within this decade at around 450 million people.
- However, the population growth rates will vary across different member countries, with some reaching their peak earlier than others.
- A slight decline in the total population is anticipated from 2030 onwards.

The **economic outlook** for the EU27 shows a gradual slowdown of GDP growth over the forecast period, reaching around 0.8% Compound Annual Growth Rate (CAGR) from 2030 to 2050. This is based on a more cautious assumption of economic growth in a scenario of climate neutrality.

Chart 4

Population evolution in the EU27[15]

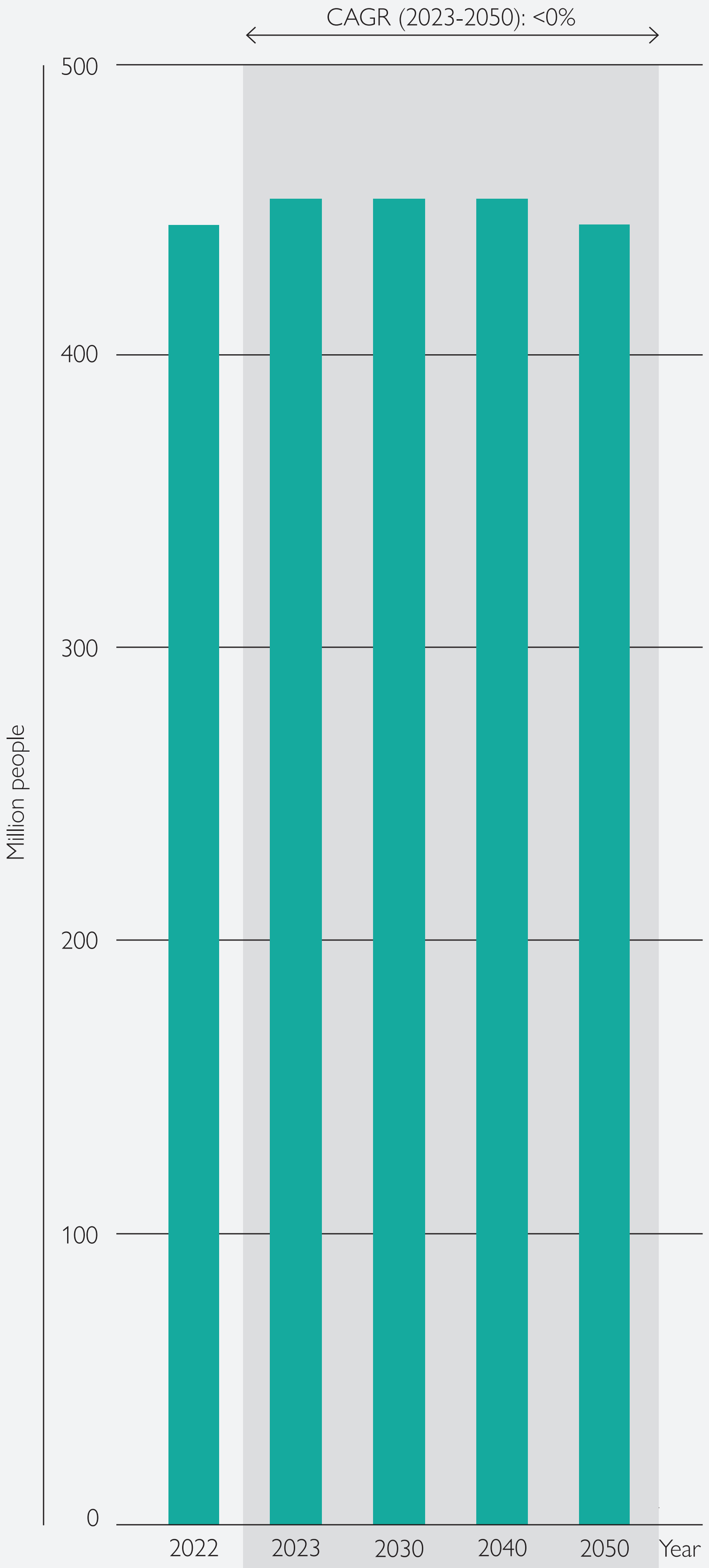
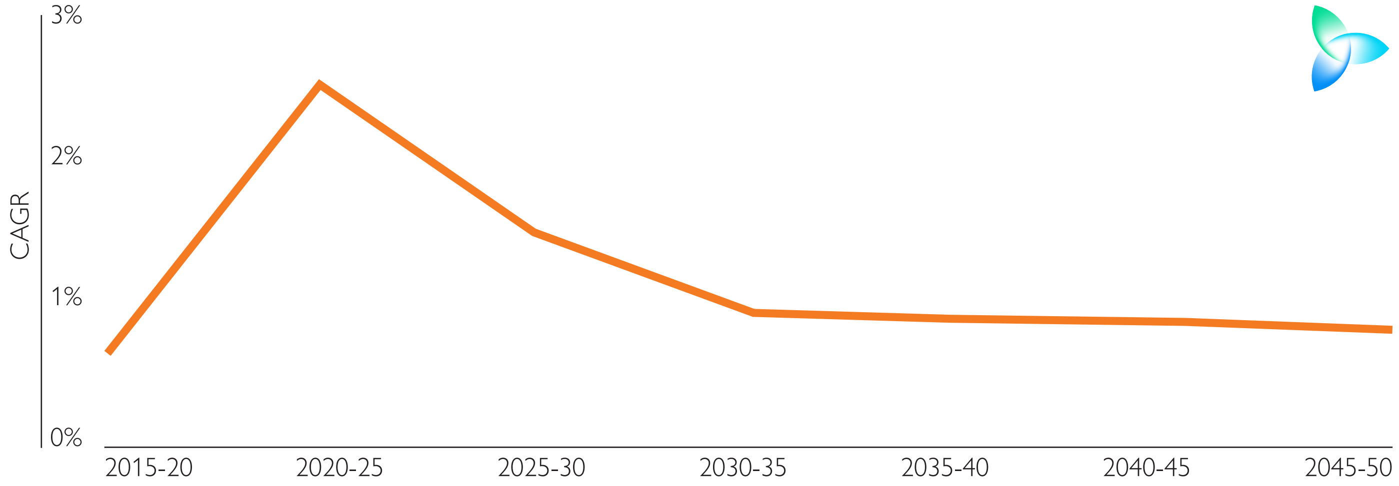


Chart 5

GDP average annual growth assumption in the EU27[16]



End use sectors

The **building and construction** sector is expected to see increased activity as a result of the EU Renovation wave and policy incentives that encourage buildings' energy efficiency improvements. However, these factors will be partly offset by the demographic slowdown.

The **mobility** sector will undergo significant changes as the car fleet becomes more electrified, especially for passenger cars. The demand for cars will also decline due to the higher use of public transport and demographic changes. Moreover, the EU's production will face challenges from the growing exports of other regions.

The **agricultural** sector is projected to maintain a relatively stable amount of arable land, with a slight decrease according to the EU Agricultural Outlook to 2032[17]. The efficiency of fertiliser use is also assumed to improve in the region.

Considering the prospects for the construction sector, the demand for **durable consumer goods** is likely to depend mainly on the need to replace old or obsolete items, which will be stimulated by measures to enhance energy efficiency.

Packaging legislation is anticipated to have a significant influence on curbing single-use plastics by introducing bans and re-use schemes. Materials that are difficult to recycle will face negative pressure. However, plastics usage will still be driven by factors such as shelf-life extension, light-weight properties and convenience.

Impact of regulation

Regulation is expected to play a crucial role regarding future demand for chemical products and trade flows with third countries.

On the product specification side, mandatory **targets on recycled content targets** (e.g. Packaging and Packaging Waste Regulation – PPWR, Waste Framework Directive – WFD), as well as the Ecodesign for Sustainable Products Regulation (ESPR) and Single Use Plastics Directive (SUPD) will drive the reduction in plastic packaging demand. Plastics that are hard to recycle, such as flexibles and multilayer films, will face more pressure than plastics with established recycling value chains, such as PET. Potential targets to be introduced for the automotive sector would be a driver for increasing PP recycling. For some applications that require high performance and/or traceability, mechanical recycling will not be sufficient to meet the targets. In these cases, chemical recycling can offer a complementary solution.

A range of policies that aim to enhance **energy efficiency,** such as the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED), are likely to stimulate demand for plastics in insulation applications (e.g. PS and Expanded Polystyrene – EPS). Other plastics related to building and renovation works are also expected to see a rise in demand (e.g. PVC).

Targets for emissions reduction in the **transportation sector,** like CO_2 performance standards for cars and vans, are likely to boost lightweighting, providing an

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[15] Source: EUROSTAT

[16] Source: ICIS research & analysis based on Oxford Economics

[17] European Commission. (2022). EU agricultural outlook for markets, income and environment, 2022-2032. European Commission, DG Agriculture and Rural Development. agricultural-outlook-2022-report_en_0.pdf (europa.eu)

opportunity for increasing plastics use. GHG emissions reduction targets for the shipping sector are likely to boost demand for low emission fuels, including ammonia and methanol alternatives.

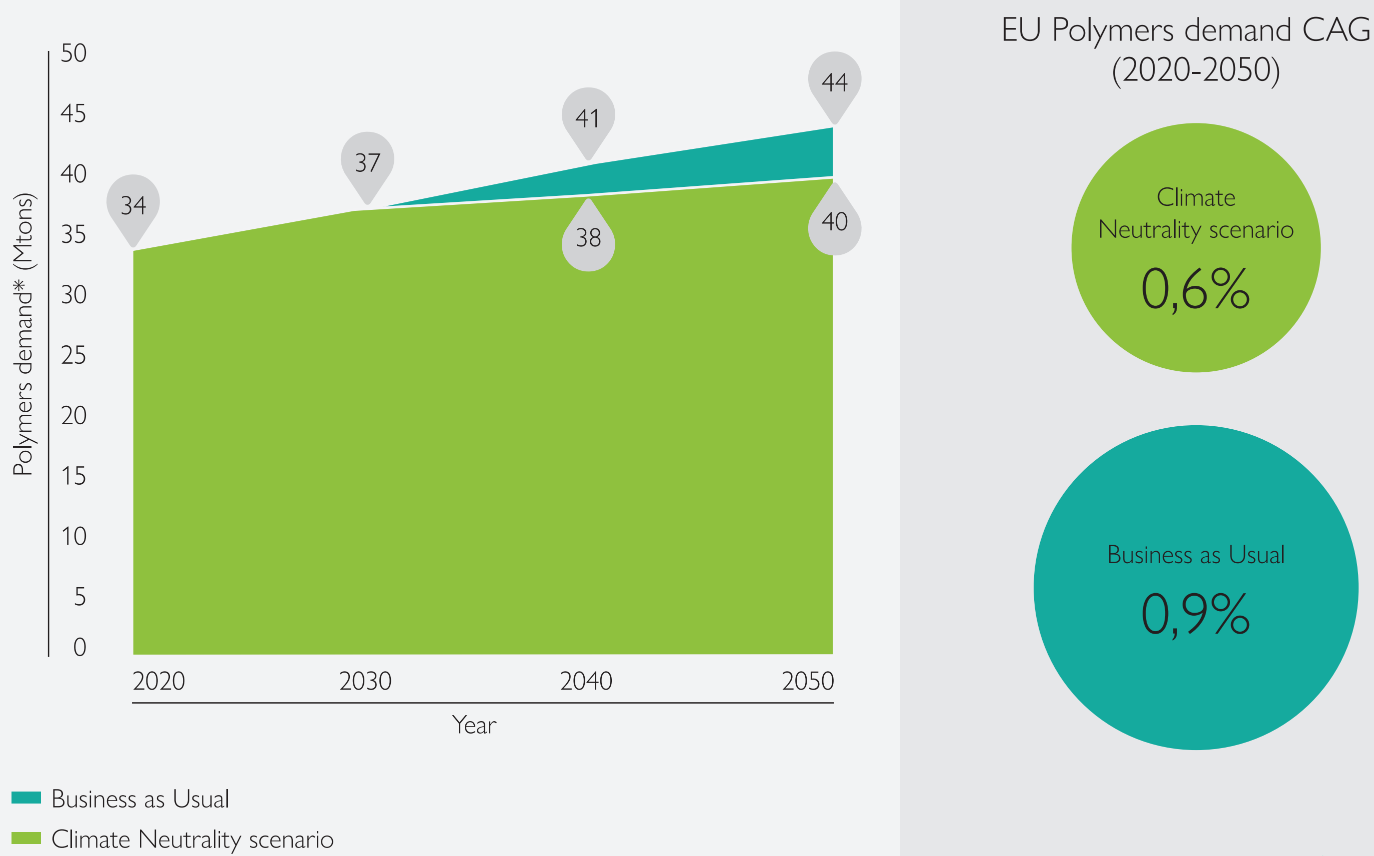
Considerable uncertainty exists regarding future **trade flows and competition with the Rest of the World** and the role Carbon Border Adjustment Mechanism (CBAM) in changing those, with a potential roll out to petrochemicals. In this demand scenario, free allowances for petrochemical producers are assumed to be entirely phased out by 2040, which would be aligned with CBAM (or a similar mechanism) implementation to reduce the risk of carbon leakage and to level the playing field for the industry.

Volumes resulting from the analysis

ICIS considers that in a climate-neutrality scenario, it is likely that regulation incentivising reduce/reuse of single-use and hard to recycle products will play an important role in moderating the **polymers’ demand** growth rate in the EU. These policies are expected to drive demand down by around 4Mtons, compared to a Business-as-Usual scenario.[18] Consequently, converter’s demand is expected to grow at an CAGR of 0.6%, reaching 40Mtons by 2050.

Chart 6

Polymers demand in the EU27 Climate-neutrality vs. Business as Usual (BAU) scenario[19]



*PP, PE , PET (resins only), PVC and PS. Refers to converters consumption in the EU27, i.e., pellets used.

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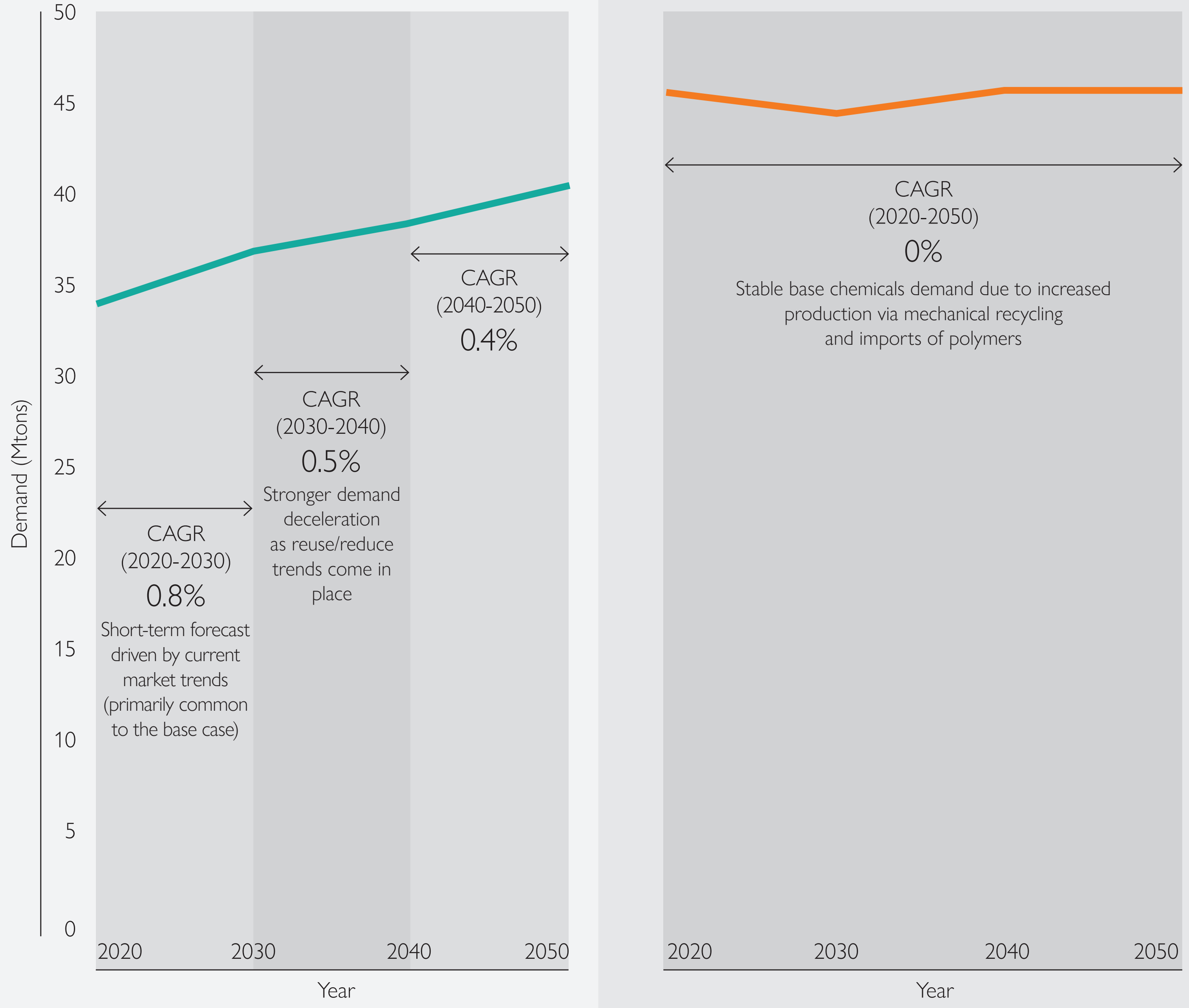
[18] Considering that these initiatives would only be enforced when able to provide positive environmental outcome and that it could require investments in infrastructure and new use/delivery models, ICIS adopted a more conservative view, with a smaller reduction potential than other sources such as Plastics Europe, OECD and SystemIQ.

[19] Source: ICIS Research & Analysis

Base chemicals demand is expected to remain stable over the next years. The moderate growth in demand for polymers is not expected to drive demand growth for base chemicals at the same pace, due to mechanical recycling and changes in trade patterns.

Chart 7

Polymers demand in the EU27 under a climate-neutrality scenario



Olefins & Aromatics demand in the EU27[20]

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[20] Source: ICIS Research & Analysis; Note: Polymers = PE, PP, PVC, PET (resins only), PS ; Olefins & Aromatics = ethylene, propylene, benzene, toluene, mixed xylenes

Mechanical recycling forecast

ICIS's methodology for forecasting output production via mechanical recycling includes the analysis of four main drivers:

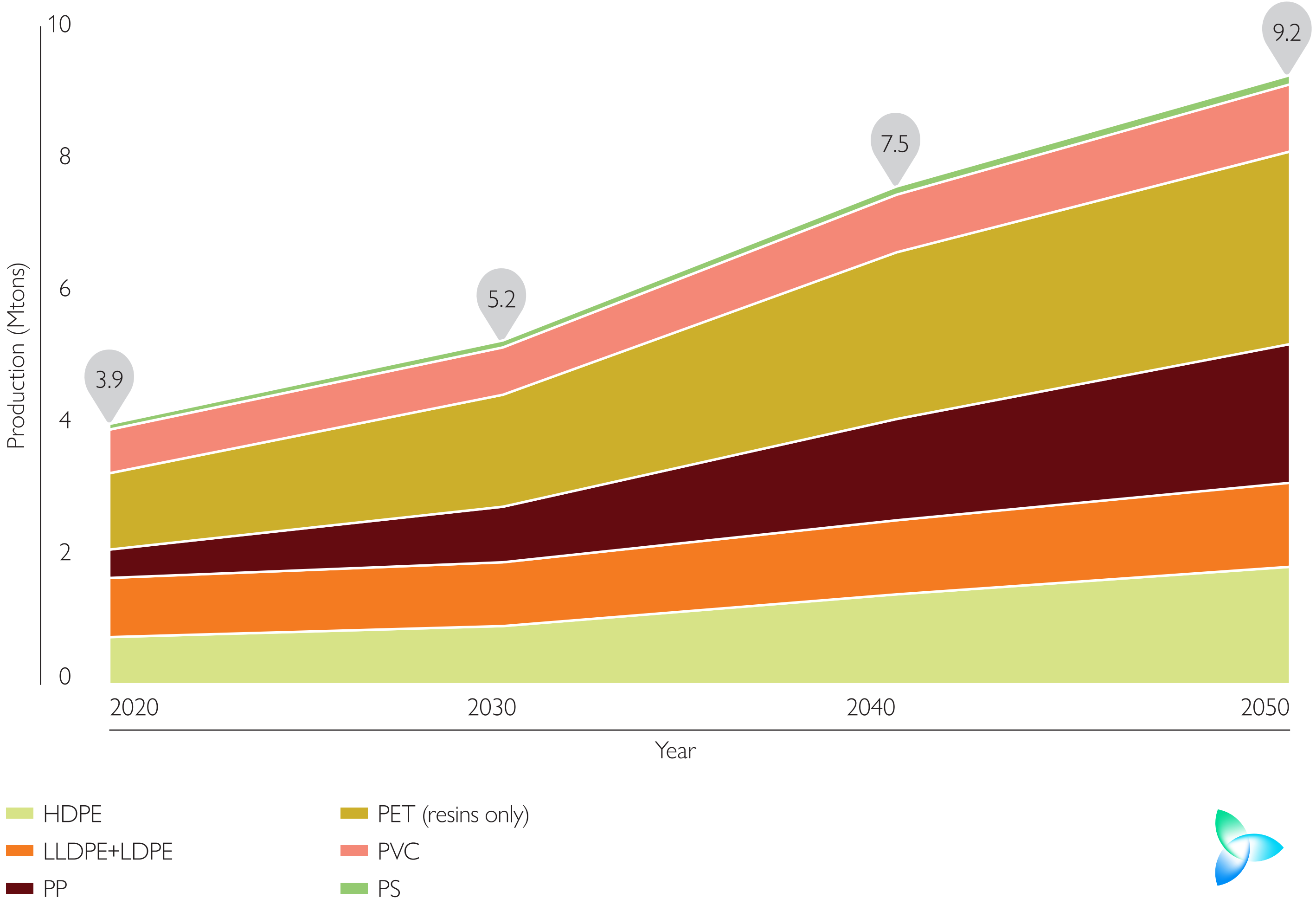
- **Legislative:** Recycled content mandates, SUPD, recycling targets, Extended Producer Responsibility, taxes, etc.
- **Voluntary sustainability commitments and societal pressure** as well as increasing consumer awareness and voluntary brand commitments.
- **Waste management infrastructure** including Deposit Return Systems (DRS) implementation status, collection and sorting coverage.
- **Actionability of the recycling agenda** with infrastructure developments, political will, enforceability and consumer willingness to pay potential premium.

Though recycled content mandates are expected to be the main driver for production via mechanical recycling, it is unlikely that all recycled content targets will be met via mechanical recycling, particularly in the case of flexible applications and/or uses with strict quality and traceability/certification requirements (e.g. European Food safety Authority — EFSA — requirements for food contact applications). Chemical recycling is expected to play a complementary role to mechanical recycling, playing a crucial role in hard-to-recycle applications (e.g. multilayer flexible films), as well as uses that require virgin-like properties and/or specific certifications (e.g. contact sensitive uses).

Consequently, ICIS assumes polymers production via mechanical recycling to reach over 9Mtons by 2050.

Chart 8

Mechanical recycling production in the EU27[21]



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[21] Source: ICIS Research & Analysis. Note: only PET Resins are included. Interregional trade is assumed to be limited, given growing pressure to increase circularity.

Impact of trade

In recent years, global operating rates have followed a downward trend, due to large capacity additions and weaker than expected demand. EU27 operating rates have been falling even further down relative to global averages. Capacity additions are set to continue, driven by China and Middle East-backed projects. While petrochemical demand has proven robust in wake of the COVID-19 pandemic and Russia's war of aggression against Ukraine, demand volumes are significantly lower than pre-pandemic expectations and growth has been hampered by high inflationary environment.

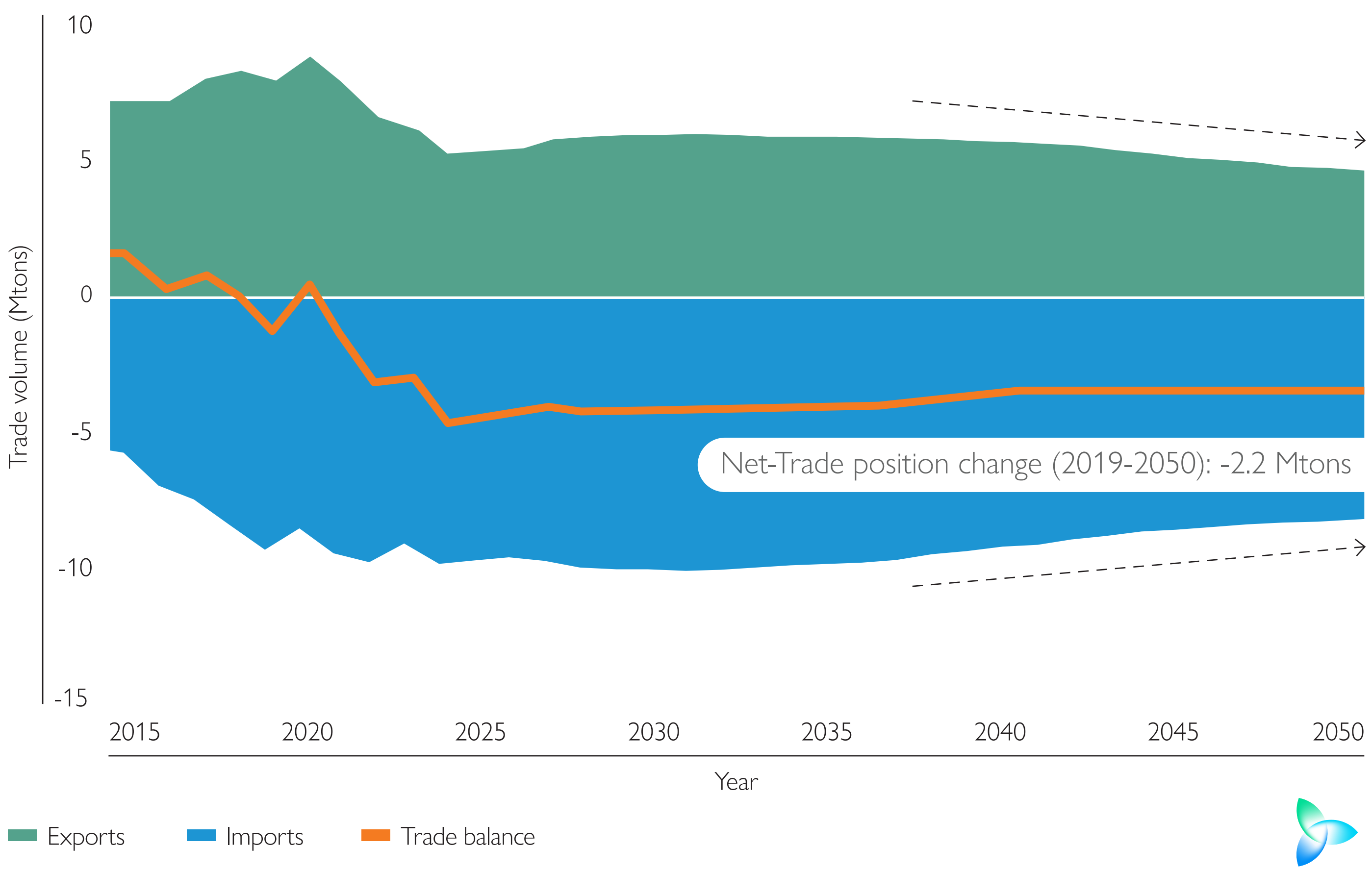
European **production costs** have increased relative to other regions in recent years, largely due to increased energy costs. This has led to **increased import pressures,** fewer export opportunities and compressed margins for local producers. Polymers imports into EU27 have been increasing over recent years, while exports have been pushed downwards since 2021.

Based on those key drivers and trends, ICIS forecasts the EU27 to remain a **net importer of polymers** throughout the forecast period. While the evolution of net-exports position varies across the different polymers, on an aggregated level, EU27 is expected to keep a deficit position through the forecast. Over the last decade, imports have increased significantly in the region, whilst exports evolved from a stable to a declining position as the region's cost competitiveness worsened.

This net deficit position is expected to see small improvements in relation to 2023 levels as operating rates partially recover, in part supported by expectations of lower energy costs. Recovery is limited due to the **new capacities** coming on-stream in other regions before 2030. Increased demand for **recycled products** is expected to be a limiting factor on imports of products from other regions, as domestic waste is assumed to be recycled within the region. From the late 2030s onwards, implementation of protection measures such as the **CBAM** are envisaged to come into force. This is expected to make imports less attractive, but the phase out of free allowances during the same period is expected to negatively impact export volumes from the EU to countries without similar regulation in place.

Chart 9

Polymers interregional net-exports position — EU27[22]



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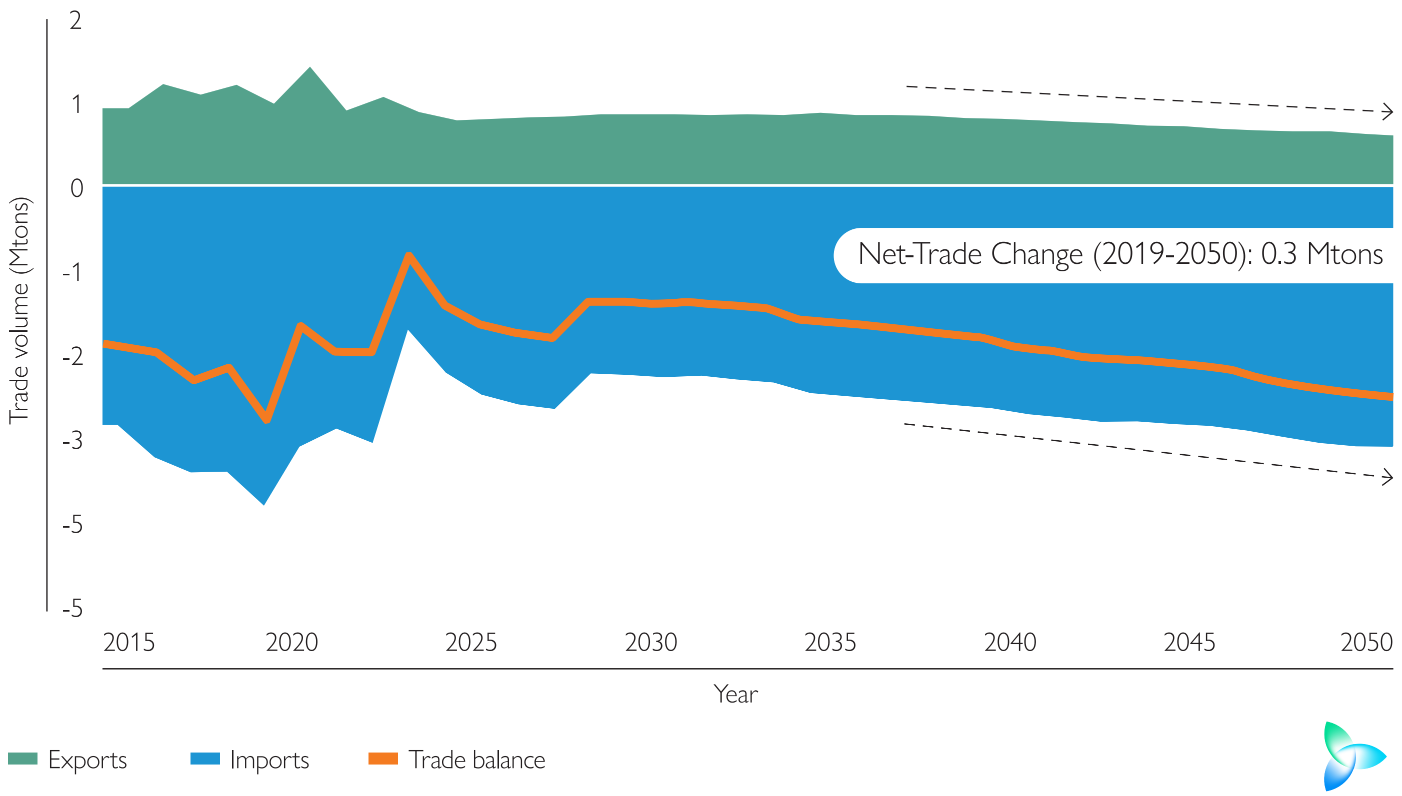
[22] Source: ICIS Research & Analysis; Note: Polymers = PE, PP, PVC, PET (excl. fibres), PS

Chart 10

Olefins and aromatics interregional net-exports position — EU27[23]



Methanol and ammonia demand

In a drive towards climate-neutrality by 2050, demand for low-carbon footprint **bunker fuels** is likely to increase in Europe, creating an opportunity for ammonia and methanol use as fuels. One of the key drivers for alternative fuels incorporation in Europe is the implementation of the “Fit for 55” package, a set of proposals to revise legislation, so that it is in line with the legal obligation of reducing emissions in by at least 55% by 2030 relative to 1990 levels. Part of the “Fit for 55” package, the fuel maritime initiative has set reduction targets for emissions from ships. According to the legislation agreed between European Parliament, Council, from 2025, over 5,000 gross tonnage will have to comply with increasing GHG intensity reduction targets up to 80% against the 2020 baseline level of 91.16g $CO_{2\text{-eq}}$/MJ in 2050 for all intra-EU voyages and 50% of energy used on extra-EU voyages.

At a global level, the International Maritime Organisation (IMO) has defined an ambition to achieve net-zero by around 2050. Measures including goal-based marine fuel standard and a maritime GHG emissions pricing mechanism to meet the targets will be adopted by 2025 and enter in force in 2027. Starting in 2024, Carbon Intensity Indicator (CII) will have to be reported so yearly changes can be monitored against the targets. These legislations are **key drivers of demand** for alternative low-carbon marine fuels. Potential options include synthetic fuels, renewable fuels, ammonia, methanol and bio-Liquified Natural Gas (bio-LNG).

Under ICIS scenario, the **FuelEU Maritime targets** are assumed to be met. The targets set out in the IMO’s revised GHG Strategy, on the other hand, are not assumed to be met given that specific measures are still being discussed and agreed upon. ICIS considers that by 2050 **ammonia** could account for about 12.5% of maritime fuel demand on an energy basis, while **methanol** could represent about 14.6% of demand for maritime fuels on an energy basis. There is a lack of clarity on how the fuel mix will evolve over the next years and it will be influenced by a myriad of factors including costs, feedstocks availability, fuel production technology scale-up, and fuel handling safety. ICIS’s scenario assumes that the electrification of the car fleet would make bio-feedstock more available for maritime fuels and that bio-fuels would remain competitive against e-fuels.

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[23] Source: ICIS Research & Analysis

Overall, this additional demand is not expected to change EU27 historical position of **net importer** for both ammonia and methanol. Additional domestic production of green/low-carbon ammonia and methanol are not expected to be enough to meet the additional demand, therefore imports are expected to increase in the long-term.

Other chemicals

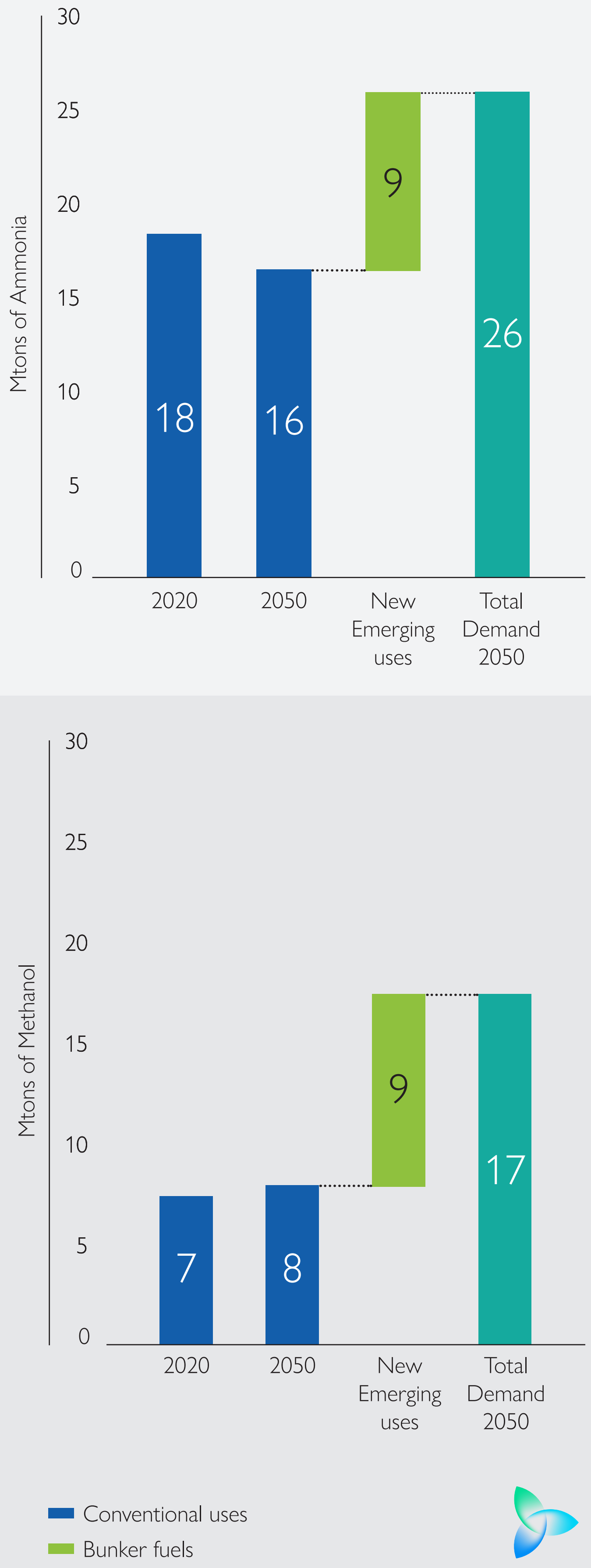
Production volumes for the **“Rest of industry”** in 2019 were calculated by subtracting the production of the 18 chemicals from the total chemical production based on Eurostat[25]. The energy demand and emissions of the “Rest of industry” were adjusted according to the methodology described in section “Aggregated modelling for the “Rest of industry”.

The **average growth rate** for the 18 chemicals was used to project the chemical production of “Rest of industry” up to 2050. As the feedstock for the “Rest of industry” mainly consists of the 18 chemicals that are modelled in iC2050, no additional feedstock was assumed to be needed for the “Rest of industry” aggregate.

The volumes of **“REST Bio”** in 2019, which are not directly sourced from the 18 chemicals, were estimated based on the “Insights into the European market for bio-based chemicals” by the European Joint Research Center (JRC)[26]. The compound annual growth rate for “REST Bio” was estimated to be 3.8% based on the same JRC study and was kept constant up to 2050.

Chart 11

EU 27 – Ammonia and methanol demand in the EU27[24]



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[24] Source: ICIS Research & Analysis

[25] Source: Eurostat. Total production [ds-056121__custom_12579949]

[26] Spekreijse, J., Lammens, T., Parisi, C., Ronzon, T., Vis, M. (2019). Insights into the European market for bio-based chemicals, EUR 29581 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-01501-7, doi:10.2760/18942, JRC112989. JRC Publications Repository - Insights into the European market for bio-based chemicals (europa.eu)

Technology and carbon capture solutions

The **investment cost, operating cost, energy use, feedstock use, associated emissions,** and **date of availability** to 2050 were estimated based on analyses that have been conducted by TNO from public sources. The technology costs that have been taken into consideration for each technology are shown in Annex 3.

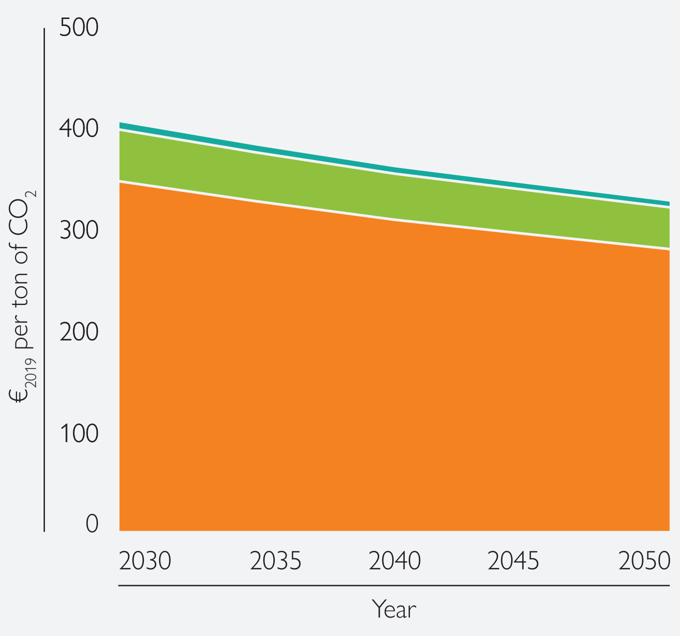
The **substitution and deployment rates** are used to prevent rapid technology switching that diverges from reality as described in Annex 1. The substitution rates used for chemical and heat processes are 10% and 14% respectively. The deployment rates for chemical production, feedstock production and heat generation technologies are assumed to be equal at 12%.

Regarding **carbon capture,** the assumed **rates of CO_2 that is captured** from pipe emissions in the Base Case scenario are set at 98% and 90% for high and low CO_2 concentration streams respectively. The **levelised cost** of net carbon capture in the “Base Case” scenario is shown in Chart 12.

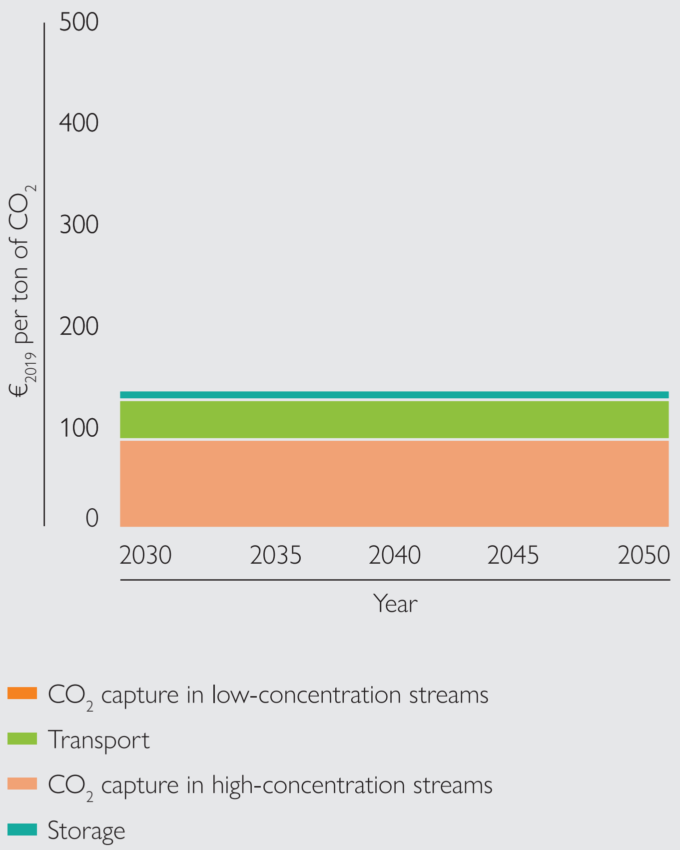
Chart 12

“Base Case” assumptions on the levelised cost of carbon capture and storage

CCS for low-concentration streams



CCS for high-concentration streams



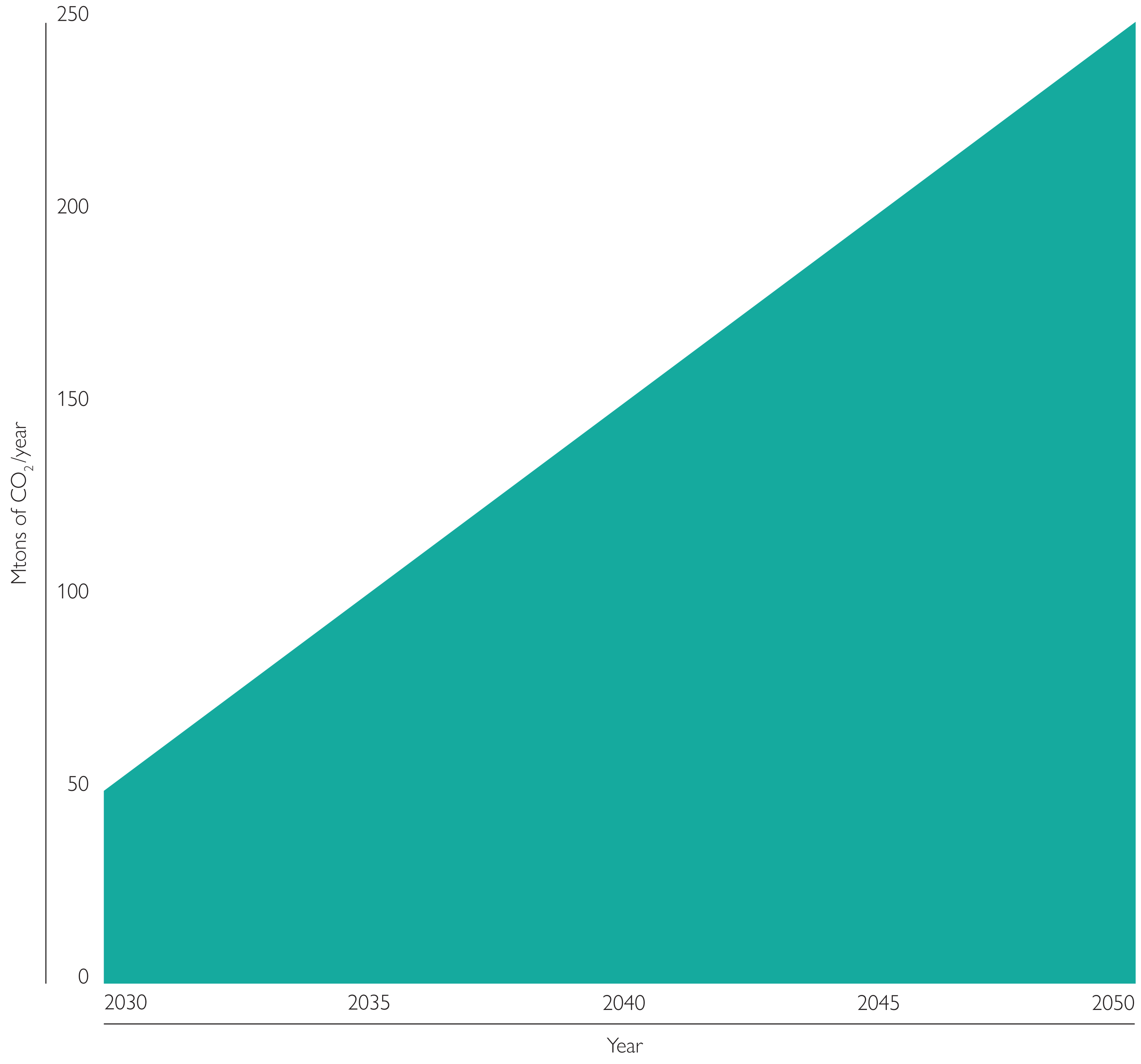
The assumed total yearly **storage capacity,** which is limited by the injection capacity available for each year, is shown in Chart 13.

The **distance parameters** represent a hypothetical distance, which could vary depending on the development of the CO_2 European transport network and, which depends on the purpose and mode of transport. The following average distances are assumed based on expert consultations:

- **Inland transport distance for CO_2 storage:** 700 km
- **Subsea transport distance for CO_2 storage:** 300 km
- **Transport distance for CO_2 usage:** 125 km

Chart 13

"Base Case" assumptions on the yearly injection capacity for CO_2 storage



Resources

Availability

Fossil fuels

The EU27 chemical industry mainly relies on fossil fuels as feedstock at present[27]. However, we expect the availability of fossil fuels to become more and more **constrained** by technical, economic or political factors. In the "Base Case" scenario, we use the **"Fit-for-55"** package and **REPowerEU communication** as a source of information regarding future fossil feedstock availability. According to the REPowerEU strategy, natural gas supply would decrease by 30% in 2030 compared to 2019[28]. Oil and derivatives supply is assumed to be constant and unlimited up to 2050. The assumed availability for fossil-based feedstock is shown in Annex 4.

Sustainable biomass

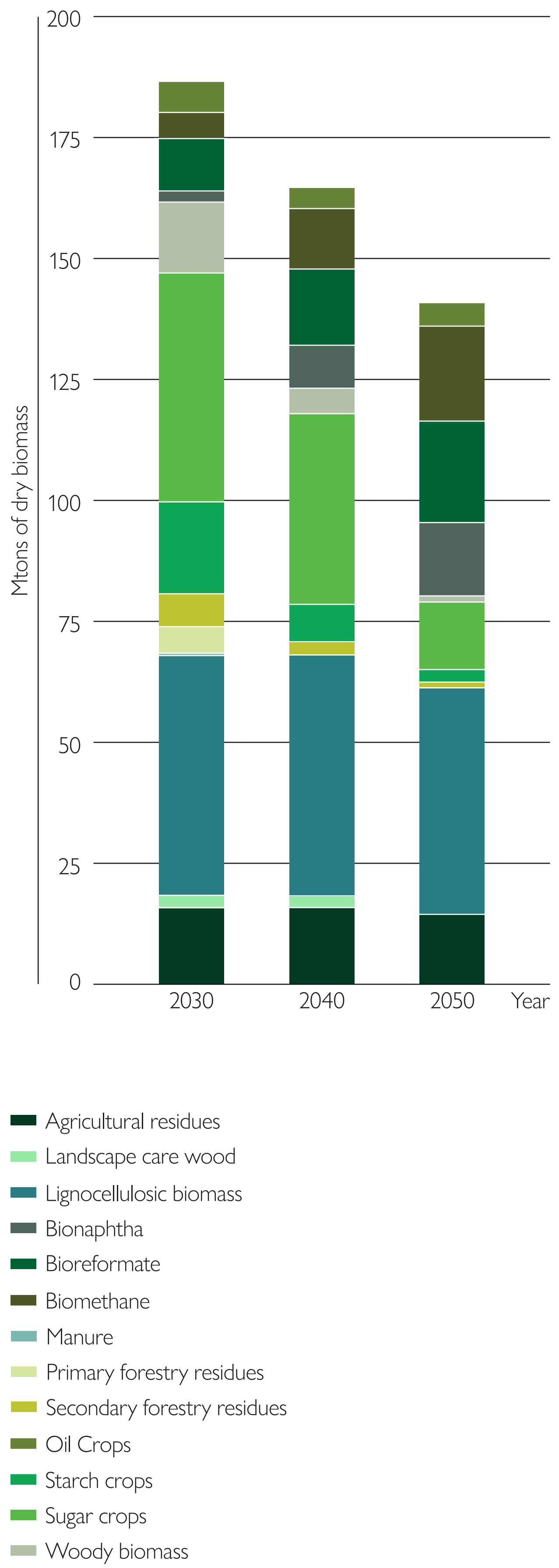
For the "Base Case" scenario, we choose the **"Low" sustainable biomass availability scenario** as presented in Chart 14 based on a CE Delft study for Cefic in 2021 (see Annex 5 for more details). The **oil crops** availability is assumed to remain stable up to 2050 to meet the feedstock demand of "REST Bio" based on the assumed CAGR. The availability of **agricultural residues** has been reduced compared to the "Low" sustainable biomass availability scenario but this is counterbalanced by additional availability of **biomethane** as a fuel and feedstock source on the market.

Electricity

We implemented an upper limit on the yearly electricity supply available in the model. This is to avoid unrealistic electrification of processes that does not match the development of electricity generation capacity in the EU27. The **generation capacity** is expected to grow in future years, and the electricity demand will also increase in several sectors such as the road transport sector. The chemical industry consumed 165.7 TWh of electricity in 2021, which accounts for almost 19% of the total electricity consumption in the EU27 industrial sectors. The S2 scenario in the 2040 Target Impact Assessment[30] (S2 scenario) results in a 12% increase in the industry electricity consumption in 2040 compared to 2021, and a 22% increase between 2040 and 2050. To set the upper limit for electricity availability for the chemical industry, we assume that the share of electricity consumption from the total industry in 2050 would not exceed 25%, which is 7% higher than the current share. As a result, the upper limit for **electricity availability** has been set to **300 TWh** per year up to 2050.

Chart 14

"Base Case" assumptions on sustainable biomass availability[29]



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[27] Source: Kähler, F., Porc, O. and Carus, M. (2023). RCI Carbon Flows Report: Compilation of supply and demand of fossil and renewable carbon on a global and European level. Renewable Carbon Initiative, RCI's scientific background report: "RCI carbon flows report – Compilation of supply and demand of fossil and renewable carbon on a global and European level" (Oct. 2023) | Renewable Carbon Publications (renewable-carbon.eu)

[28] Source: European Commission. (2022). Implementing the REPowerEU Action Plan: investment needs, hydrogen accelerator and achieving the bio-methane targets. EUR-Lex - 52022SC0230 - EN - EUR-Lex (europa.eu)

[29] Source: CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

[30] See European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society Impact Assessment Report. EUR-Lex - 52024SC0063 - EN - EUR-Lex (europa.eu)

GHG intensity

Feedstock

The assumed GHG intensities for feedstock are listed in Table 21 in Annex 4. The GHG intensities in the base year (2019) are sourced from **CE Delft**[31] and **S&P.** To estimate the future trajectories, the **IEA's Net Zero Emissions by 2050 scenario**[32] has been used to project the GHG intensity for fossil-based feedstock up to 2050.

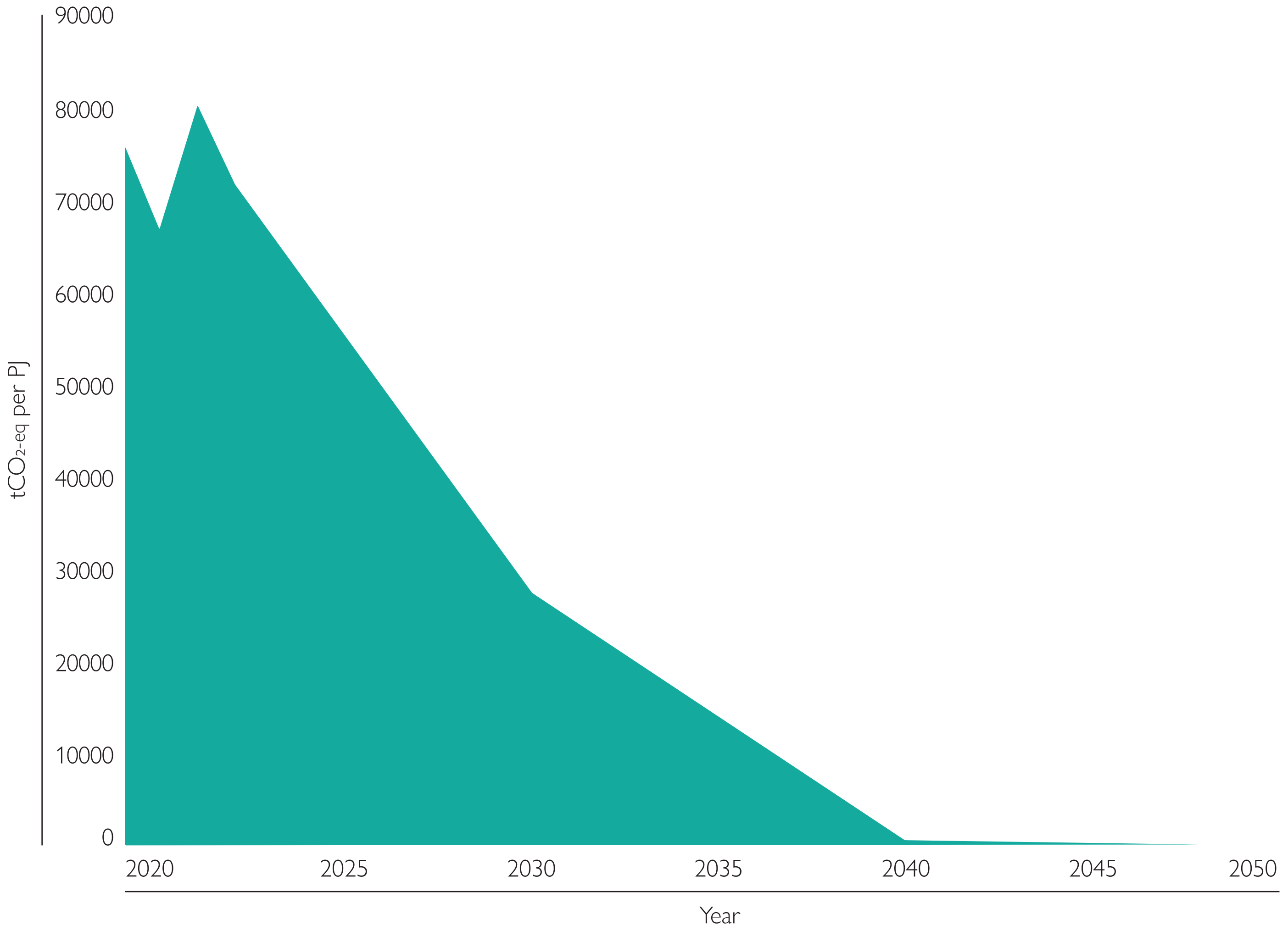
Electricity

The GHG intensity projections for electricity are based on the electricity generation and emissions data for the power sector in the S2 scenario of the **2040 Target Impact Assessment,**[33] taking into account the electricity generation and resulting emissions up to 2050.

The GHG intensity of the electricity supply is influenced by the developments in the power sector, which could vary across scenarios. The assumptions on electricity supply were derived from the S2 scenario of the 2040 Target Impact Assessment, as this scenario assumes no changes in the policy framework, and thus it is considered as a baseline for the current report.

Chart 15

"Base Case" assumptions on the GHG intensity of electricity



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[31] CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

[32] International Energy Agency. (2020). The oil and gas industry in net zero transitions. International Energy Agency. https://www.iea.org/reports/the-oil-and-gas-industry-in-net-zero-transitions

[33] European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society Impact Assessment Report Part III. resource.html (europa.eu)

Prices

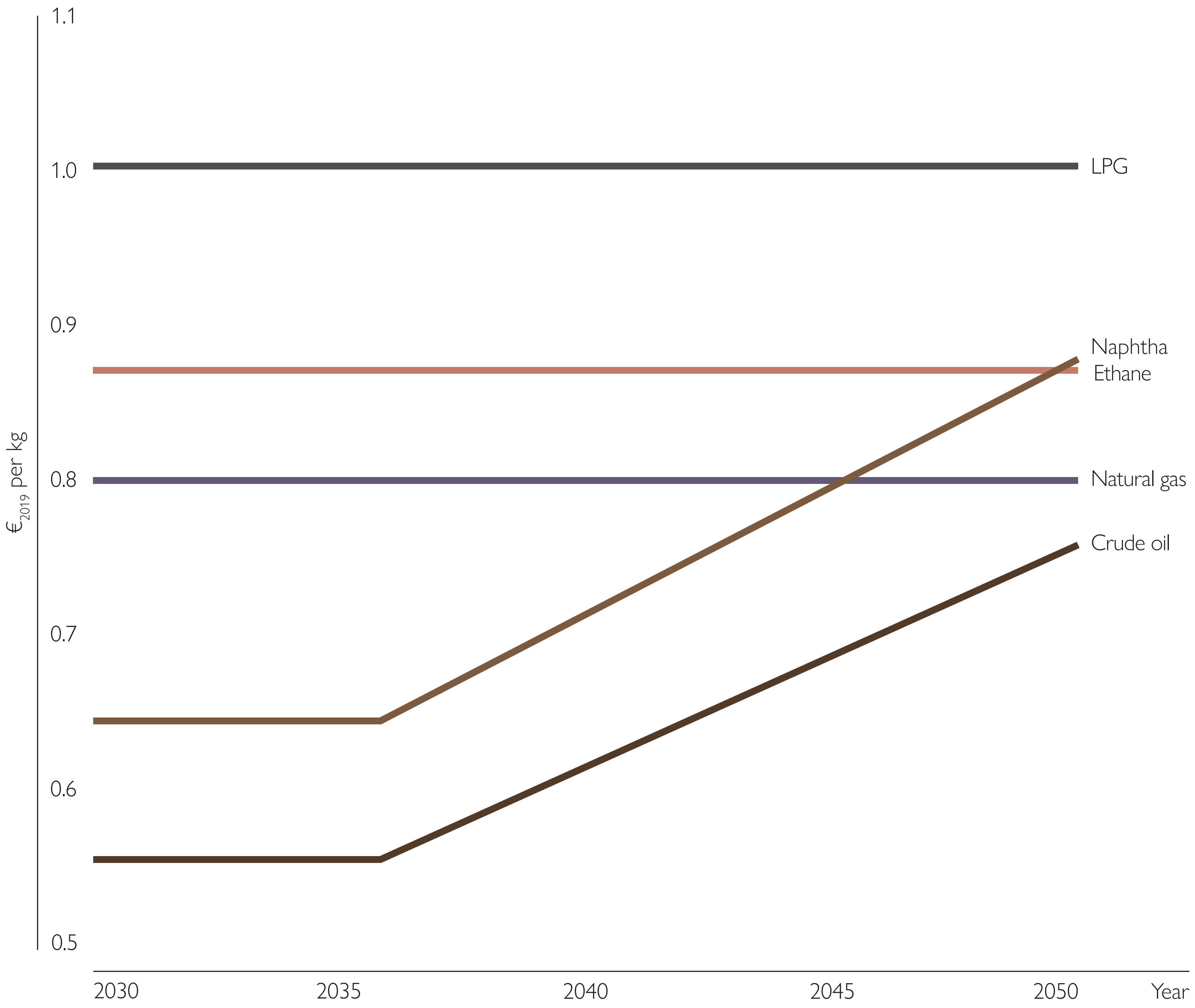
Feedstock

The aggregated prices of **natural gas** and **oil** in the “Base Case” scenario are based on the trajectories presented in the **RePowerEU analysis[34].** The derivatives of oil and gas have been assumed to follow a similar percentage of change in prices as the one for oil and gas. Chart 16 shows the fossil resource price assumptions used in the Base Case scenario. The detailed assumptions on resource prices are listed in Annex 4.

The price of biomass materials[35] is shown in Table 23 in Annex 4.

Chart 16

“Base Case” assumptions on the price of fossil-based resources



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[34] Source: European Commission. (2022). Implementing the REPowerEU Action Plan: investment needs, hydrogen accelerator and achieving the bio-methane targets. EUR-Lex - 52022SC0230 - EN - EUR-Lex (europa.eu)

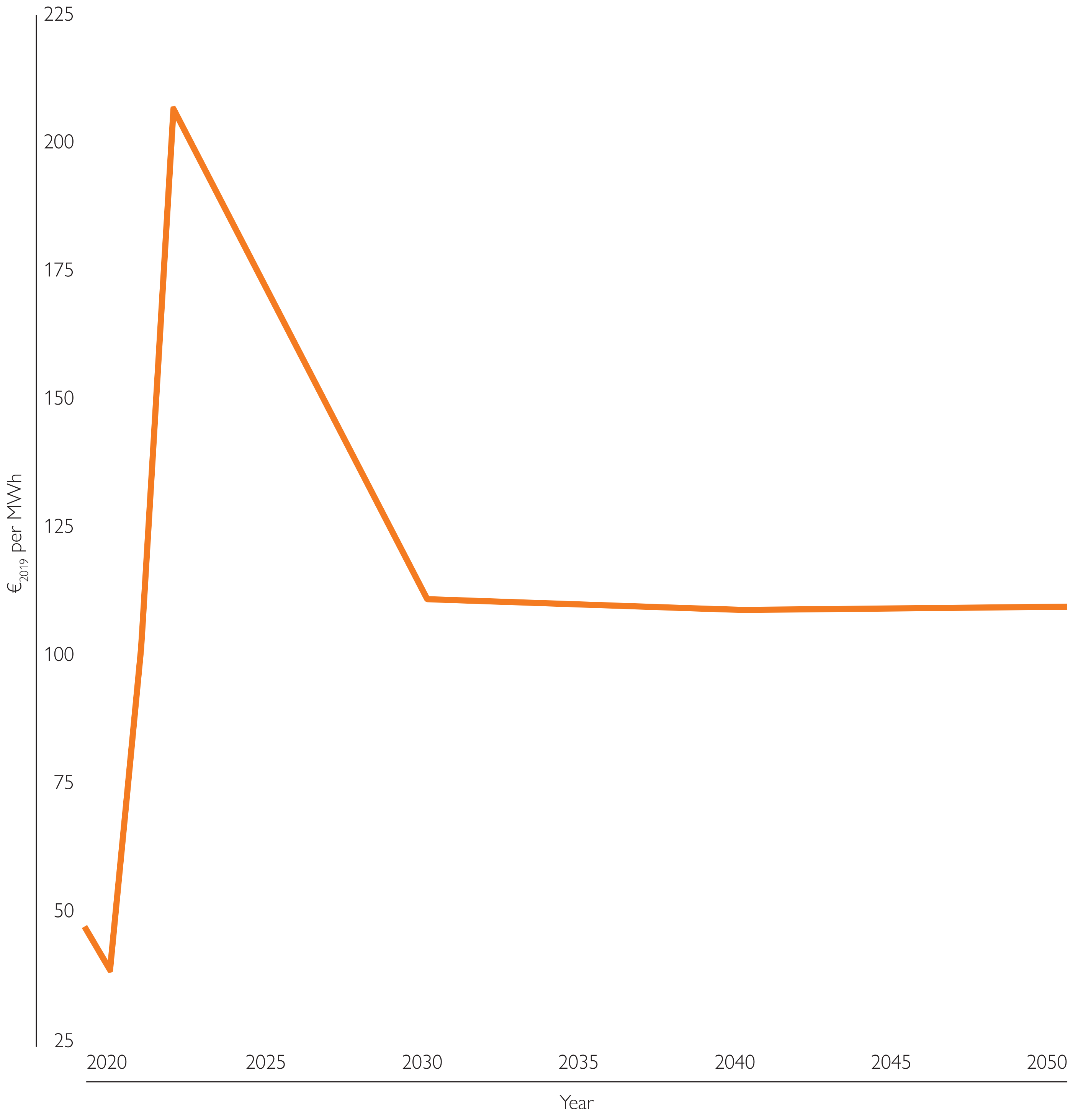
[35] Ruiz Castello P., Nijs W., Tarvydas D., Sgobbi A., Zucker A., Pilli R., Camia A., Thiel C., Hoyer-Klick C., Dalla Longa F., Kober T., Badger J., Volker P., Elbersen B., Brosowski A., Thrän D., Jonsson, K. (2019). ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials, European Commission , JRC116900.

Electricity

The default electricity price assumed in iC2050 is aligned with the S2 scenario of the **2040 Target Impact Assessment.** The price trend for electricity until 2050, which is projected on that basis, is shown in Chart 17. The price presented below is the **final price for the industry,** which includes the network costs and taxes.

Chart 17

“Base Case” assumptions on the electricity price



End-of-life of polymers

Uses and lifetime

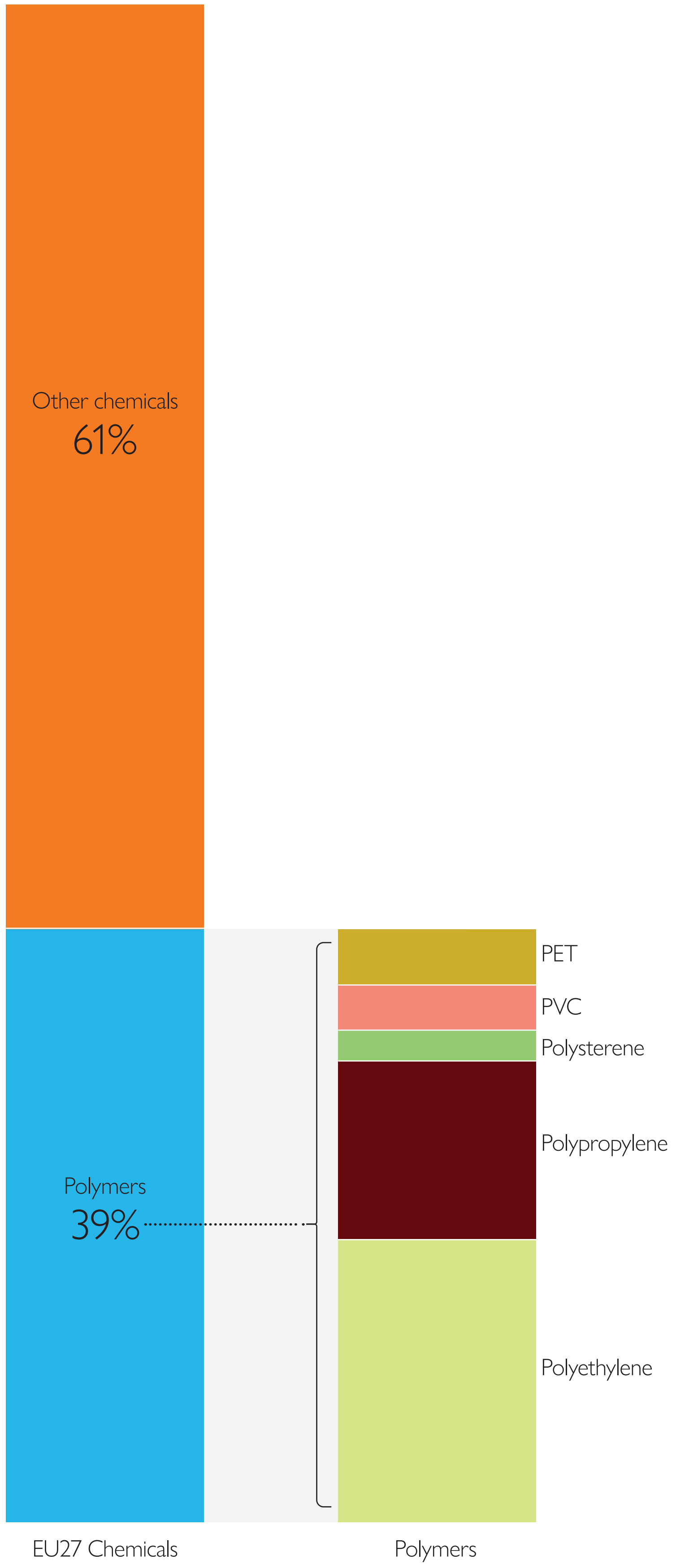
The lifetime of polymers depends on the **usage category** they belong to, and we provide the details of our assumptions on waste management and mechanical recycling in this section.

For the purpose of **carbon accounting,** we assume that half of the biogenic carbon that is incorporated into chemical products will either 1) remain in long-lasting applications (i.e. it will not be released before 2050) or 2) be recirculated through recycling or 3) be captured during waste incineration. The other half is considered as re-emitted at the end-of-life stage.

The polymers, whose end-of-life is modeled, represent **39% of the total carbon** embedded in products, as illustrated in Chart 18. The remaining 61% includes products such as methanol and ethylene that are used for various purposes in the "Rest of industry" aggregate (e.g. ethylene for vinyl acetate production, or methanol for formaldehyde production). The non-polymer chemicals usually store their carbon for a period that varies from less than a year to several decades.[36] We assume that only 15% of the cumulative carbon embedded in the non-polymer chemicals in iC2050 is retained in the products beyond the model's time horizon (2050).

Chart 18

Share of carbon embedded in polymers in the EU27 chemical industry in 2019



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[36] IEA (2019), Putting CO_2 to Use, IEA, Paris https://www.iea.org/reports/putting-co2-to-use.

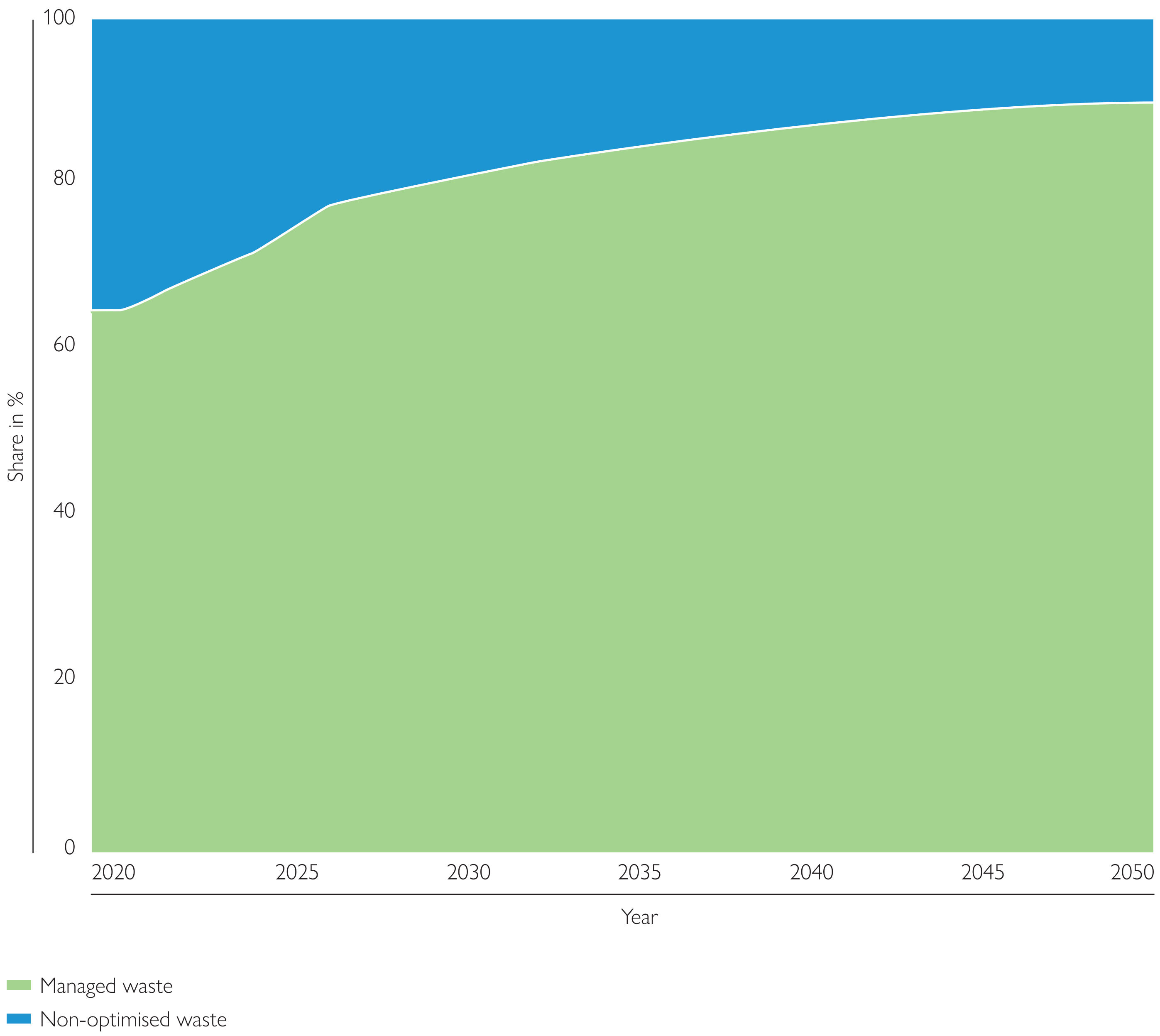
Waste collection and management

The evolution of **"managed"** versus **"non-optimised"** waste that is assumed for the "Base Case" scenario is shown in Chart 19.

We assume that the share of "non-optimised" waste decreases as shown in Chart 19 and represents 10% of the total available waste in 2050. The assumptions on the share of managed waste vary per polymer and usage category. The trajectory shown in Chart 19 is for all end-of-life polymers in the model, which is based on multiple sources including studies from Plastics Europe[37] and SYSTEMIQ[38].

Chart 19

"Base Case" assumptions on the share of "managed" waste



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[37] PlasticsEurope. (2020). Plastics — the Facts 2020. An analysis of European plastics production, demand and waste data. Plastics — the Facts 2020 • Plastics Europe

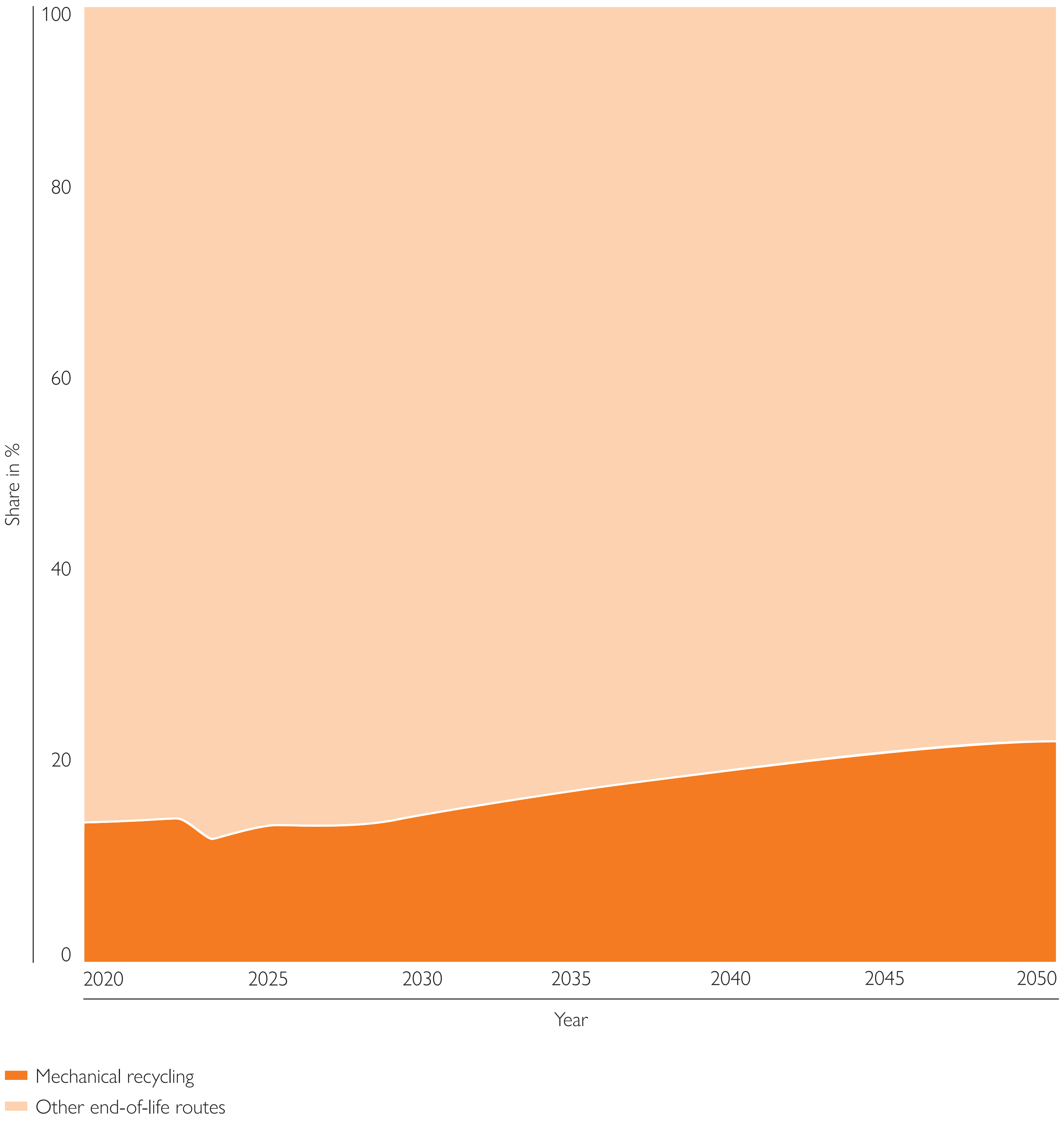
[38] Systemiq. (2023). Circularity of PET/polyester packaging and textiles in Europe — Synthesis of published research. Systemiq-PET-Circularity-Europe-Synthesis-Report-High-Res.pdf

Mechanical recycling

The overall share of mechanically recycled polymers is based on the production volumes projected by **ICIS** in their “Climate-neutrality scenario”. Chart 20 shows the evolution in the share of ‘managed’ waste, which is mechanically recycled.

Chart 20

“Base Case” assumptions on the share of mechanically recycled waste from total managed waste



Policies

Emission cap

Intermediate climate targets have been implemented **for each decade** for scope 1 emissions. For 2040, the target has been fixed based on the emission reductions that are reported in the S2 scenario for the chemical industry, in the **2040 Target Impact Assessment**[39]**.** The assumed targets are shown in 3 below:

Table 3

“Base Case” assumptions on the GHG reduction targets for scope 1 emissions in 2030 and 2040

Year	2030	2040
Scope 1 emission net reduction targets [% compared to 1990]	-71%[40]	-88%

Carbon price

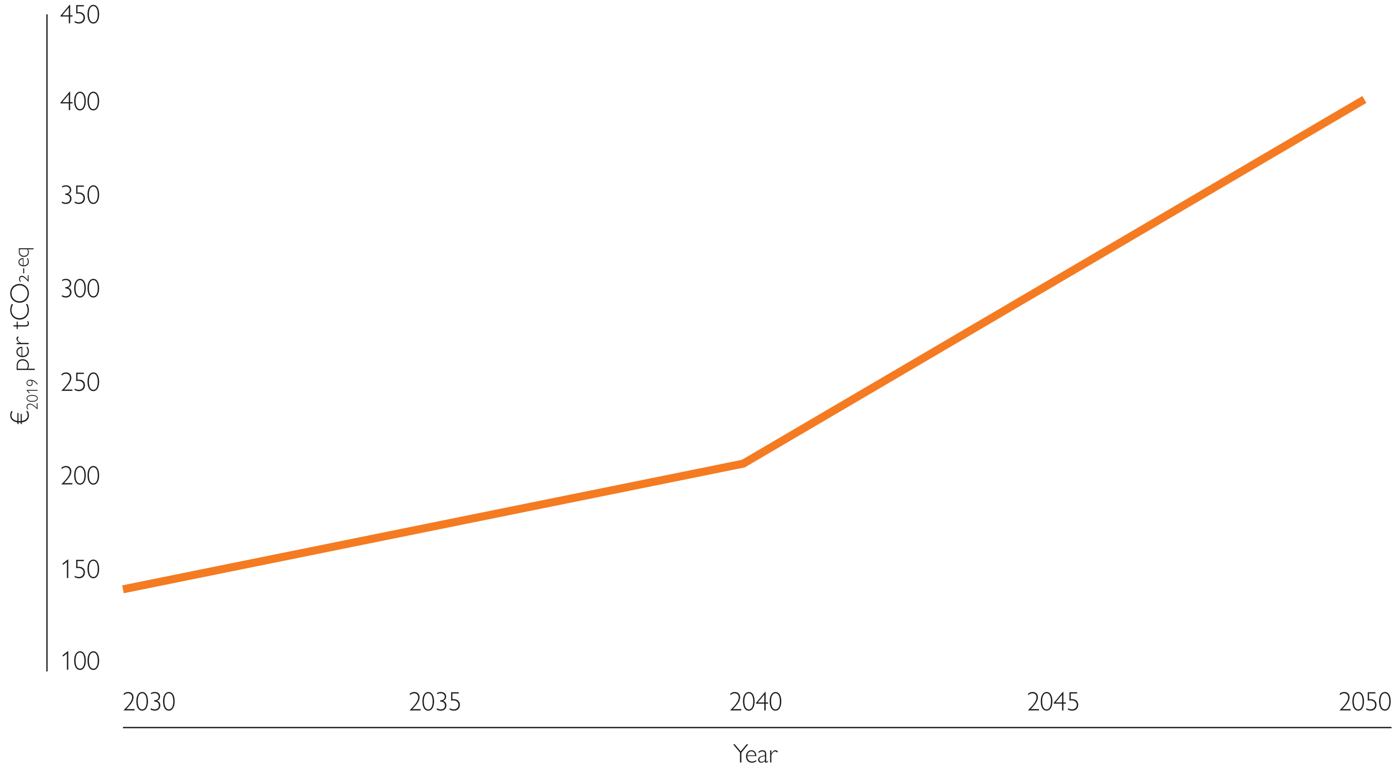
The S2 scenario of the 2040 Target Impact Assessment assumes **carbon values** that reflect the marginal cost of CO_2 emissions within the scenario. The assumed carbon price used in in the “Base Case” scenario is the same as the carbon values of the S2 scenario of the 2040 Target Impact Assessment, as shown in the Chart 21 below.

Sustainable carbon target

To reflect the aspirational objectives of the European Commission’s communication on Sustainable Carbon Cycles[41], a sustainable non-fossil **target of 20%** has been implemented in the model for carbon-containing products starting from 2030.

Chart 21

“Base Case” assumption on the carbon price



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[39] See European Commission. (2024). Europe’s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society Impact Assessment Report Part III – Annex 8, Chapter 1.4 “Industry” Figure 52 and 53. EUR-Lex - 52024SC0063 - EN - EUR-Lex (europa.eu)

[40] The 2030 reduction versus 1990 has been defined based on the ETS cap which brings emissions down by 62% compared to 2005 levels.

[41] European Commission. (2021). Sustainable Carbon Cycles. 26c00a03-41b0-4d35-b670-fca56d0e5fd2_en (europa.eu)

Section 9.2

Results of the “Base Case” scenario

The deployment of abatement solutions and corresponding resources highly depends on the **scope of emissions** that need to be abated, even if the initial set of assumptions remains the same. Here we first show modelling results when the ambition to become climate-neutral applies to all emissions that are part of the modelling scope. In a second step, we will first consider the implications of reaching climate-neutrality when looking only at direct scope 1 emissions (see section "Emission scope" for a detailed overview of emissions covered).

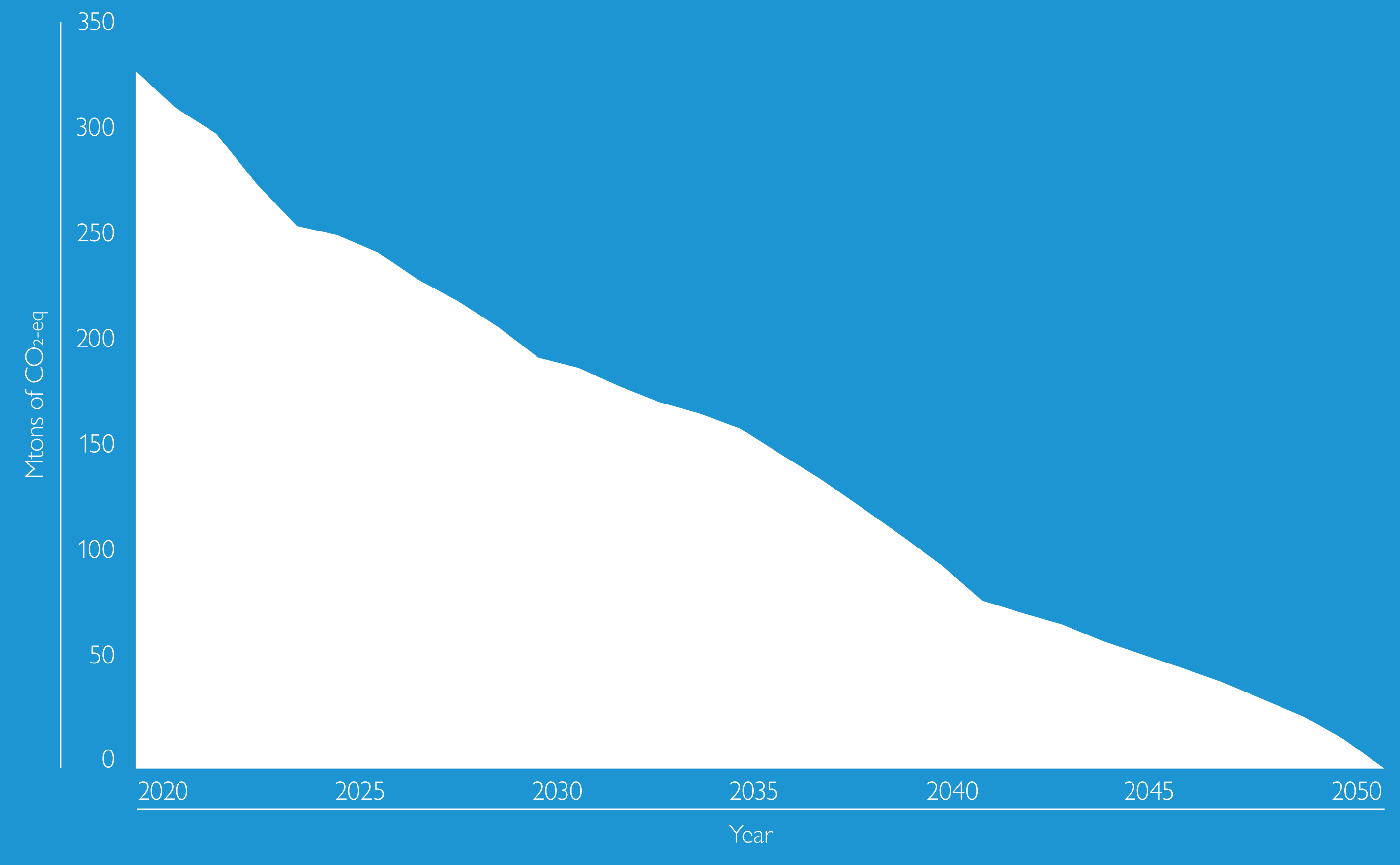
The abatement pathway

Under this scenario, intermediate emission targets are set on scope 1 emissions, while the climate-neutrality constraint applies to the full scope of emissions in 2050. Chart 22 shows the **abatement curve** for all emissions up to 2050.

We can observe a slowdown after each ten-year period, once the intermediate targets have been met. It is also possible to observe a change in the emission slope in 2030, related to **end-of-life emissions.** This temporary decrease in the pace of emissions reduction can be explained by the implementation of the landfill ban for managed waste streams: the deployment rates of mechanical and chemical recycling do not provide enough capacity by the early 2030s to prevent incineration with energy recovery. The slope of emission reduction increases between 2034 and 2040 as direct emissions have to go down by the 88% in 2040.

Chart 22

Total net GHG emissions in the "Base Case" scenario between 2019 and 2050



The pace of emission reduction varies between different emission scopes depending on the availability of abatement solutions. GHG emissions per scope in the “Base Case” scenario are shown in Chart 23.

Direct Scope 1 emissions continuously decrease up to 2050 due to switching to alternative production technologies, low-emission heat generation, and the deployment of carbon capture at the process level.

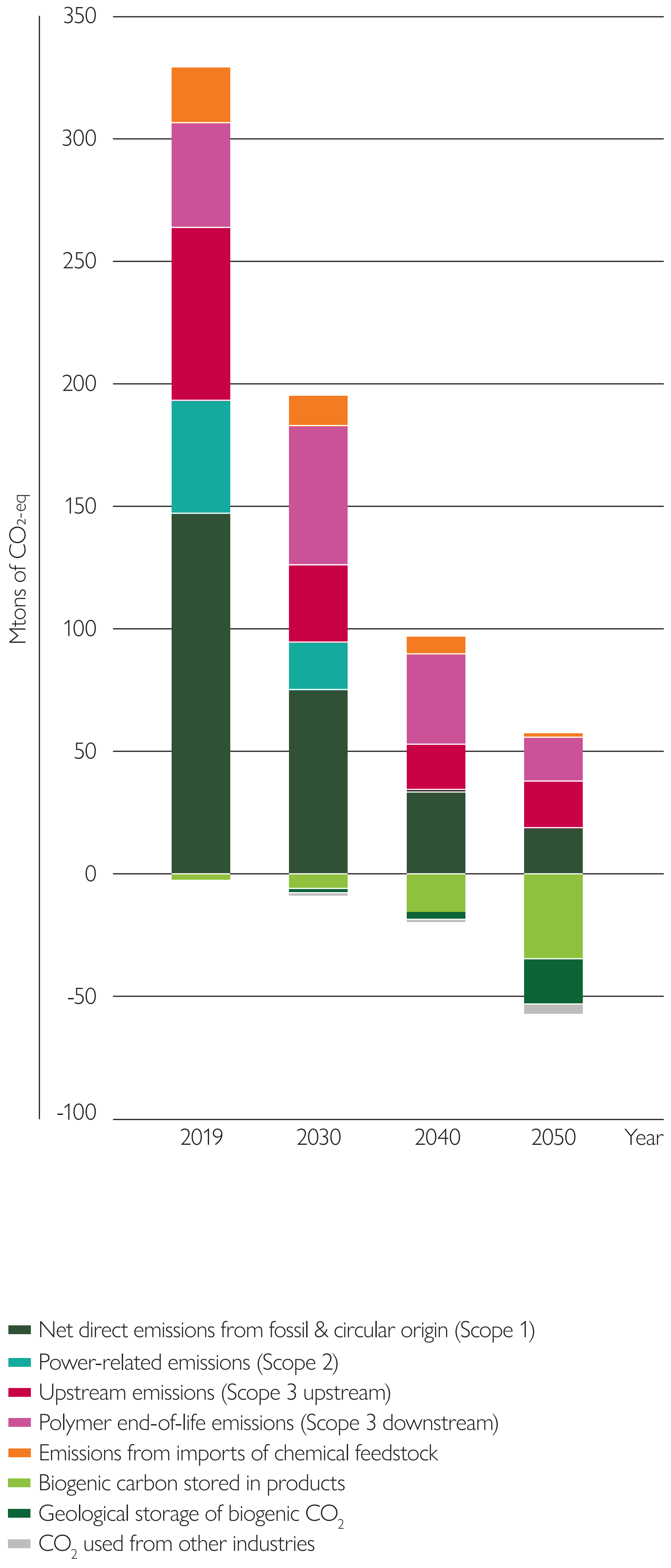
Scope 2 emissions decrease up to 2040, after which they reach zero, based on the assumption that the power sector would become almost climate neutral by the same year. Although processes and heat supply become more electrified, scope 2 emissions decrease with the lowering GHG intensity of the electricity supply.

Upstream emissions and fossil-based feedstock consumption decrease rapidly until 2040 to enable reaching the emission reduction targets and the 20% non-fossil feedstock target in 2030. The GHG intensity of fossil and bio-based feedstock is also expected to go down as shown in Annex 4. After 2040, emissions reduce at a slower pace, since the feedstock mix remains relatively stable. **End-of-life emissions** of polymers reduce mostly after 2040 as incineration of end-of-life polymers is reduced through higher chemical and mechanical recycling rates.

To reach climate-neutrality, residual emissions by 2050 should be compensated by **negative emissions.** In 2050, more than 50Mtons of $CO_{2\text{-eq}}$ are compensated by biogenic emissions that are captured and stored into geological storage or chemical products. The majority of residual emissions in 2050 fall under scope 3, while the rest are scope 1 emissions, which remain uncaptured as the capture rate is below 100%.

Chart 23

GHG emissions per scope in the "Base Case" scenario



Technology deployment

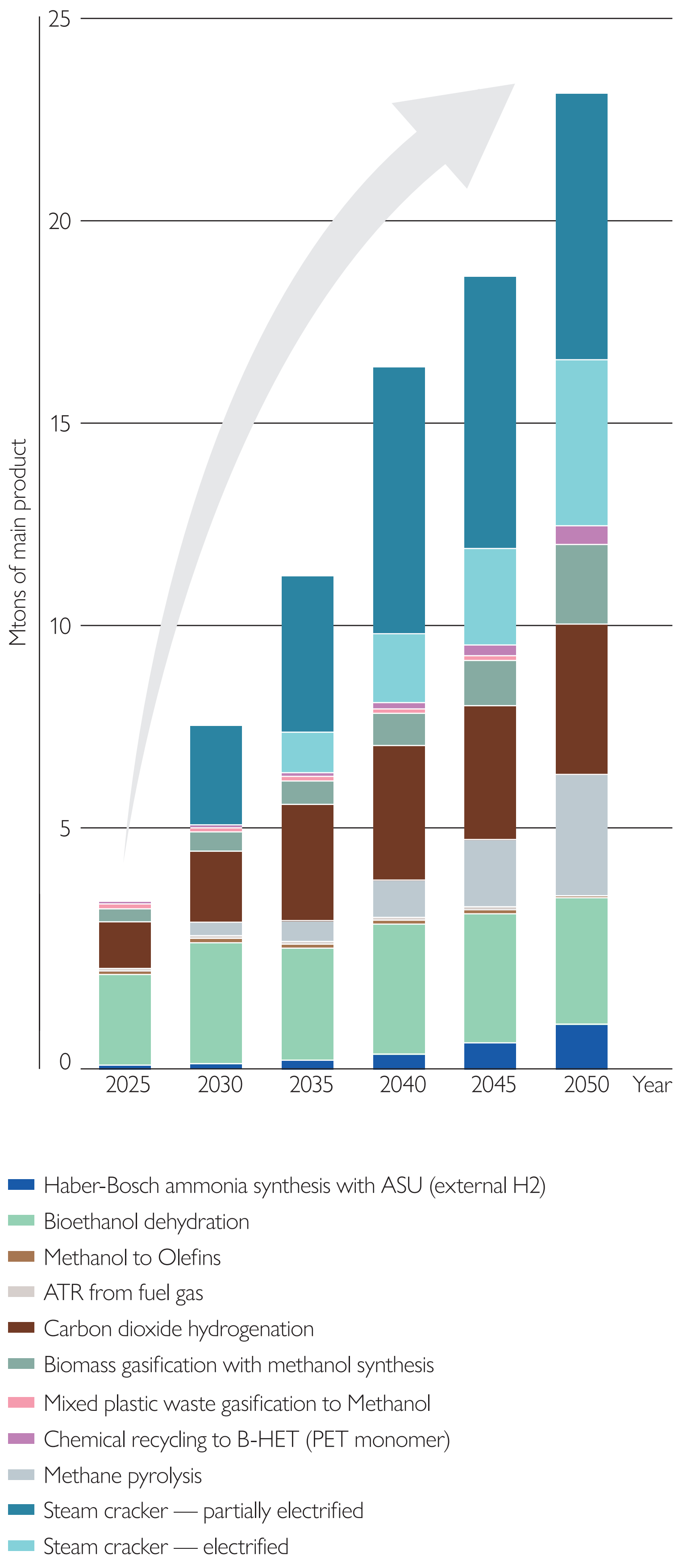
The model taps into all main categories of solution for abating direct GHG emissions: switching to alternative processes and production routes, changing the heat source, and capturing CO_2.

Chart 24 shows the **capacity deployment** across the modelling period for alternative technologies to produce the 18 main chemicals. This excludes feedstock production and heat production. (Partial) **electrification of the steam cracking** processes emerges as a key technology to abate direct emissions from traditional steam cracking. The decarbonisation of the power sector, which becomes almost climate neutral after 2040, drives the model to invest in the electrification of crackers.

Alternative production routes also represent the most important share of the new innovative production capacity: methanol is produced via **biomass and CO_2 hydrogenation** (CCU) to meet the growing demand for bunker fuels, while bioethanol dehydration develops as an alternative ethylene supply route. **Methane pyrolysis** emerges as an alternative technology for the production of hydrogen, while autothermal reforming is not significantly deployed within the "Base Case" scenario.

Chart 24

Cumulative capacity for new production technologies in the "Base Case" scenario



The distribution of **capital investments,** which confirms these trends, is shown in Chart 25[42]. To meet the 2040 climate target on direct emissions, most investments take place between 2030 and 2040.

Over the entire period, the largest amount of capital investments (149 Bio€) goes to the **production of alternative feedstock,** within the perimeter of the chemical industry. Investments are made in biomass gasification for the production of biomethane as it is used as both a source of feedstock and fuel for heat generation. Chemical recycling, in particular plastic waste pyrolysis, also starts early in the period, as it is one of the main instruments available in the model to abate end-of-life emissions for polymers. After 2030, these investments nearly triple compared to the first decade.

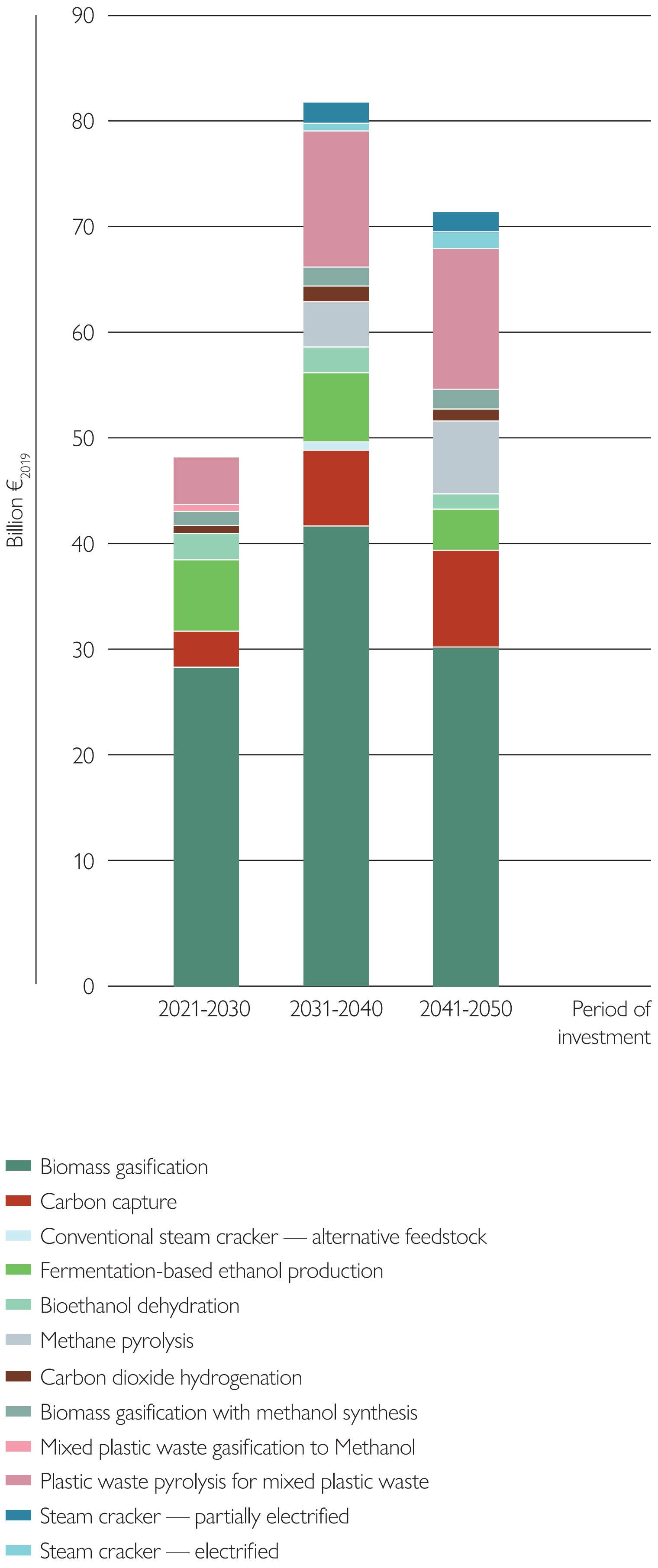
Carbon capture solutions which start to receive financing around the mid-2020s also represent a significant share of investments (19.5 Bio€), especially after 2030.

Conventional technologies, like steam cracking also require some investments (1 Bio€) into retrofitting, in order to process new types of feedstock (e.g. bio-naphtha or py-naphtha).

The deployment of abatement solutions for the 18 chemicals represent altogether **more than 200 Bio€.** A share of these investments, which are reported under each individual process are directed to **electric and biomass boilers.** Altogether, these investments represent 6.5 Bio€ over the assessed time period.

Chart 25

Capital investment going to new technologies[43]



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[42] The investments shown in chart 25 are annualised, and discounted to the base year which is 2019. The salvage value of annualised investments after 2050 are not presented in this figure.

[43] See Annex 2 for a full list and description of technologies

Production of olefins and aromatics

Electrification of steam cracking units

Over the entire period, the biggest share of olefins and aromatics is produced via steam cracking, although this share goes down as new production routes start to emerge (see Chart 29). **Electrification** and partial electrification of steam cracking are some of the key solutions to abate direct emissions, and take place starting the 2030's. Due to the upper limit of 300 TWh/year that has been set in the "Base Case" scenario, the total share of electrified cracking is bound by this the assumed availability.

As shown above, conventional crackers, still represent a significant share of olefins and aromatics production by 2050. However, **carbon capture,** which is already deployed in the mid-20s and captures 88% of CO_2 emissions by 2050, allows to mitigate the related emissions.

Chart 26

Electrification of steam cracking capacity

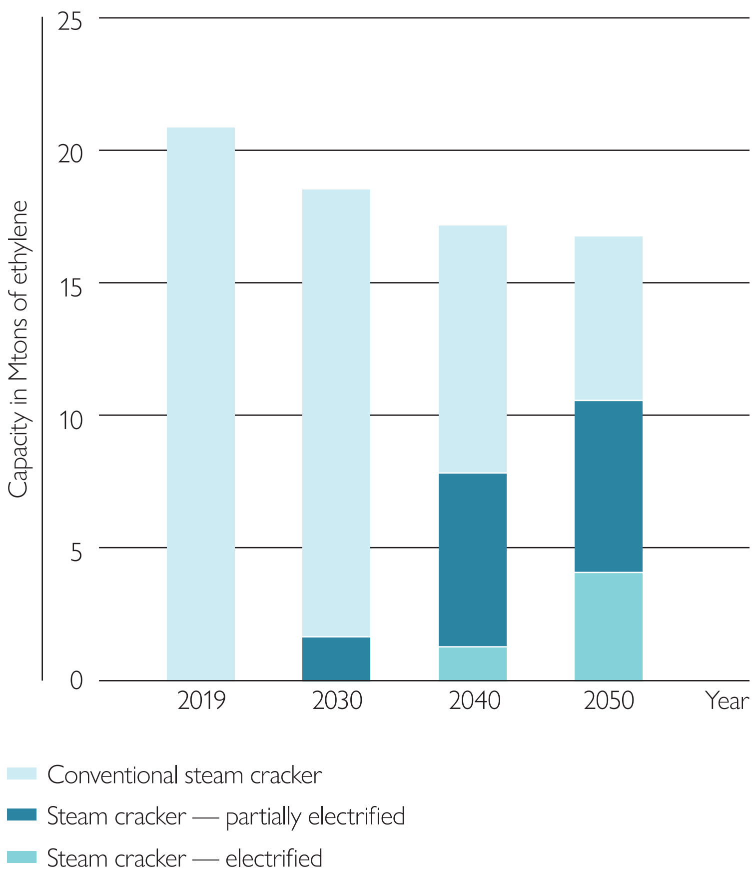
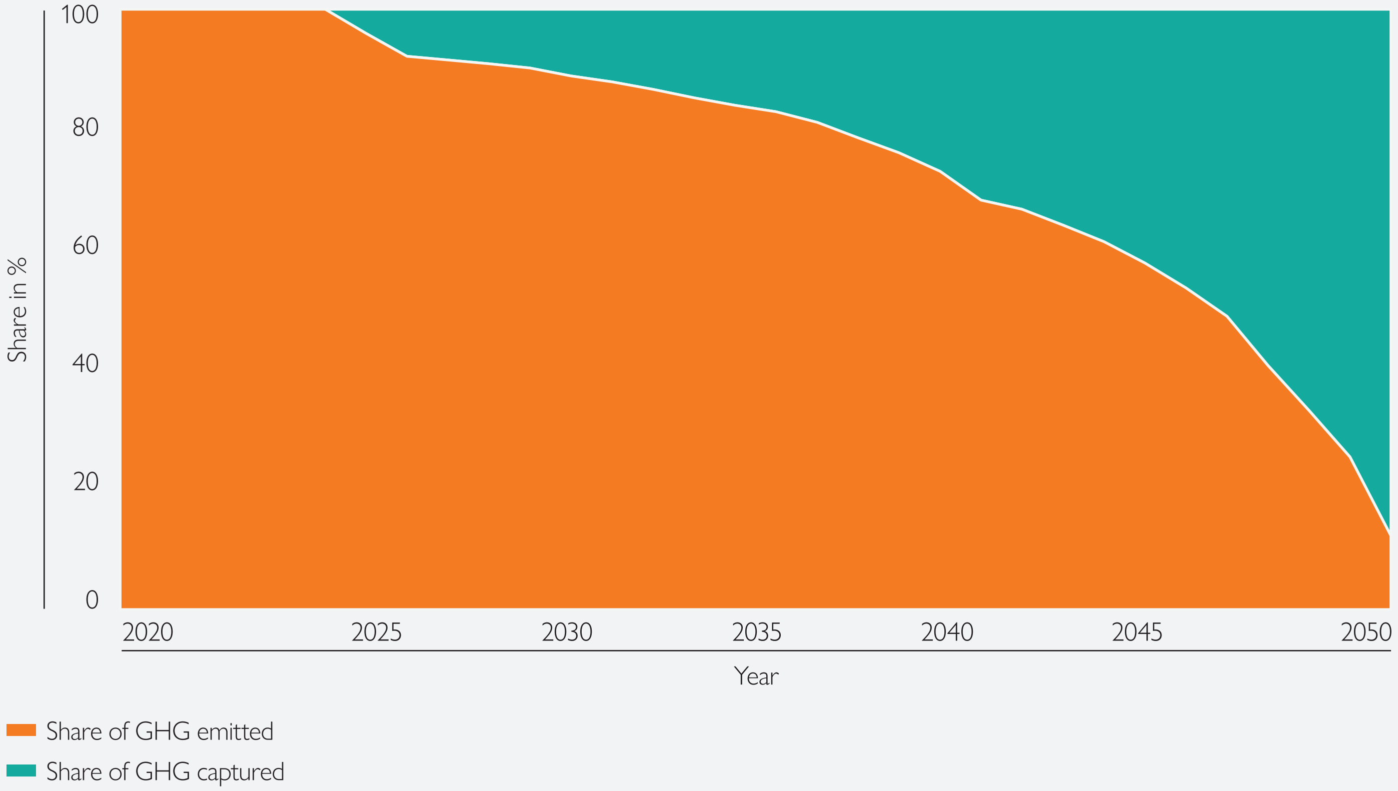


Chart 27

Carbon capture deployment on traditional steam crackers

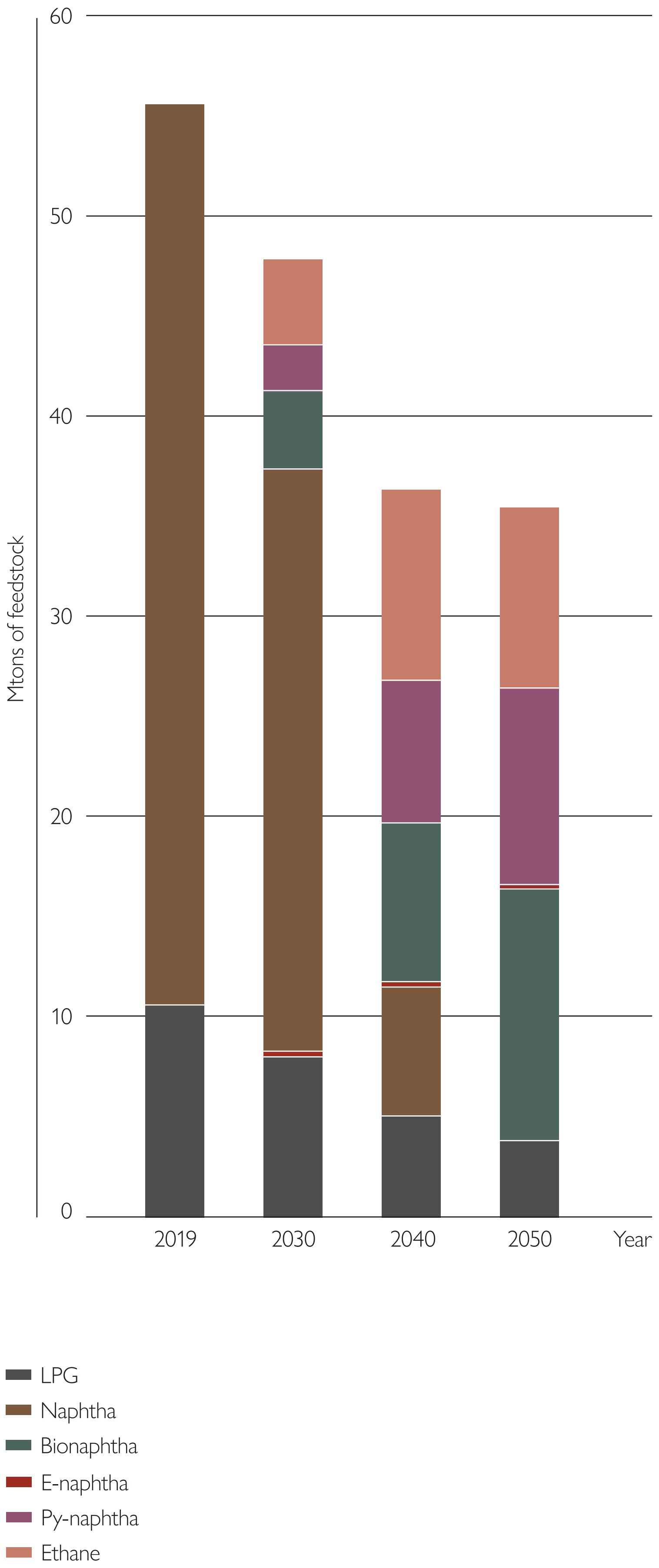


Switching to alternative feedstock for steam cracking

Feedstock switching is one of the key abatement levers to reduce the GHG footprint of olefins and aromatics production. The main sources of feedstock in 2019 are fossil-based naphtha and Liquid Petroleum Gas (LPG). The consumption of both sources decreases, as steam cracking units switch to lower emitting feedstock (ethane), py-naphtha (i.e. pyrolysis naphtha from chemical recycling of mixed plastic waste) and bio-naphtha. E-naphtha, which is one of the available abatement solutions, is not selected by the model due to the assumption of limited availability on the market.

Chart 28

Steam cracker feedstock consumption

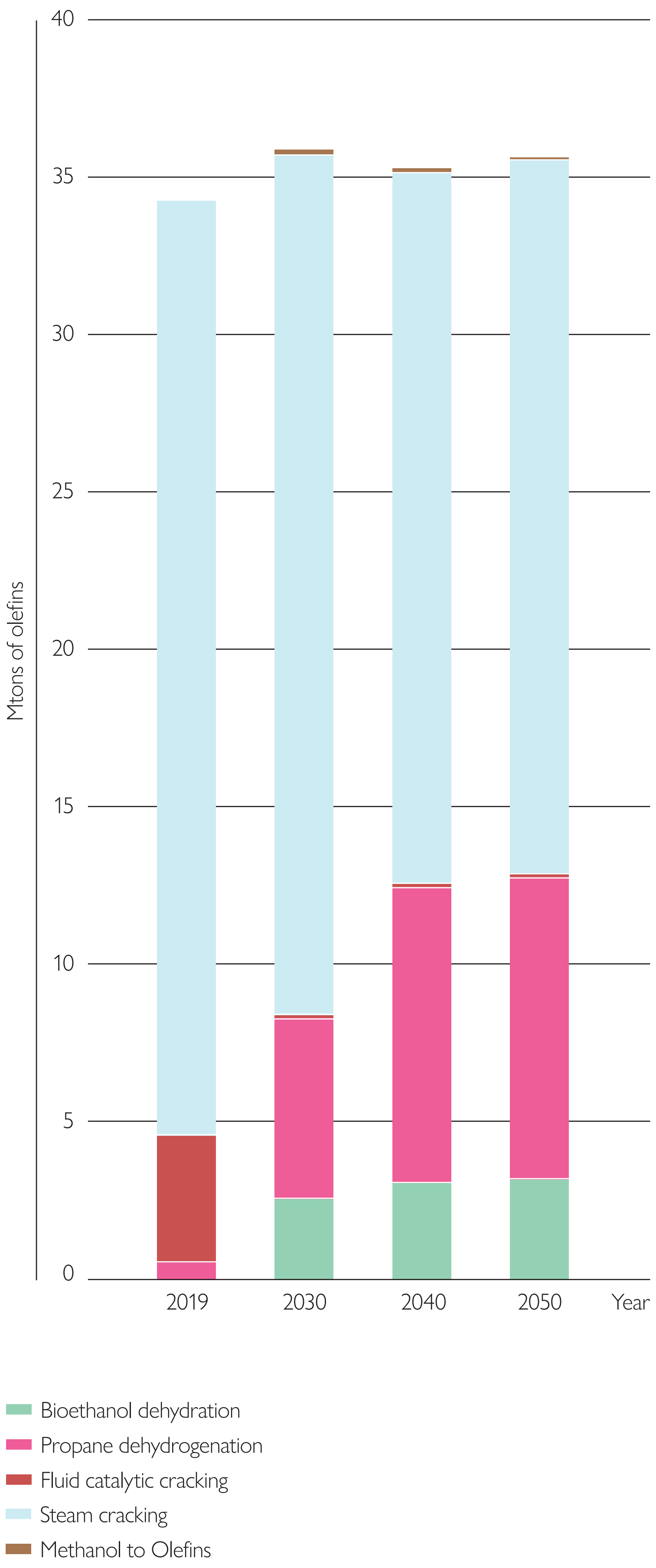


Alternative production routes

Olefins can also be produced via alternative routes other than steam cracking. FCC is gradually phased out after 2020, while the share of production stemming from conventional steam cracking gradually reduces and is replaced by bioethanol dehydration and propane dehydrogenation. The methanol-to-olefins routes is not retained by the model in the “Base Case” scenario.

Chart 29

Olefin production routes



Hydrogen production

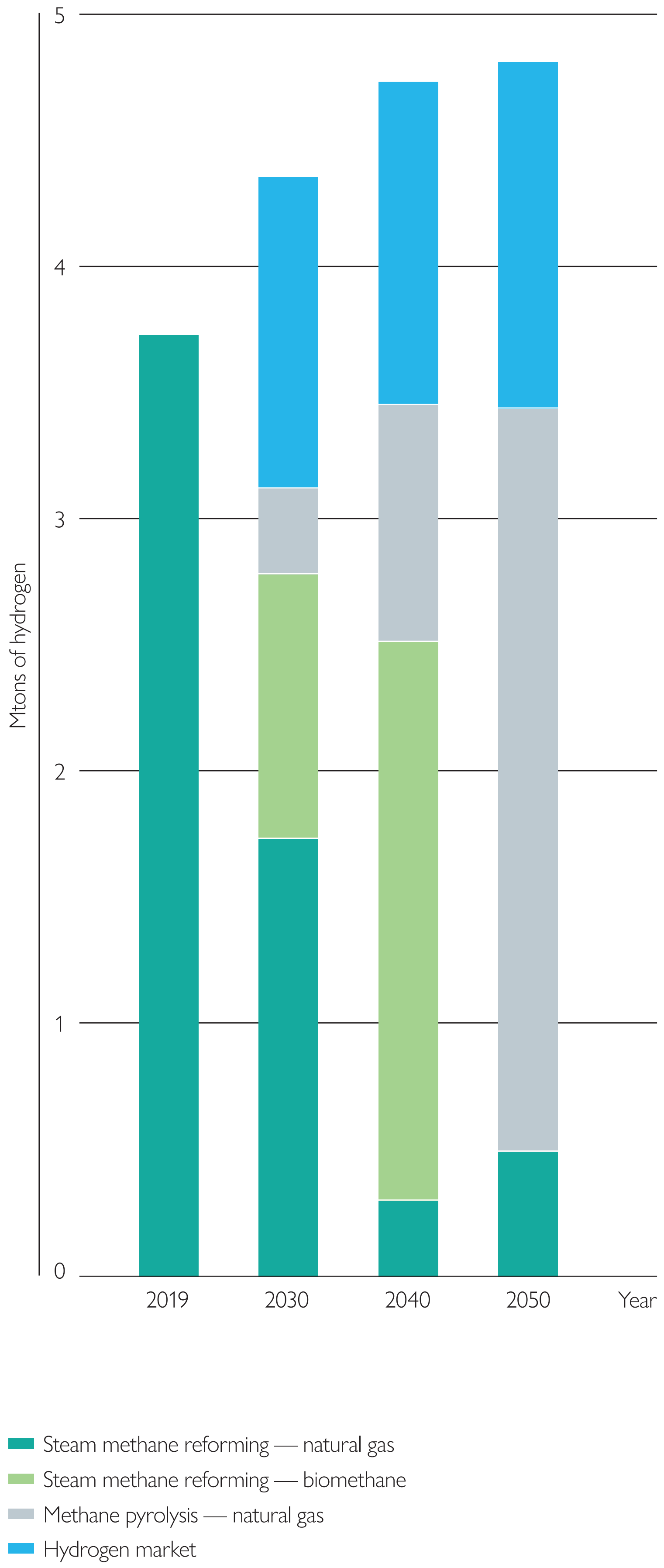
Hydrogen is a **final product**[44]**, as well as a feedstock and fuel source** within the chemical industry. Hydrogen production routes can vary across scenarios and the model can increase the production of hydrogen in order to feed a growing demand within the sector. The volumes of hydrogen required to produce ammonia are calculated by the model, and are added to the market demand that is defined in the scenario assumptions. Hydrogen production in the “Base Case” scenario is done through different technologies as presented in Chart 30.

At the start of the period, hydrogen is exclusively produced via SMR of fossil methane and thus resulting in significant amounts of **process emissions.** A rapid switch to biomethane as alternative feedstock allows to neutralise these emissions or even result in carbon removals, when coupled with CCS. **Methane pyrolysis** is also deployed in the 2030s in combination with natural gas, as an alternative route to SMR, preventing process emissions.

Hydrogen from electrolysis is notably missing due to the high capital investment required and the limited yearly availability of electricity, which is prioritised elsewhere by the model (e.g. for heat and electrification of crackers). Other production methods and buying hydrogen from the market where rated by the model as more cost attractive solutions.

Chart 30

Hydrogen production by technology



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[44] Manufacture of industrial gases (NACE 20.11), which includes hydrogen manufacturing, is classified under the “Manufacture of chemicals” (NACE 20) in the statistical classification of economic activities in the European Community

Resource consumption

The availability of resources that are bought on the **market** is defined within the scenario as an upper limit. The decision whether to consume a certain resource – fully or partially – is based on the cost minimisation objective and is bound by the different constraints within the model. Chart 31 shows the amount of resources consumed versus available resources in the "Base Case" scenario.

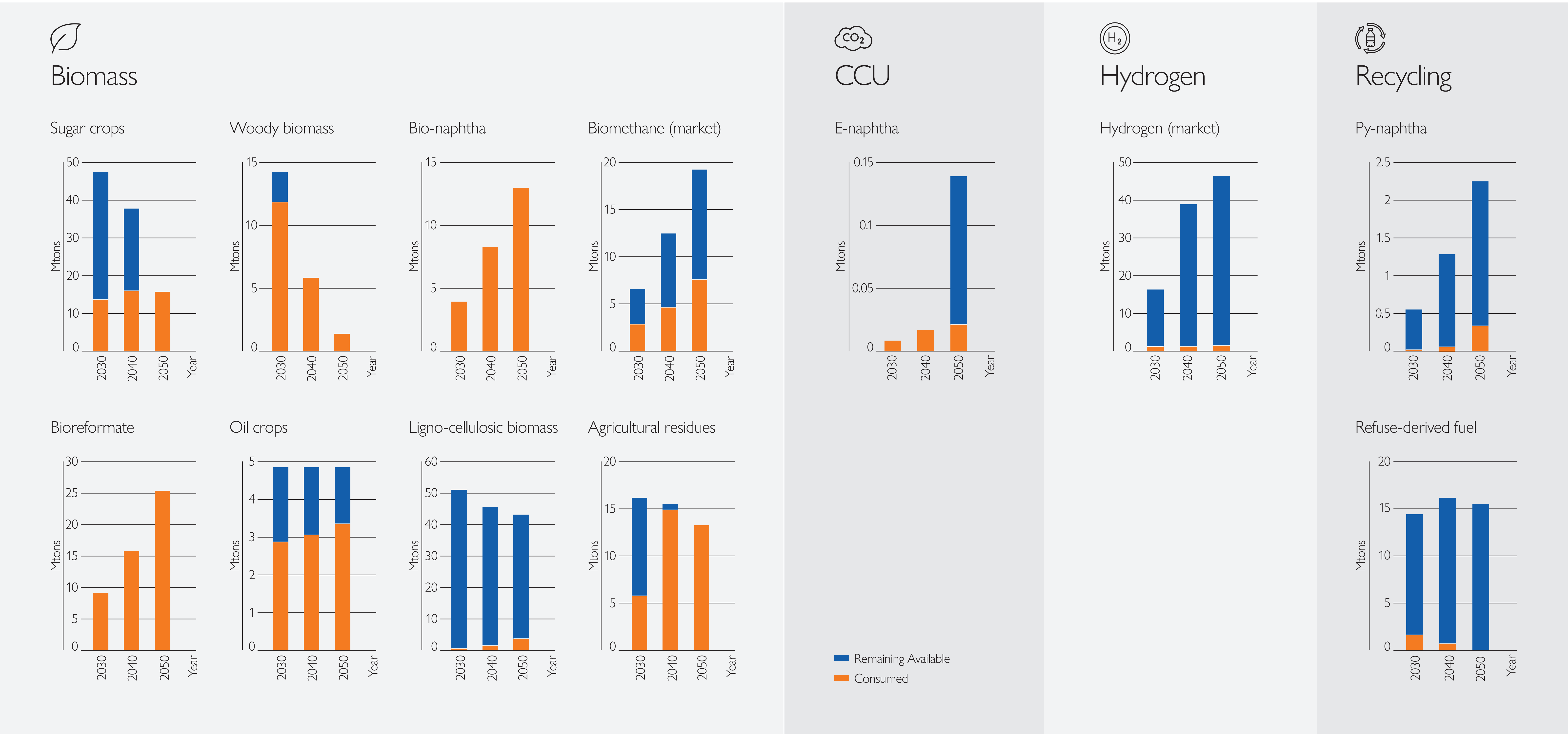
For **biomass,** the preferred resource is agricultural residues, which is consumed up to the maximum declared availability in 2050. They are used within the model to produce biomethane, which is used both as feedstock and fuel. Bio-naphtha and bioreformate (from bio-refineries) are also both fully consumed as they offer low-emission solutions for the production of olefins and aromatics. The availability of woody biomass, which is used for heating and bio-naphtha production decreases up to 2050 (see Annex 5 for more details), forcing the industry to switch to biomethane as an alternative fuel. Ligno-cellulosic biomass, which is used for ethanol and methanol production, is only partially exploited, since alternative solutions for the production of olefins and methanol are available at a lower overall cost. The demand for sugar crops, which is related to ethanol production remains stable over the entire period, but its potential is not fully untapped until 2050.

For **waste-based feedstock,** the model only selects a small quantity of refuse-derived fuel (RDF) for methanol production. Under the "Base Case" conditions, the production of methanol through alternative routes such as biomass gasification or carbon dioxide hydrogenation are seen as more cost effective solution, compared to waste gasification.

Py-naphtha can be either produced within the industry through mixed plastic waste pyrolysis or bought on the market. Self-production of py-naphtha helps reducing end-of-life emissions for polymers, and decreasing the demand for raw materials.

Chart 31

Availability versus consumption, by type of resource available on the market



Energy consumption

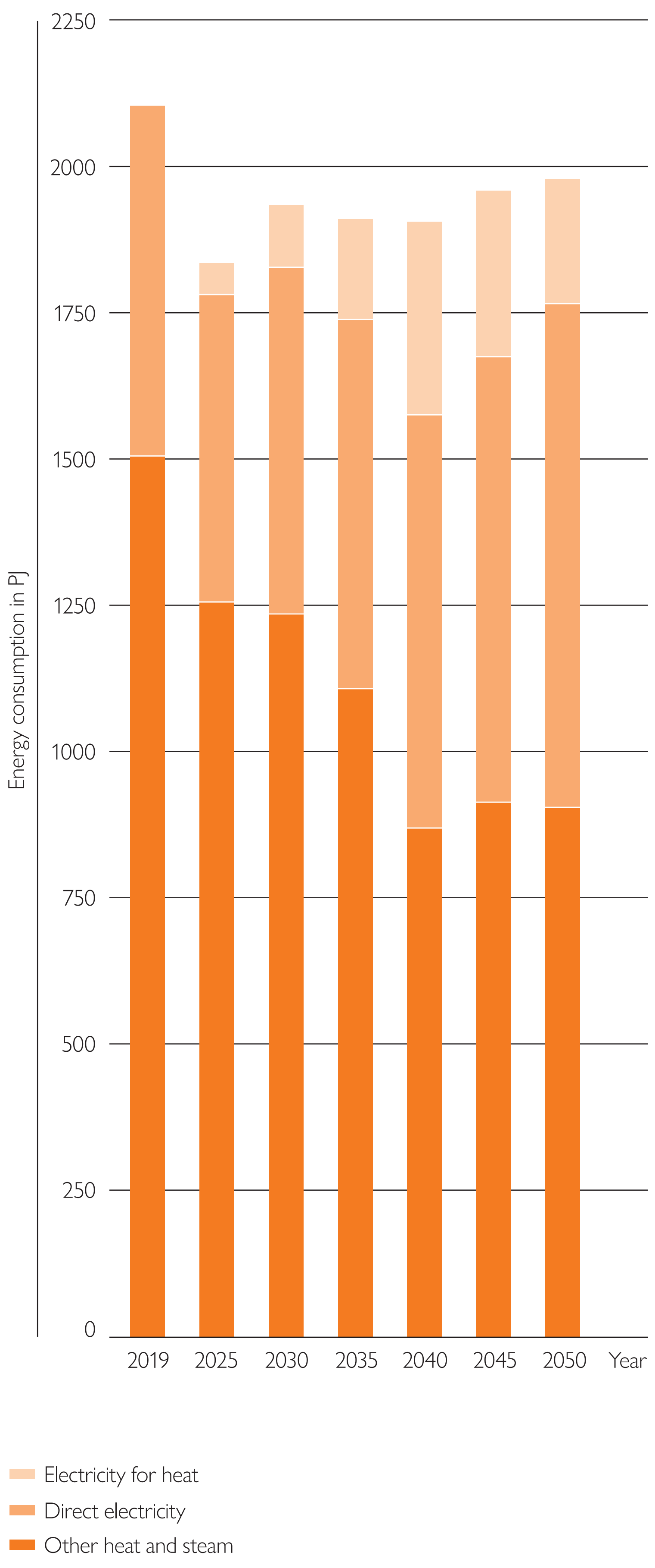
Total energy consumption first decreases until 2025 due to decreasing demand after 2021 (see Section "Assumptions in the “Base Case” scenario" for more details). As demand recovers, energy consumption reaches a stable level after 2030. After 2030, demand growth is mitigated by further improvements in **energy efficiency** and **technology switching,** keeping the Final Energy Demand (FED) relatively stable.

The share of electricity from total final energy consumption increases gradually up to 2050, where it reaches the upper limit of the availability constraint at 300 TWh. The increase in electricity consumption is due to the deployment of electric boilers as a source of low-emission heat, and the deployment of alternative production technologies like (partially-)electrified cracking that requires electricity as an energy source. Direct electricity consumption for hydrogen and chlorine production also increases over the entire period.

The shift towards electrification of processes and heat generation, along with the deployment of alternative production technologies, results in an increase in energy efficiency. The final energy consumption per unit of production decreased by **17% in 2050** compared to 2019. Energy consumed as feedstock per unit of production decreased by 16% in 2050 compared to 2019. This is due to the switch to more efficient alternative production processes, and the use of recycled materials that replace the raw material consumption.

Chart 32

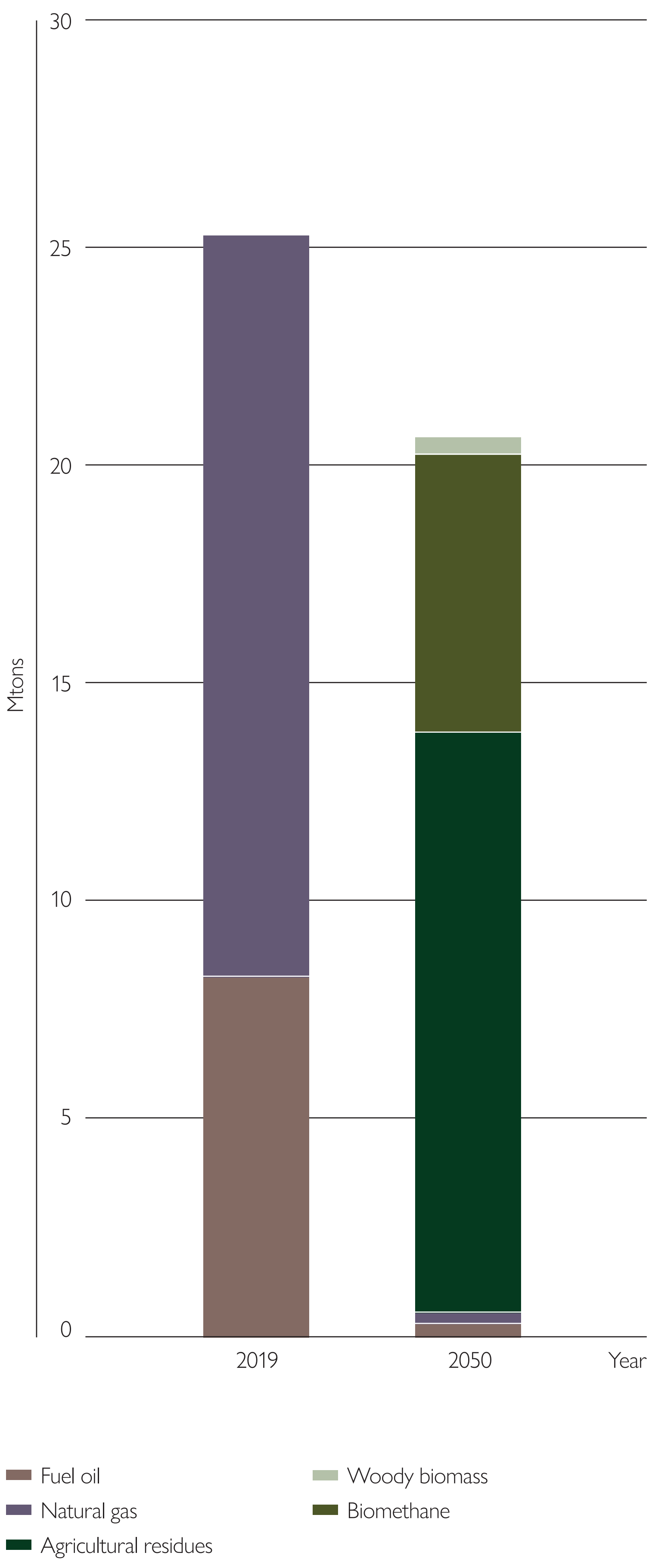
Final energy consumption by energy vector



Material consumption as a fuel depends on the type of heating technology used within the scenario. The model includes several alternative **heating technologies** such as electrical boilers, or boilers running on hydrogen or biomass. Between 2019 and 2050, the model switches from fossil fuels to agricultural residues and biomethane, as a preferential source, due to the decreasing availability of woody biomass. Fuel gas consumption for integrated fuel gas furnaces is not reported under Chart 33, as it is a co-products of steam cracking and as feedstock is accounted for separately.

Chart 33

Fuel consumption by source in 2050

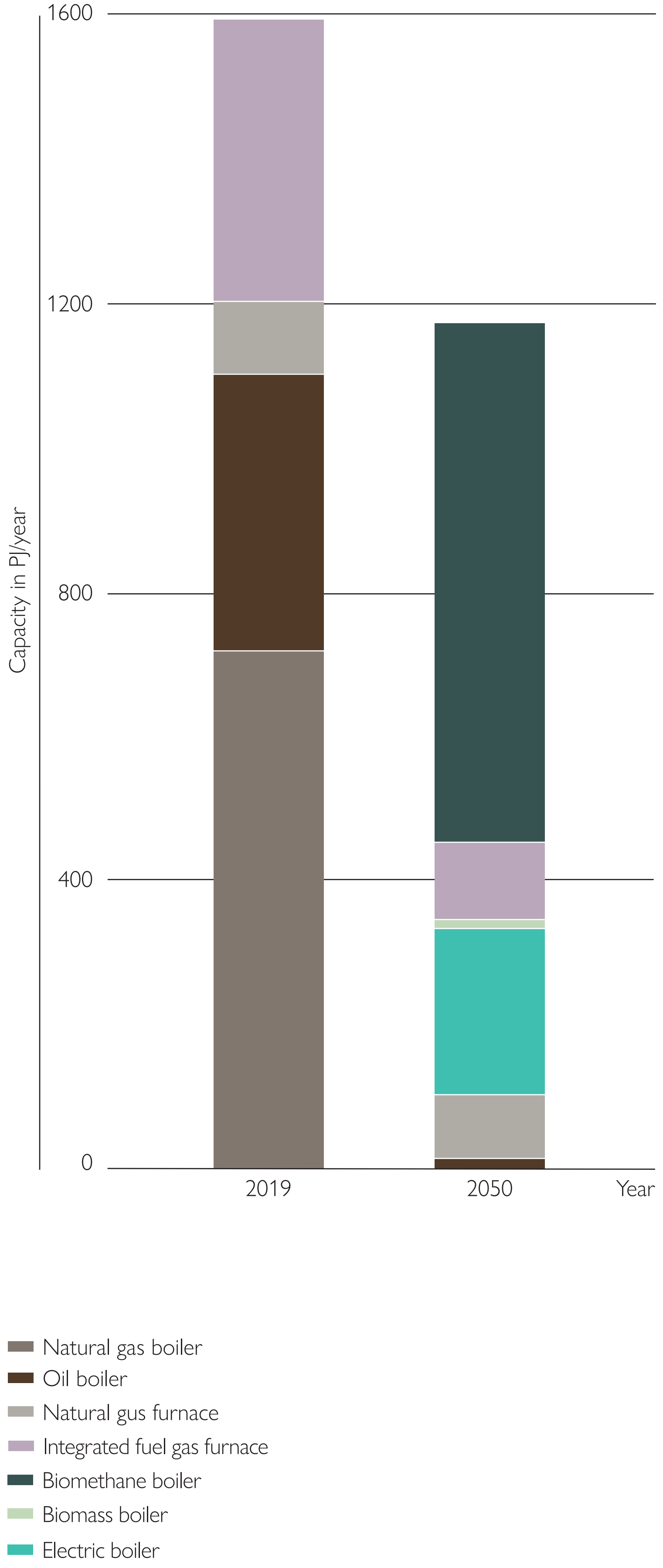


Fuel switching requires investing into alternative heating technologies, representing 6.5 Bio€ over the entire period. Heat generation in 2019 was done through fossil-based heating technology using mainly natural gas and fuel oil. Due to the limited electricity available in the “Base Case” scenario, the model also chooses to utilise biomethane as a low-emission source of heat generation to supply low and high temperature heat. The capacity deployment of heat generation technologies is shown in Chart 34.

The total installed capacity of heat generation technologies decreases due to energy efficiency improvements and the direct electrification of processes. **Biomethane** and **electrical boilers** are the main source of heat generation in 2050 replacing natural gas and oil boilers that were the main technologies deployed in 2019.

Chart 34

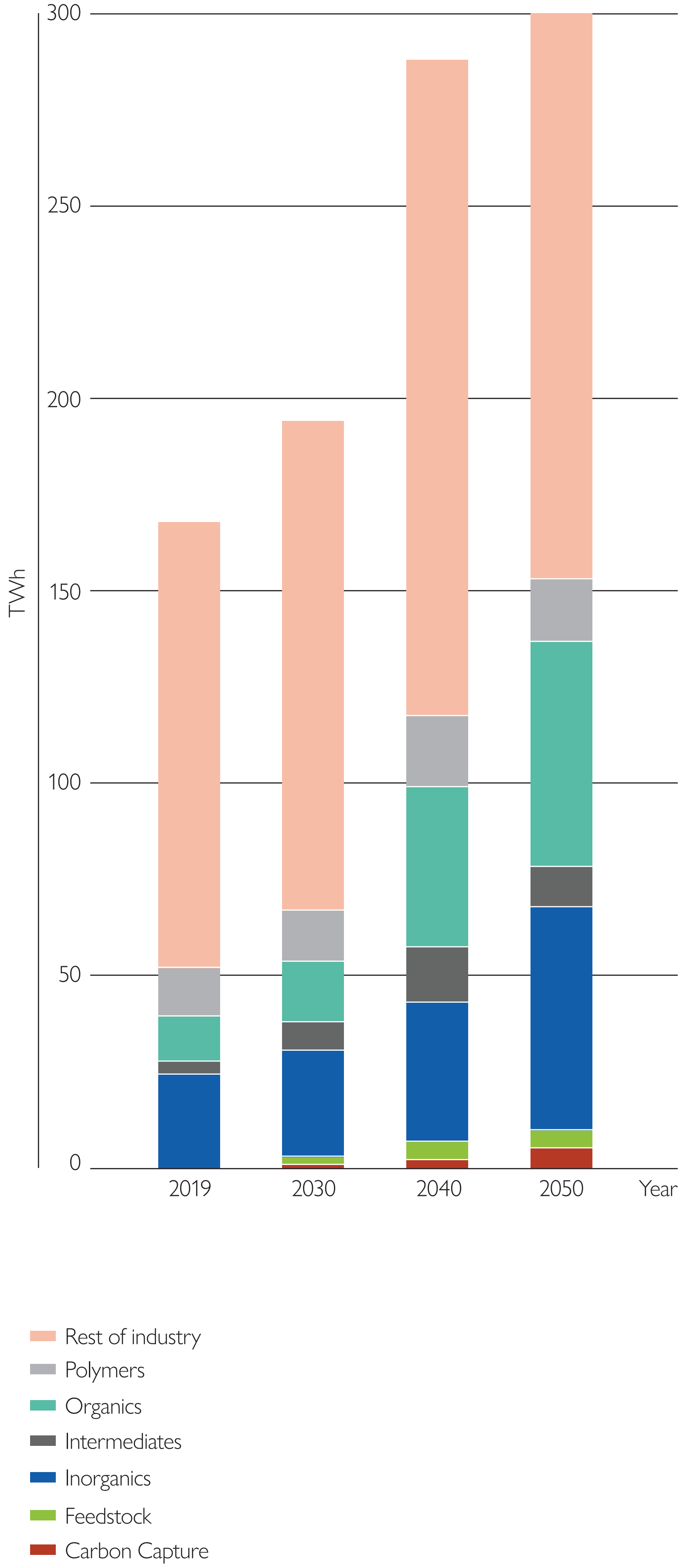
Installed heat capacity in 2050



In 2019, most of the electricity is consumed by the “Rest of industry” aggregate. Afterwards, electricity demand growth is mainly driven by organics (cracker electrification) and hydrogen production, under inorganics. In 2050, heat generation through electric boilers (excluding electrified steam cracking) reaches 20% of total electricity consumption.

Chart 35

Breakdown of electricity consumption



Feedstock consumption

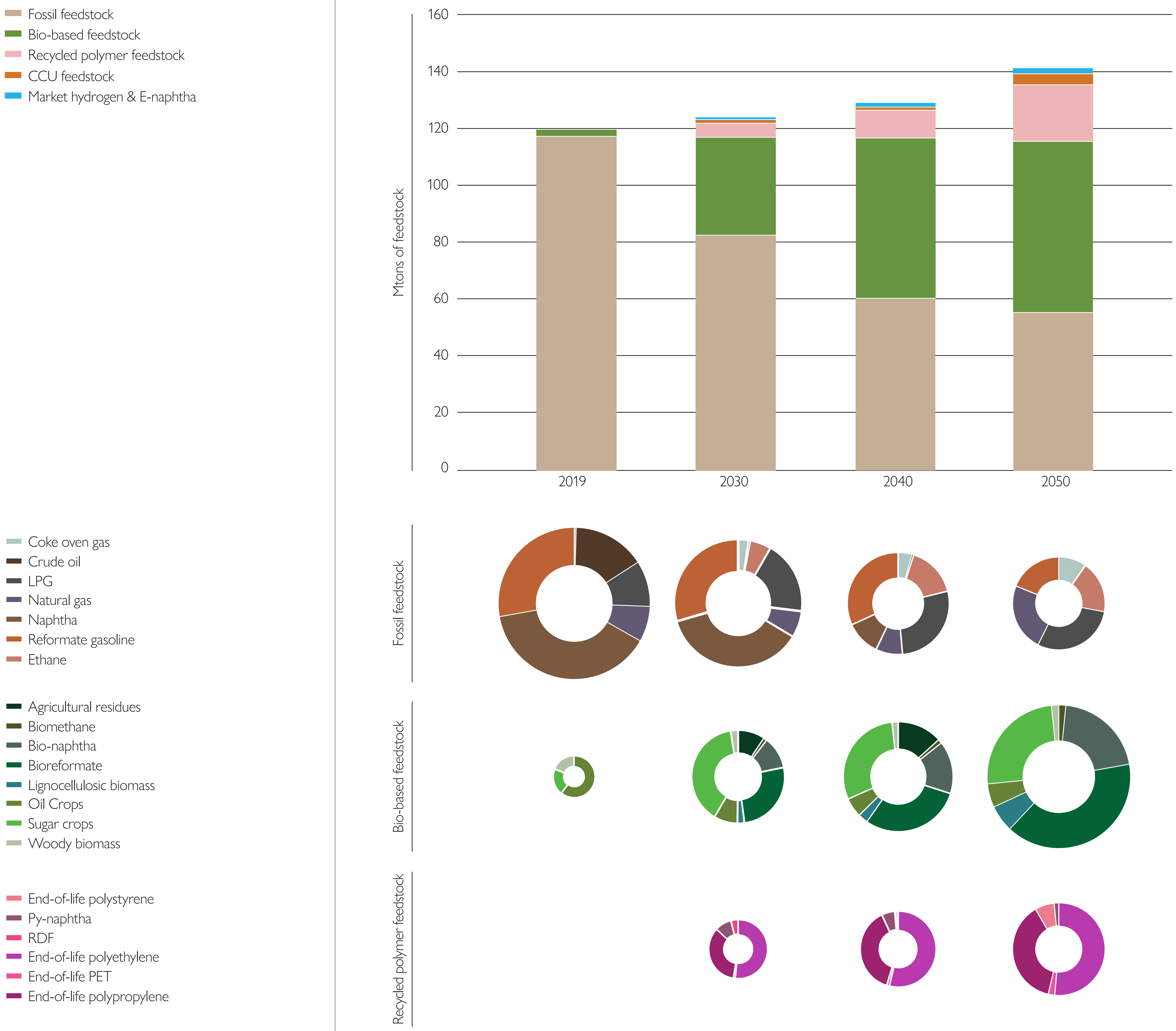
The total mass of feedstock consumed by the chemical industry **increases by 15%** compared to 2019, driven by demand growth.

Chart 36 shows the evolution of feedstock consumption between 2019 and 2050. In 2019, the majority of the feedstock consumption is fossil-based (95% of total feedstock mass consumed), with the biggest share related to fossil naphtha going to steam crackers, and reformate gasoline for the production of aromatics.

By 2050, the share of **bio-based feedstock** increases above **40% of total consumption,** while the share of fossil feedstock decreases to around 35%. **Feedstock from chemical recycling** of polymers emerges as one of the technologies to abate end-of-life emissions and as an alternative source of feedstock. It represents **14.6% of the total feedstock** consumption in 2050.

Chart 36

Evolution of the feedstock mix between 2019 and 2050



Carbon capture

Carbon capture is deployed as one of the solutions for emission abatement in the "Base Case" scenario. Most of the captured CO_2 is stored into **geological storage (CCS),** while a smaller share is used as alternative feedstock in combination with hydrogen. The total amount of captured CO_2, both from concentrated and unconcentrated sources, increases to **almost 35Mtons in 2050,** as shown in Chart 37.

Carbon capture is deployed mostly on production (process emissions) but also to a much smaller extent on heat generation, as shown in Chart 38.

Chart 37

Total CO_2 captured by use

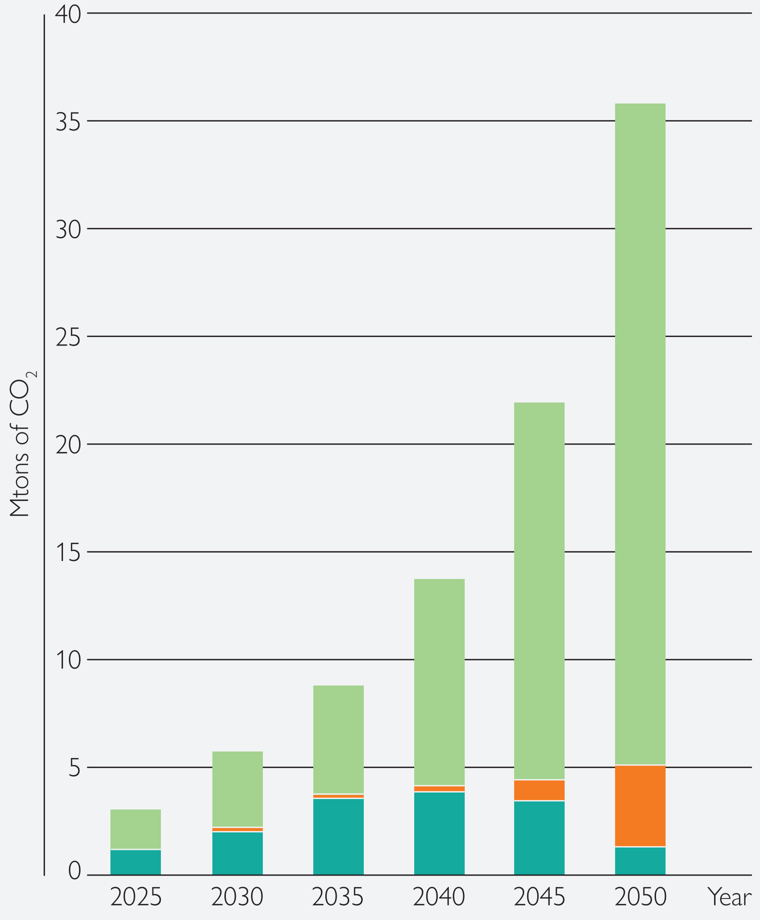
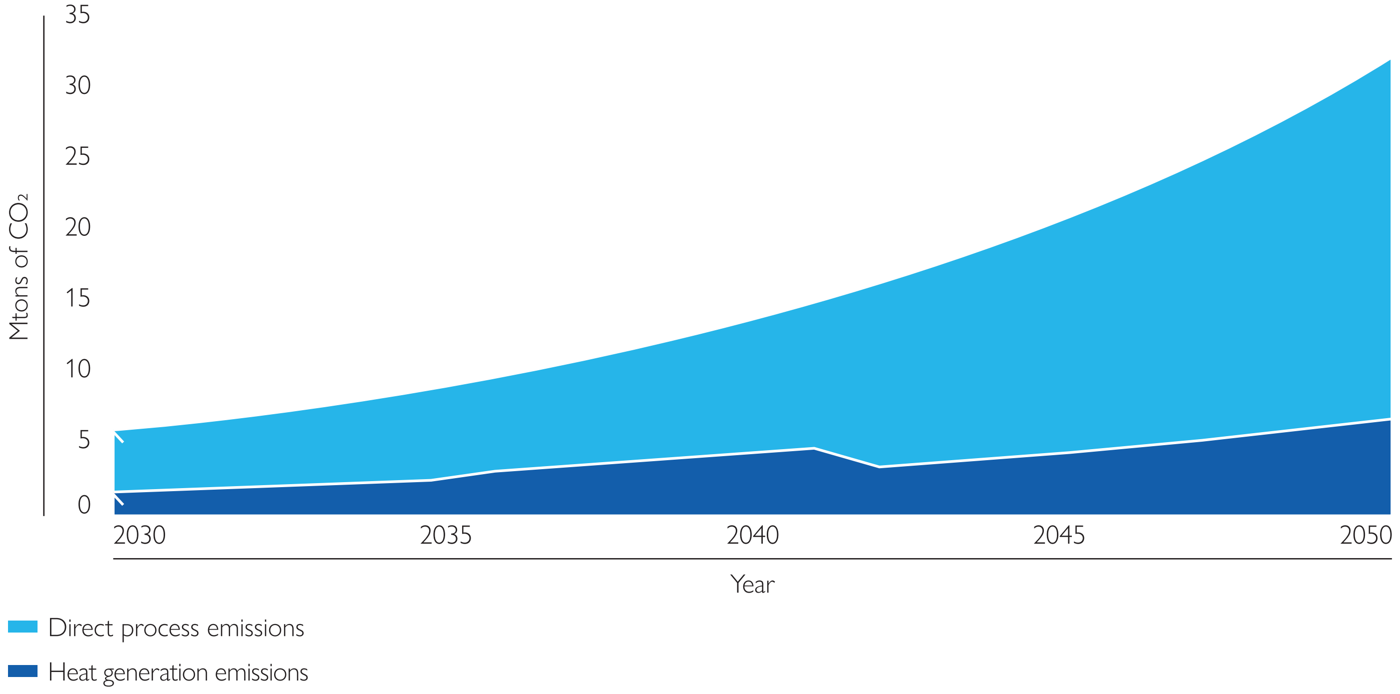


Chart 38

Volume of captured CO_2 by type of emission



End-of-life for polymers

To determine whether the chemical sector becomes climate-neutral across the entire modelling scope, iC2050 needs to identify whether the embedded carbon within those products is **"kept within the loop"** and re-circulated, or whether it is emitted as CO_2 into the atmosphere. The end-of-life routes of the five polymers in the product scope that result from the "Base Case" scenario are shown in Chart 39.

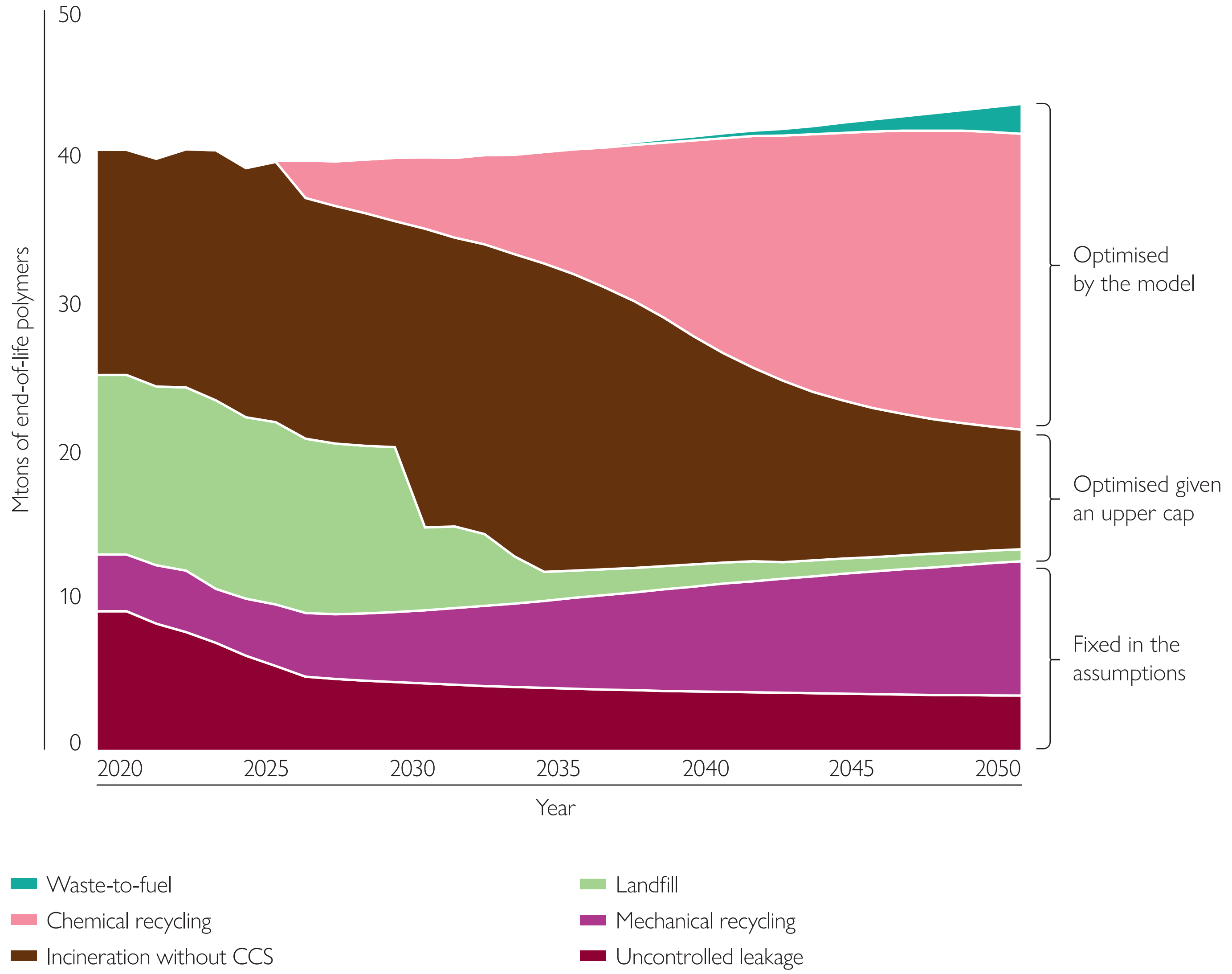
In 2019, 90.5% of the total volume of polymers reaching the end of their life goes to incineration, landfill or uncontrolled leakage. Only 9.5% of the total volume of polymers is recycled through mechanical recycling.

In the mid-20s, **chemical recycling** is deployed and rapidly scaled up, covering **45.7% of the total volume** of polymers by 2050. Chemical recycling allows to reduce emissions from polymer incineration, while providing recycled feedstock and reducing the consumption of virgin raw materials. **Mechanical recycling** is exogeneous and based on the figures provided in the ICIS forecast. The model chooses to deploy chemical recycling capacities as a complementary solution to achieve circularity and climate-neutrality targets. **Waste-to-fuel** allows processing end-of-life polymers to produce alternative fuels. The remaining share of chemically recycled feedstock is used within the chemical industry to produce circular olefins.

Another option available by the model is to **capture and store CO_2 emissions** from waste incinerators. However, based on the model's arbitration, this option is not chosen, as the CCS potential is fully dedicated to direct emissions of chemical operations.

Chart 39

End-of-life routes for polymers



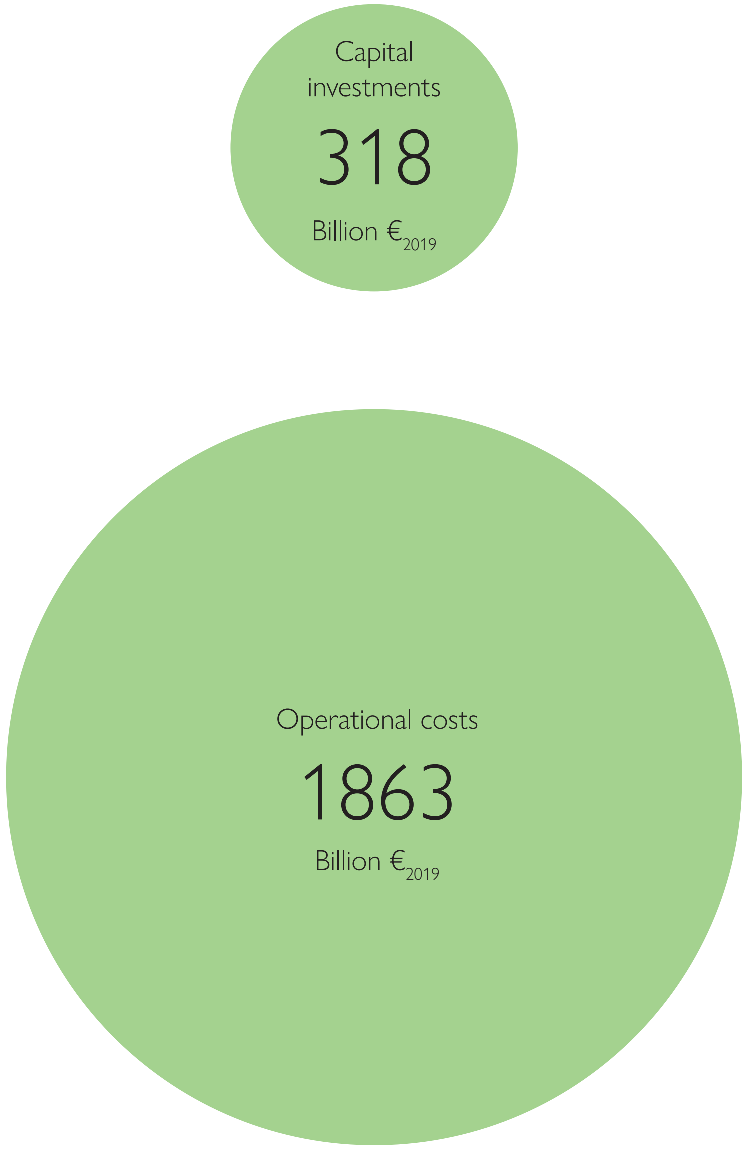
Costs

The deployment of solutions for reaching the climate and circularity objectives result in a **NPC of €2.18 Trillion,** divided between capital and operational expenses.

The cumulative discounted capital investments between 2019 and 2050 reach 318 Bio€, as shown in Chart 40. The operational costs related to the purchase of alternative materials and energy adds up to 1,863 Bio€ by 2050.

Chart 40

Cumulative costs of GHG abatement and circularity solution in 2050



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[45] Including the discount rate

How does a reduced emission scope change the abatement pathway?

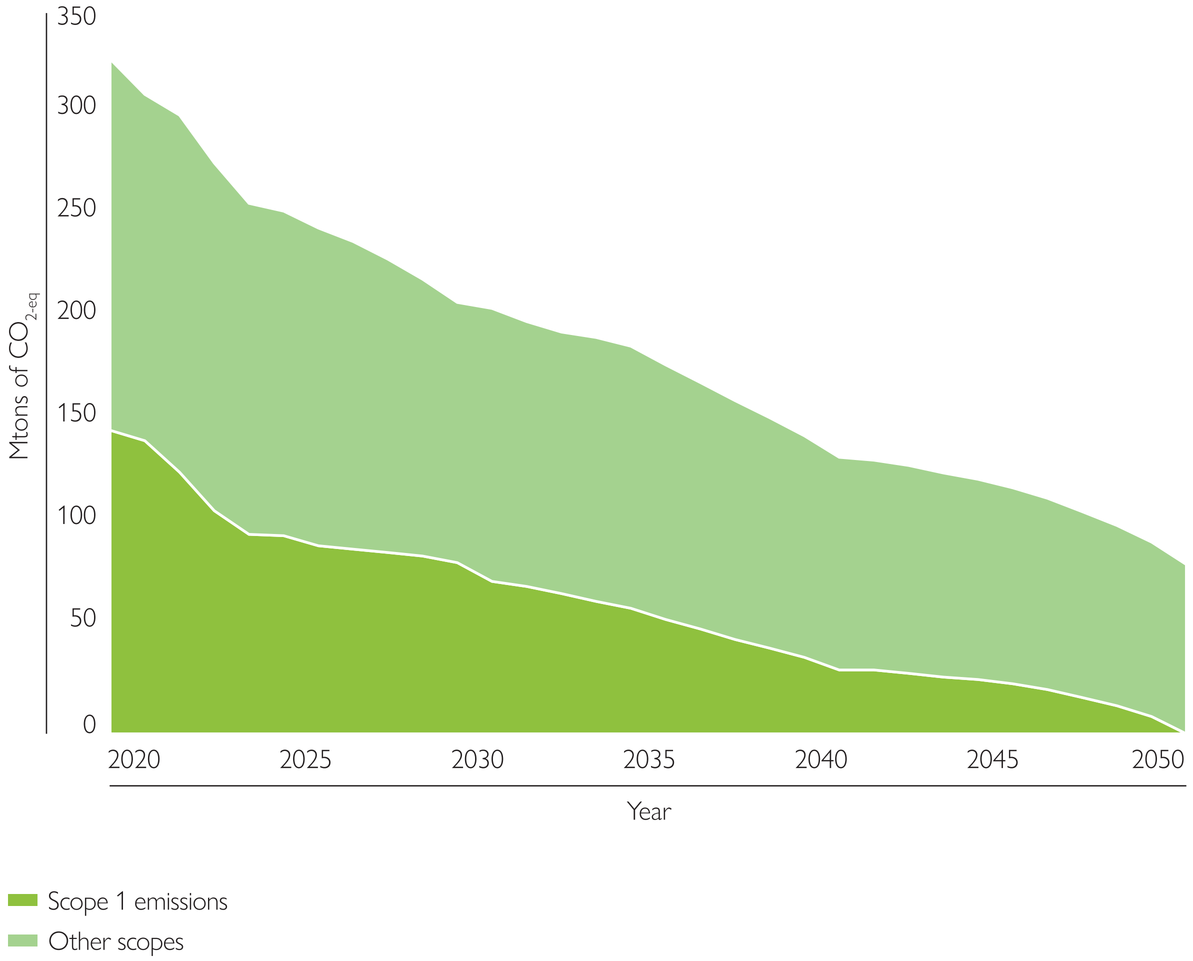
The iC2050 model offers the possibility to apply the climate-neutrality target only to **direct scope 1 emissions.** A narrower scope results in a different emission pathway as described below. The **"Base Case M4" scenario** refers to the case where the climate-neutrality constraint is narrowed only to scope 1 emissions.

The abatement pathway

The climate-neutrality constraint is set for 2050 and takes into account only scope 1 emissions of the chemical industry, as well as the intermediate 2030 and 2040 targets. The resulting net emission curve is shown in Chart 41. It shows that **scope 3** emissions are still at **81Mtons in 2050.**

Chart 41

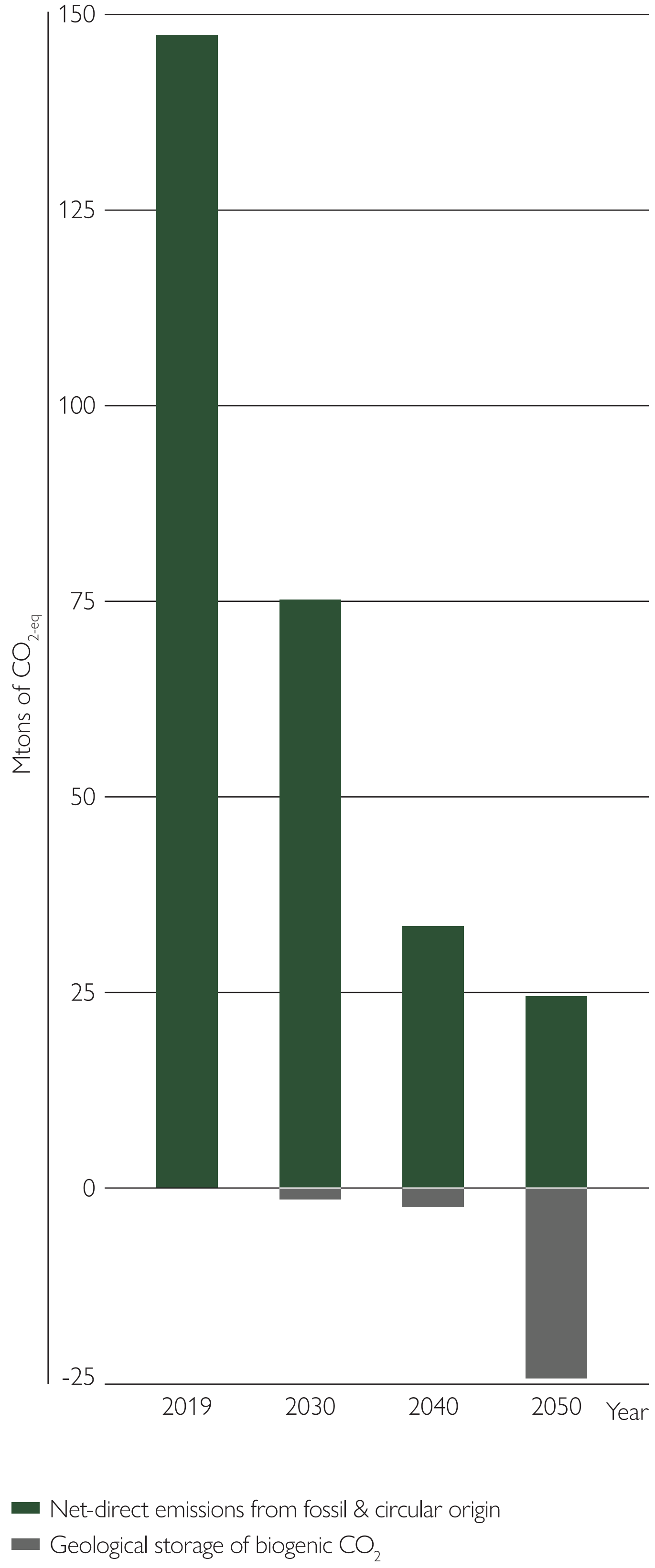
Total net GHG emissions between 2019 and 2050, without climate neutrality constraint on scope 3 emissions



In Chart 42, scope 1 emissions, which accounts for all emissions independently of their origin, decline gradually over the entire period. Residual emissions in 2050 are at **24Mtons** and are entirely neutralised by geological storage of biogenic CO_2.

Chart 42

Direct emissions and removals

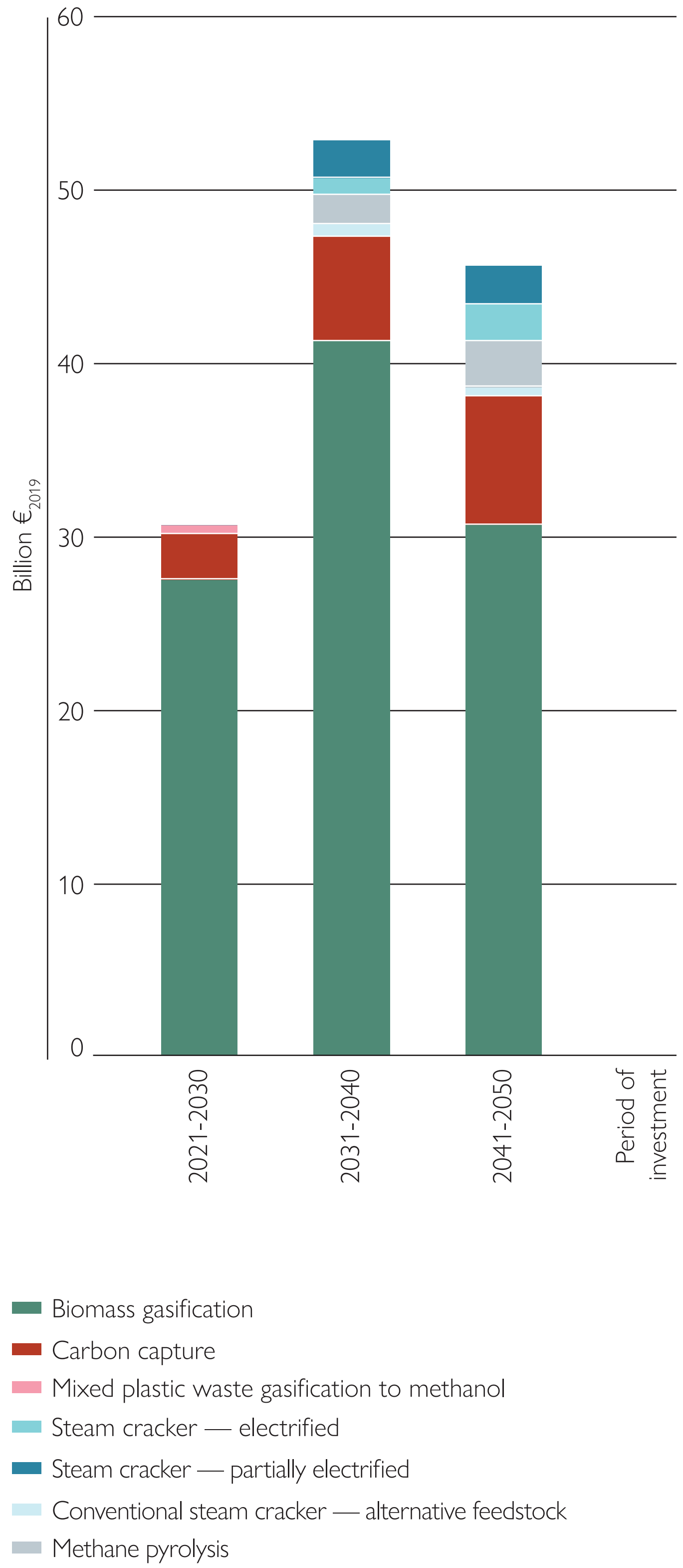


Technology deployment

Applying the climate-neutrality target to scope 1 emissions only results in much more targeted investments, aiming at abating direct emissions. **Biomass gasification** and **carbon capture** still represent the bulk of investments. On the contrary, capacities related to the production of waste-based feedstock or bioethanol as an alternative feedstock, are not deemed as needed anymore.

Chart 43

Capital investment going to new technologies



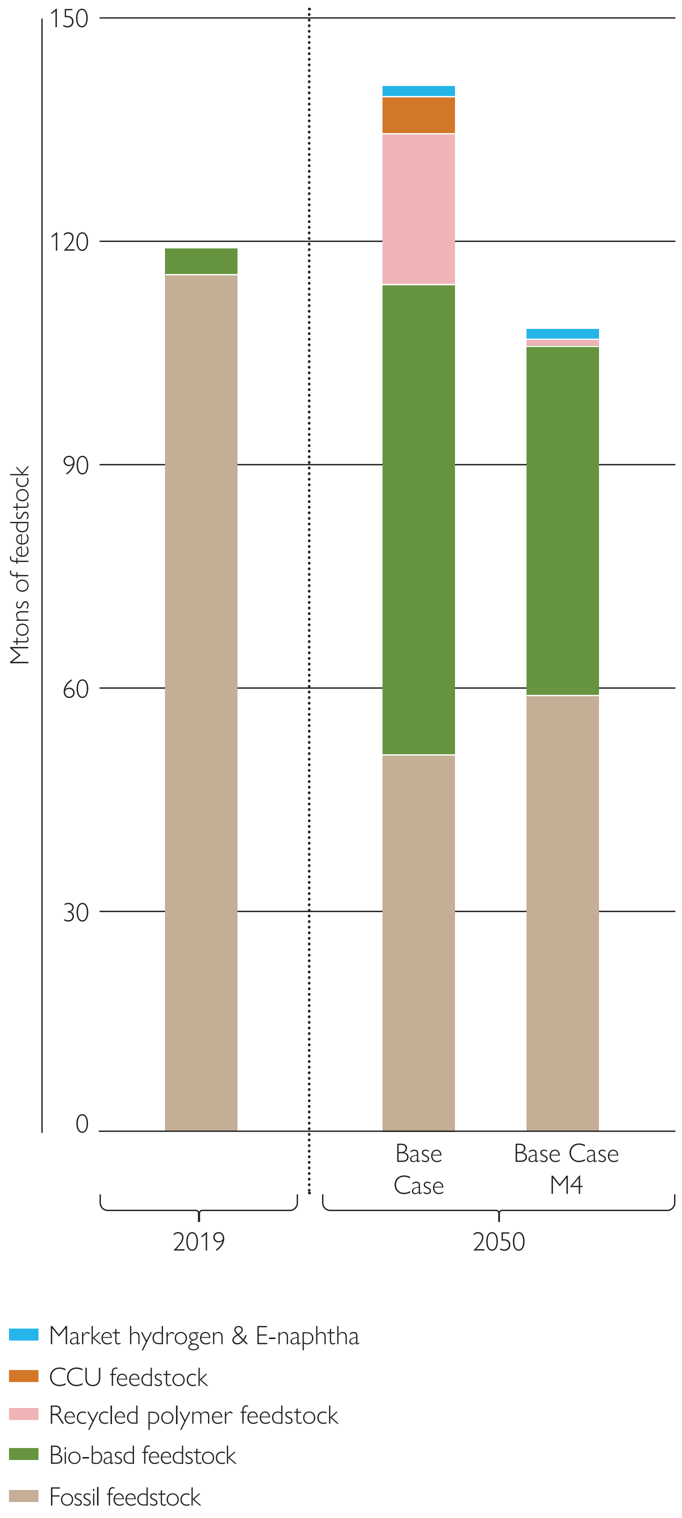
Feedstock

Applying the climate-neutrality constraint to all emissions in scope (versus scope 1 only) results in an overall increase of the amount of feedstock consumed by the sector. Such increase is explained by the fact that a bigger mass of bio-based feedstock is needed to supply the same amount of carbon for production.

Moreover, applying the climate-neutrality constraint on scope 3 emissions related to feedstock sourcing and end-of-life is clearly a driver for the use of recycled polymer feedstock, which is one of the main solutions to abate emissions related to polymers' end-of-life. It also drives the use of bio-based feedstock, which allows temporarily removing CO_2 into chemical products.

Chart 44

Carbon-based feedstock and hydrogen consumption – full climate-neutrality scope versus reduced scope

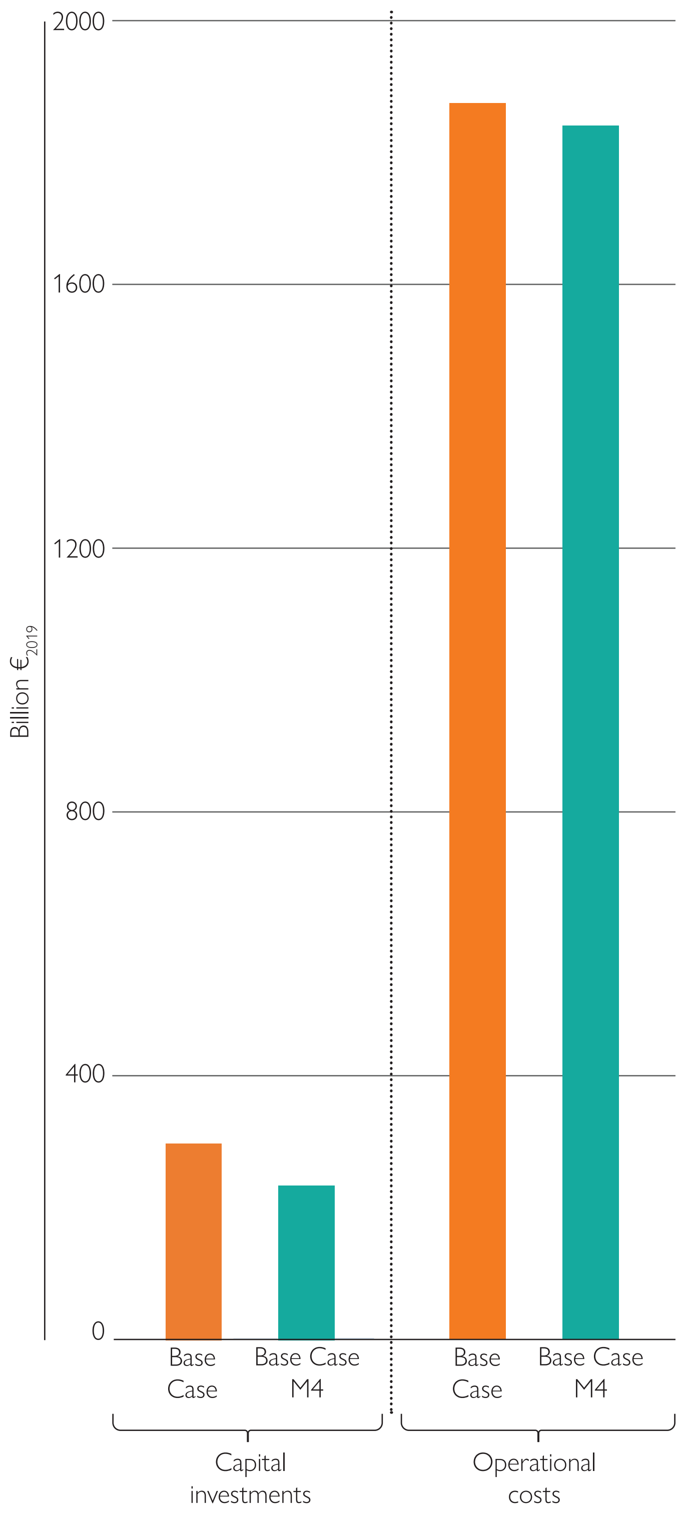


Costs

In accordance with the additional investment requirements for circularity solutions, expanding the climate-neutrality constraint to all emissions in scope drives up capital costs for the chemical industry **by 36.5%** and the total NPC **by 5.8%.** Operational costs only increase by 2% when the climate-neutrality constraint is applied across all emission scopes. The difference is very small because both scenarios correspond to the same levels of production and because both scenarios consume the upper limit of available electricity by 2050. When the climate-neutrality constraint only applies to scope 1 emissions, the lower recycling rates at the end-of-life still need to be compensated by the purchase of virgin raw materials.

Chart 45

Cumulative costs of GHG abatement and circularity solutions in 2050 – full climate-neutrality scope versus reduced scope



Section 10

The impact of policies

In this section, we consider the impact of policies and specifically of **targets,** on the abatement pathway of the EU chemical sector. As a first sensitivity analysis, we will look at the impact of intermediate climate targets for **2040.** Then, we will study the role of feedstock and carbon sources and look at the changes that occur when fixing minimum shares of **non-fossil sustainable carbon** in the industry's feedstock supply. Last but not least, we will zoom-in on hydrogen and consider the impact of targets for **renewable fuels of non-biological origin** (RFNBOs) has mandated by the Renewable Energy Directive.

Section 10.1

The 2040 level of ambition

The European Commission's Communication on a 2040 Climate target was supported by an impact assessment and three scenarios, corresponding to three different levels of ambition[46]:

- up to 80% (S1 scenario of the 2040 Target Impact Assessment), consistent with the **'linear' trajectory** between 2030 and 2050 referred to in the Climate Law;
- at least 85% (S2 scenario of the 2040 Target Impact Assessment) corresponding to a range of 85-90% reduction;
- at least 90% (S3 scenario of the 2040 Target Impact Assessment) corresponding to a range of 90-95% reduction.

Changes in assumptions

The contribution of each sector (energy, buildings, industry, transport and agriculture) towards the achievement of these targets is not the same. In order to model the impact of different 2040 target levels for the chemical industry, we therefore had to estimate the corresponding amount of GHG emission reductions that are expected from the chemical industry. The results of this estimation[47], are summarised in Table 4. In the S3 scenario of the 2040 Target Impact Assessment, the chemical sector would have to reduce its emission by a **greater amount** than the average of the EU economy.

Table 4

2040 climate targets and contribution from the chemical sector

Net GHG emissions (Mtons CO_2eq/y)	2015	2040 S1	2040 S2	2040 S3
Economy-wide	3592	1051 (-78% vs. 1990)	578 (-88% vs. 1990)	477 (-90% vs. 1990)
Chemical industry	122	≈49 (-81% vs. 1990)	≈32 (-87.5% vs. 1990)	≈15 (-94% vs. 1990)

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[46] Source: European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society – executive summary of the impact assessment report. 06182e00-03ac-4b6b-a58c-54cb45b080c2_en (europa.eu)

[47] Source: European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society Impact Assessment Report Part III. Annex 8 – Figure 52 and 53

The intermediate targets that were set in the "Base Case" scenario were based on S2 scenario of the 2040 Target Impact Assessment. In this section, we are going to assess how the 2040 level of ambition impacts the chemical industry's pathway towards climate-neutrality.

Here, the **sensitivity analysis** focuses on the level of climate ambition only. All remaining assumptions stay as in the "Base Case" scenario.

Impact on the abatement pathway

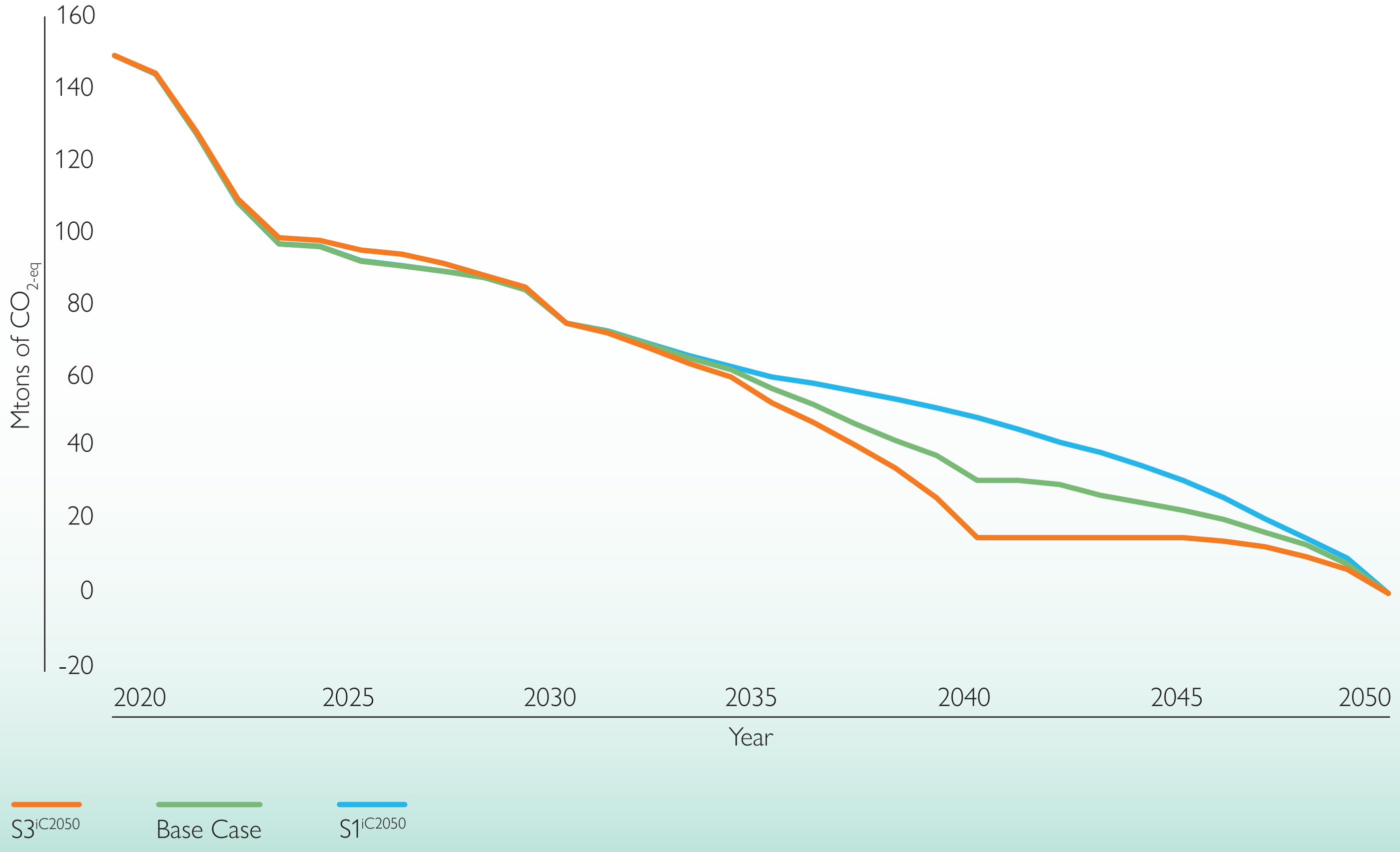
The abatement curve resulting from the change in climate targets is shown in Chart 46. The emission curves start deviating between the $S1^{iC2050}$ scenario and the other scenarios after 2030.

When reducing the 2040 level of ambition for the chemical sector to **– 81%,** the abatement curve of the chemical sector follows a more **linear trajectory.** This is consistent with the European Commission's projection on a 'linear' trajectory of net GHGs emissions between 2030 and 2050, which is outlined in $S1^{iC2050}$ scenario.

When increasing the 2040 level of ambition for the chemical sector to **– 94%,** the emission curve starts deviating from the "Base Case" (middle ambition) just before 2035: emission abatements need to be **frontloaded** to meet the 94% reduction objective, resulting in a smoother abatement curve after 2040.

Chart 46

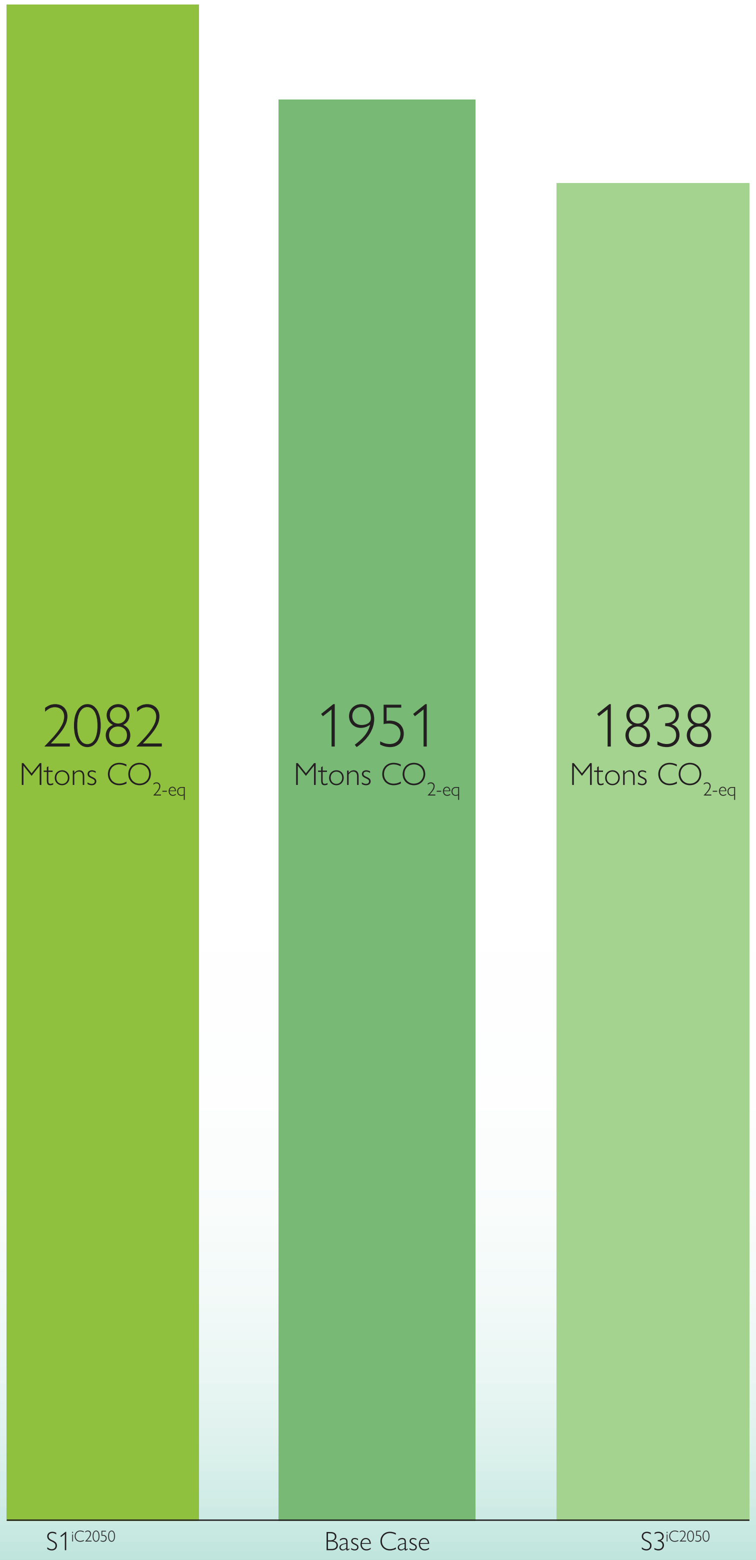
Net direct emissions between 2019 and 2050 – "Base Case" versus $S1^{iC2050}$ and $S3^{iC2050}$ scenarios



Cumulative direct emissions decrease in line with the emission reduction target in 2040 as shown in Chart 47: they are 6.3% lower in the “Base Case” versus S1^{iC2050} and 11.7% in S3^{iC2050} versus S1^{iC2050}.

Chart 47

Total cumulative direct emissions between 2019 and 2050 – “Base Case” versus S1^{iC2050} and S3^{iC2050} scenarios



CO_2 emissions per scope as reported in Chart 48 show that a more aggressive intermediate target for 2040 results in a higher amount of residual emissions related to polymers’ end-of-life, which needs to be neutralised with a higher amount of carbon removal. This is because the model allocates less capacity to chemical recycling capacity as it would shift part of the **end-of-life** emissions into scope 1, which is where the industry has to increase its ambition.

Chart 48

GHG emissions per scope – “Base Case” versus S1^{iC2050} and S3^{iC2050} scenarios

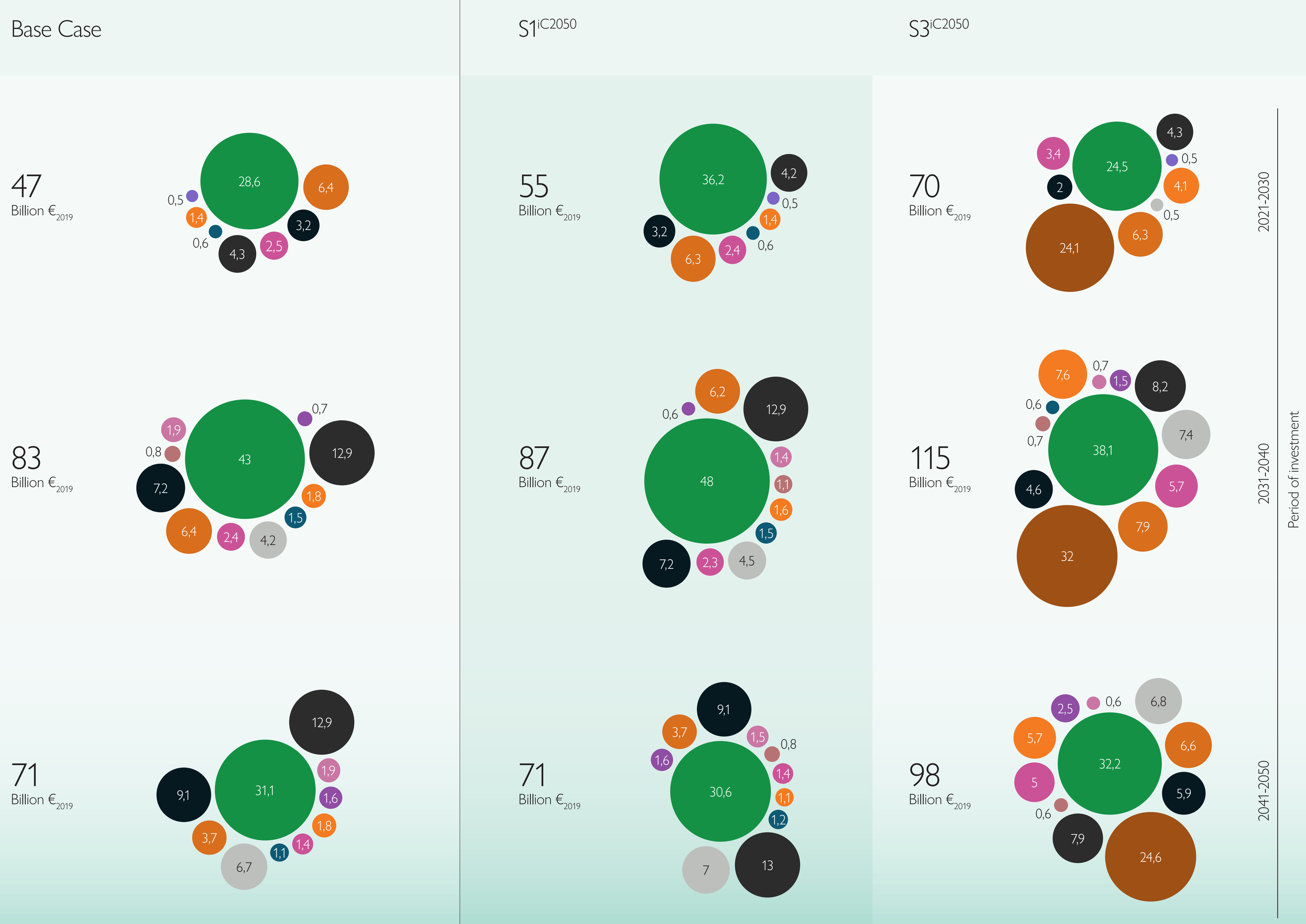
Impact on technology deployment

Implementing a more aggressive intermediate target requires earlier investments in abatement solutions. In all scenarios, most of the spending takes place between 2030 and 2040, as shown in Chart 49.

All solutions are deployed before 2030, except for (partially-)electrified cracking. The mix of abatement solutions remains rather stable across all periods and does not greatly vary from one level of ambition to the other, with the exception of **enzymatic hydrolysis and fermentation,** which is only deployed in the higher-ambition scenario. Variations for different levels of ambitions are therefore rather related to the **speed and extent of deployment.**

Chart 49

Capital investment going to new technologies – "Base Case" versus S1^{iC2050} and S3^{iC2050} scenarios[48]



- ■ Biomass gasification
- ■ Carbon capture
- ■ Conventional steam cracker – alternative feedstock
- ■ Fermentation-based ethanol production
- ■ Bioethanol dehydration
- ■ Methanol to Olefins
- ■ Methane pyrolysis
- ■ Carbon dioxide hydrogenation
- ■ Biomass gasification with methanol synthesis
- ■ Mixed plastic waste gasification to Methanol
- ■ Plastic waste pyrolysis for mixed plastic waste
- ■ Chemical recyling to B-HET (PET monomer)
- ■ Steam cracker – partially electrified
- ■ Steam cracker – electrified
- ■ Enzymatic hydrolysis and fermentation

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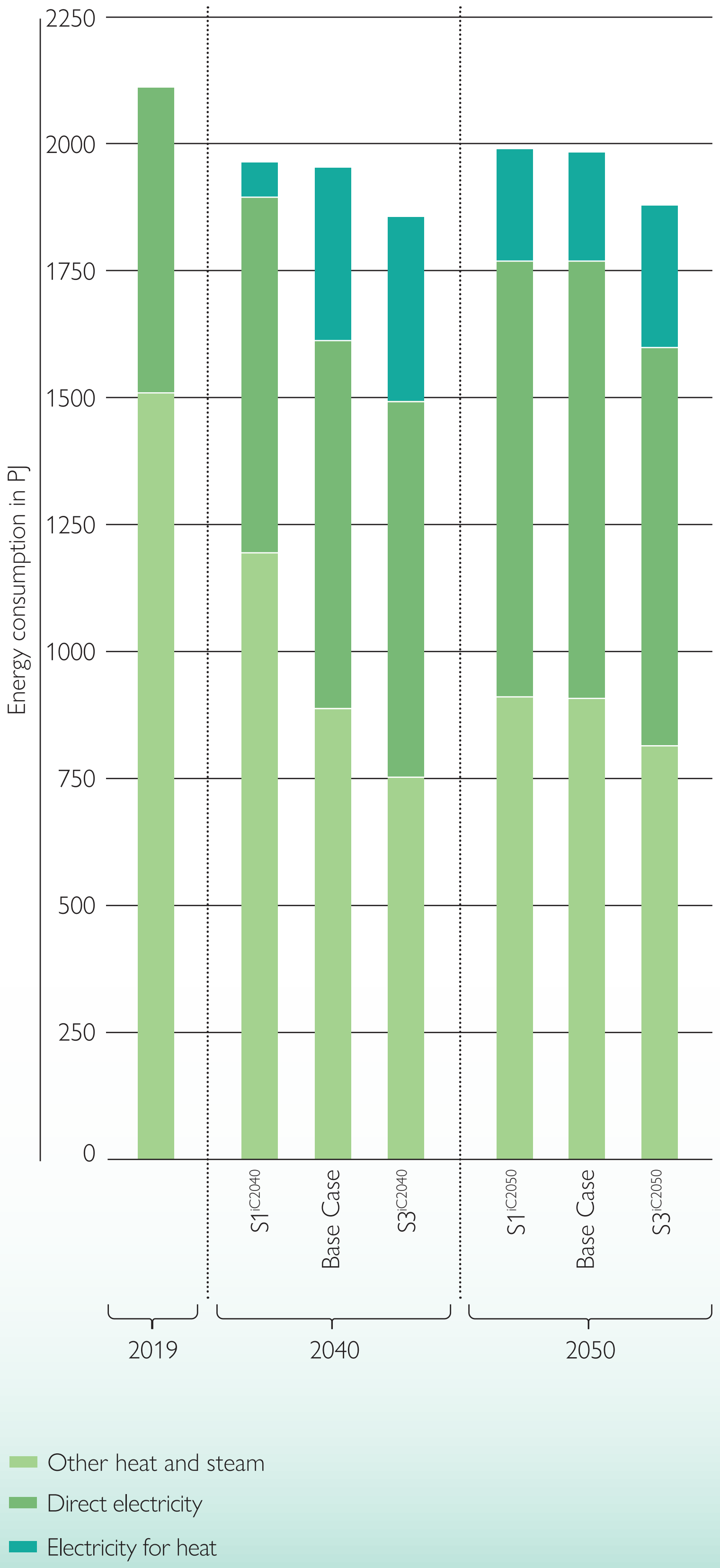
[48] See Annex 2 for a full list and description of technologies

Impact on energy demand

As shown in Chart 50, the FED decreases in all scenarios until 2040 and then increases slightly again, especially in the $S3^{iC2050}$ scenario. The **share of electricity** increases until 2040 proportionally to the level of ambition. After 2040 the share is similar across scenarios. As the scenario assumptions set a limit of **300 TWh** for yearly available electricity, the upper limit is reached by 2040 in the case of $S3^{iC2050}$ as electricity is used for both heating and direct electrification of processes.

Chart 50

Final energy consumption by energy vector – "Base Case" versus $S1^{iC2050}$ and $S3^{iC2050}$ scenarios

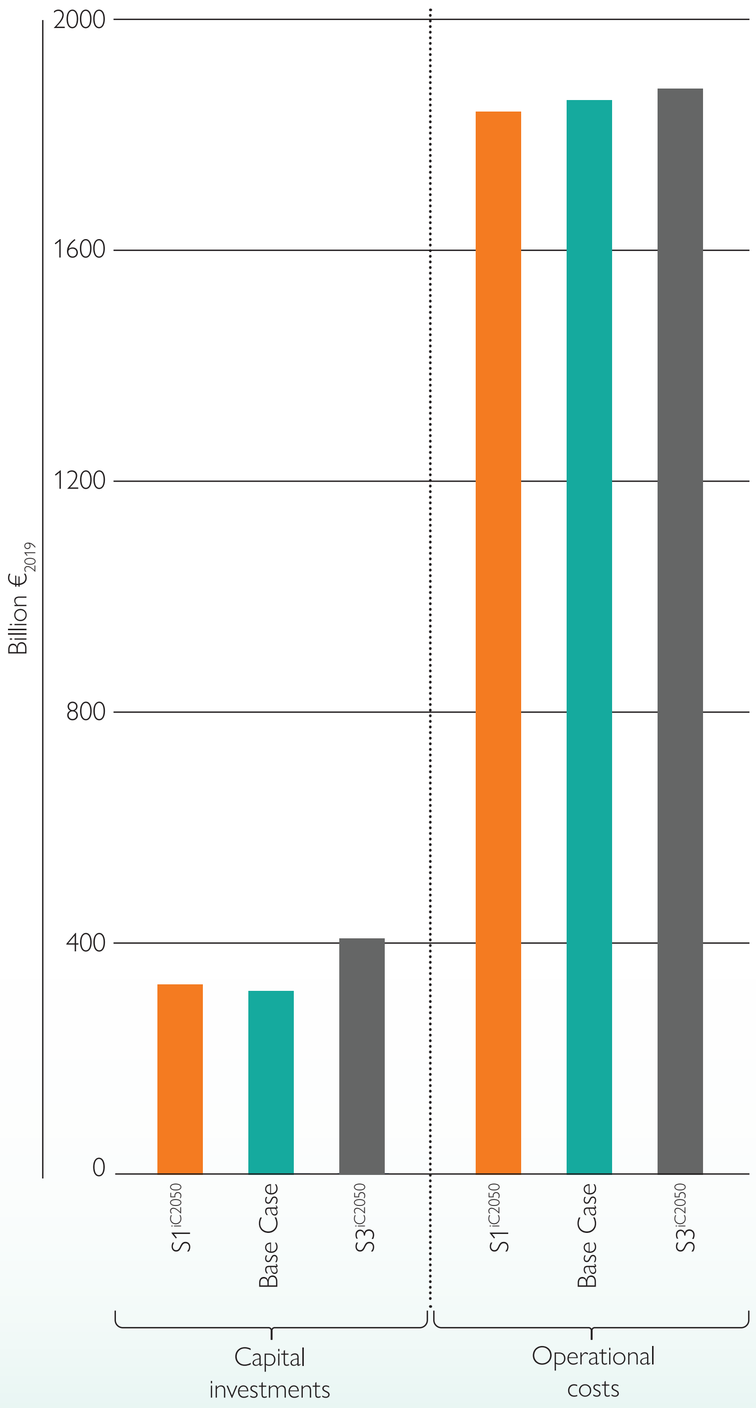


Impact on costs

A higher level of ambition results in a significantly higher **capital investments** (406 Bio€ in total) and **NPC** (2,285 Bio€) compared to the other scenarios as shown in Chart 51. This is due to the fact that **less mature** abatement solutions need to be deployed earlier, at a higher cost. It is worth emphasising as well that under $S1^{iC2050}$ higher capital investments (326 Bio€) are needed compared to the "Base Case" scenario. However, the $S1^{iC2050}$ scenario results in significantly lower operational costs (1,838 Bio€) and therefore a lower NPC (2,164 Bio€) than the "Base Case" scenario. Implementing a lower emission target in 2040 in the $S1^{iC2050}$ scenario allows for an **additional investment cycle** where the model can deploy technologies in the mid-2020s and withdraw them at the end of their economic lifetime after 2040. This results in a decrease of the operational costs over the modelling period but a slight increase in capital costs. The total NPC would therefore be lower in the $S1^{iC2050}$ compared to the "Base Case" scenario.

Chart 51

Cumulative costs of GHG abatement and circularity solutions in 2050 – "Base Case" versus $S1^{iC2050}$ and $S3^{iC2050}$ scenarios



Section 10.2

Setting feedstock targets: The SBTi case

Along with the main emission constraint that sets a net zero target in 2050, the “Base Case” scenario includes an additional constraint that sets a 20% target on the share of sustainable non-fossil carbon embedded in products. In the draft **Science Base Targets initiative (SBTi)[49] guidance document for the chemical sector,** minimum and recommended alternative feedstock targets are proposed, as shown in Table 5. These targets are calculated based on the feedstock purchased for use within the industry's operational boundary, expressed as a percentage by weight (wt.%) of carbon content.

Table 5

Alternative feedstock targets[50]

Scenario	2030	2040	2050
Minimum target (based on the combination of Systemiq’s LC-ME and LC-NFAX scenarios)	14 wt. % C	26 wt. % C	44 wt. % C
Recommended target (based on Systemiq’s LC-NFAX scenario)	16 wt. % C	38 wt. % C	83 wt. % C

In this section, we consider the **recommended target,** which implies a minimum share of alternative carbon of 38% in 2040 and 83% in 2050. However, combining these targets with the “Base Case” assumptions does not allow the model to find a feasible solution. A few constraints therefore have to be **released.**

Changes in assumptions

To enable a feasible scenario, the following constraints have been released:

- the **biomass availability** has been increased compared to the “Base Case”: the updated levels of biomass availability are based on the “High availability” projections, as presented in Annex 5. The availability of bioreformate has been increased by an average factor based on the “Medium” availability of total biomass, based on the same data.
- **Chemical recycling** deployment rates and the yields of plastic waste to py-naphtha have been increased. The detailed assumptions can be found on Page 160 under "High Recycling".
- The assumptions on **carbon capture** are more favourable and give more room for the model to capture and utilise CO$_2$ as feedstock. The detailed assumptions can be found on Page 168 under "High carbon capture".

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[49] Ambitious corporate climate action — Science Based Targets Initiative

[50] Source: See Annex 6 of the Science Based Targets initiative. (2024). Chemicals sector guidance version 0.0 | Consultation draft. DRAFT_SBTi Chemicals Sector Guidance.docx (sciencebasedtargets.org).

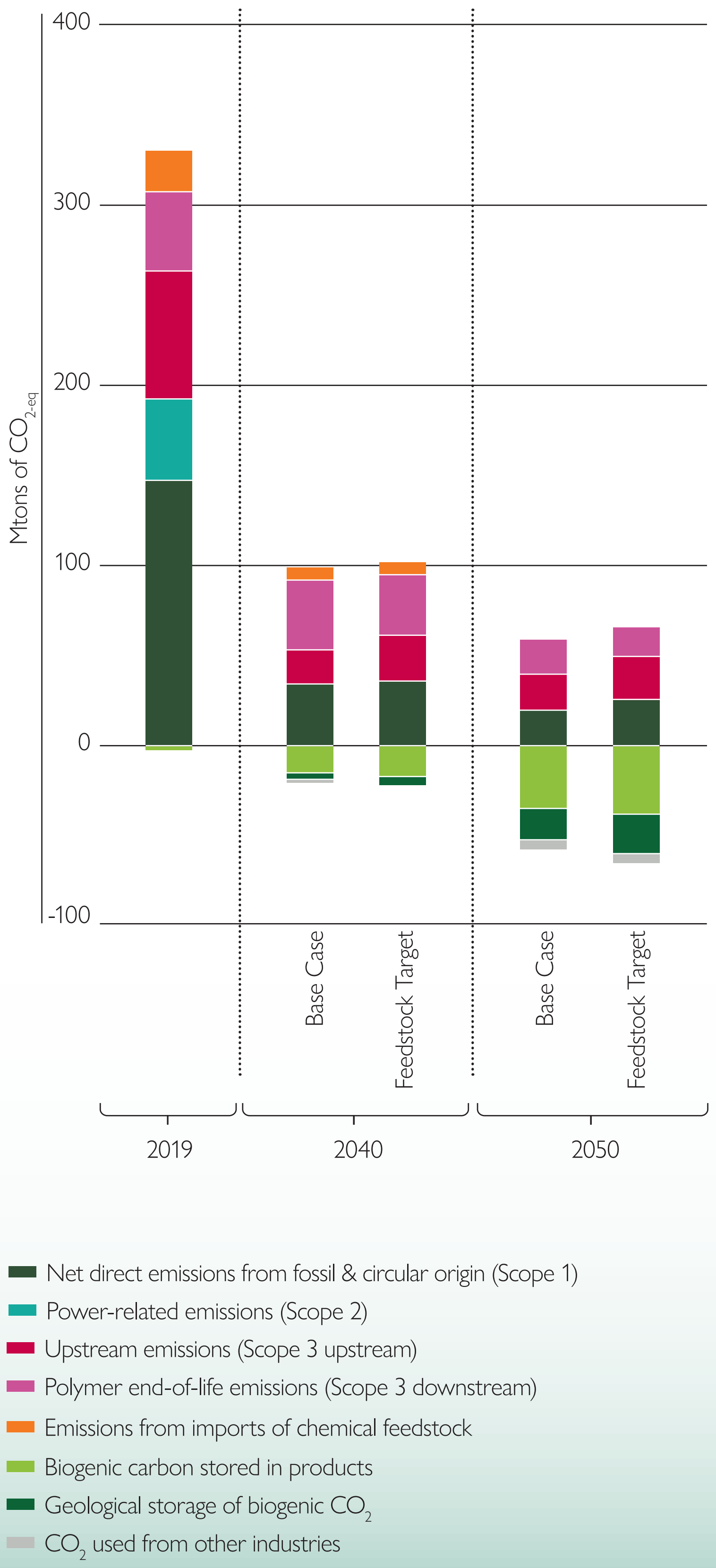
Impact on the abatement pathway

Chart 55 shows the evolution of GHG emissions per scope, comparing the “Base Case” and the “Feedstock Target” scenarios. The increasing role of biomass results in higher volumes of **carbon removals** than in the “Base Case”, which as a logical outcome, increases the amount of residual emissions that can still be emitted in 2050.

Looking more closely at modelled scope 3 emissions in 2050, results show that **upstream emissions** are going up from **19.2 to 24.2Mtons of CO$_{2\text{-eq}}$**: switching to biogenic feedstock, which has a lower carbon mass, increases total feedstock consumption. Additionally, the introduction of a higher non-fossil feedstock target would lead to the deployment of technologies that are not necessarily the most optimal in terms of cost and emissions. This is partially compensated by reducing **end-of-life emissions** of polymers, which go down from **18.7 to 17.2Mtons of CO$_{2\text{-eq}}$**.

Chart 52

GHG emissions per scope – “Base Case” versus “Feedstock Target” scenario

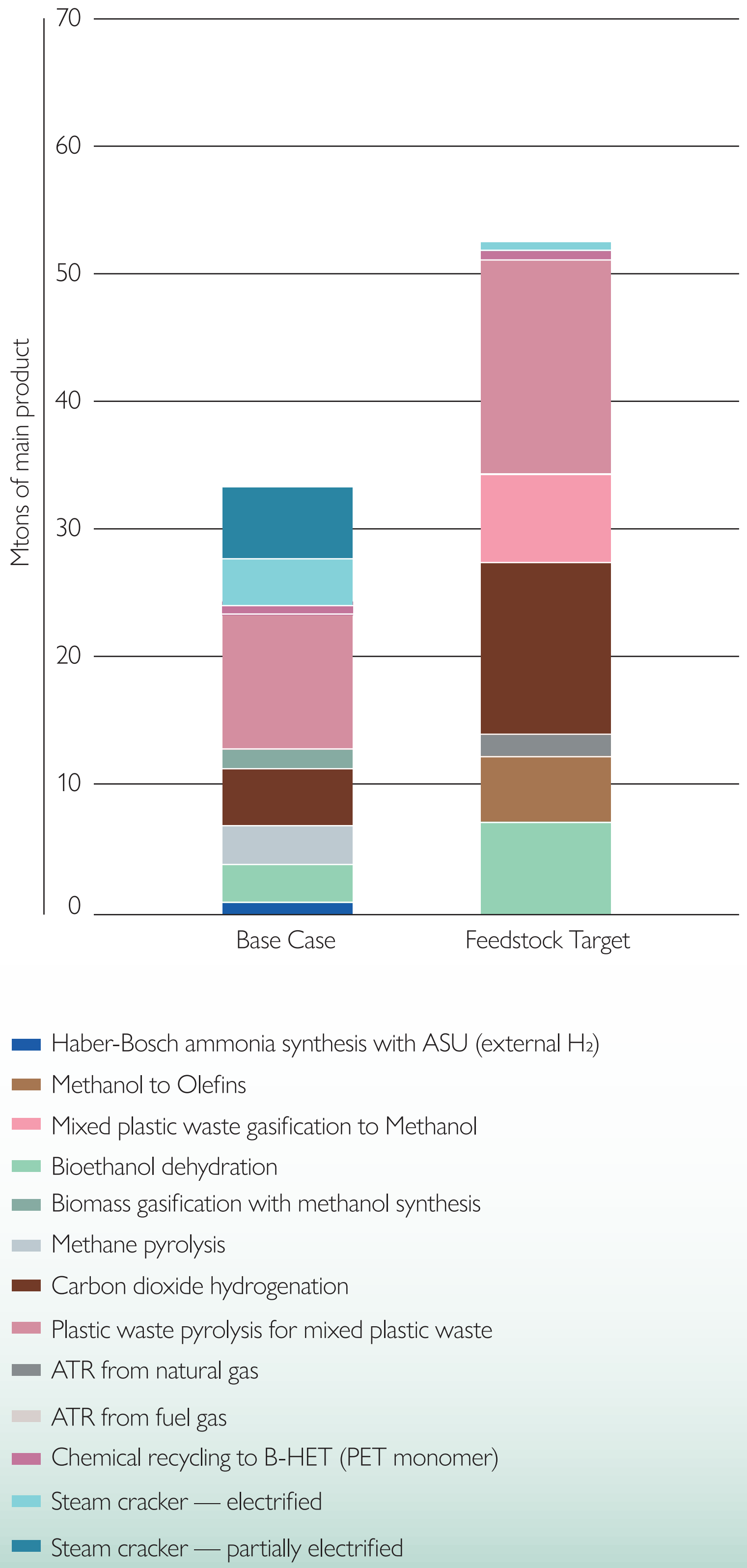


Impact on technology deployment

The introduction of sustainable non-fossil carbon targets drives up investments in technologies that process alternative materials or recycling technologies. Chart 53 shows a comparison in the deployed alternative technology capacities between the "Base Case" and "Feedstock Target" scenarios in 2050. The total alternative **capacity deployment** increases by 53% compared to the "Base Case" scenario. Some of the technologies already present in the "Base Case" are further deployed, such as bioethanol dehydration, mixed plastic waste pyrolysis, and carbon dioxide hydrogenation. Moreover, technologies such as **methanol-to-olefins** and **mixed plastic waste gasification to methanol** emerge to meet the higher targets.

Chart 53

Cumulative capacity for new production technologies in 2050 – "Base Case" versus "Feedstock Target" in 2050



Impact on the production of olefins and aromatics

Almost **80%** of the total feedstock supply of steam crackers comes from non-fossil sources in 2050 in the "Feedstock Target" scenario, as shown in Chart 54. The biggest share of the increase is driven by **chemical recycling** and the sourcing of **py-naphtha.**

Chart 54

Steam cracker feedstock consumption – "Base Case" versus "Feedstock Target" scenario in 2050

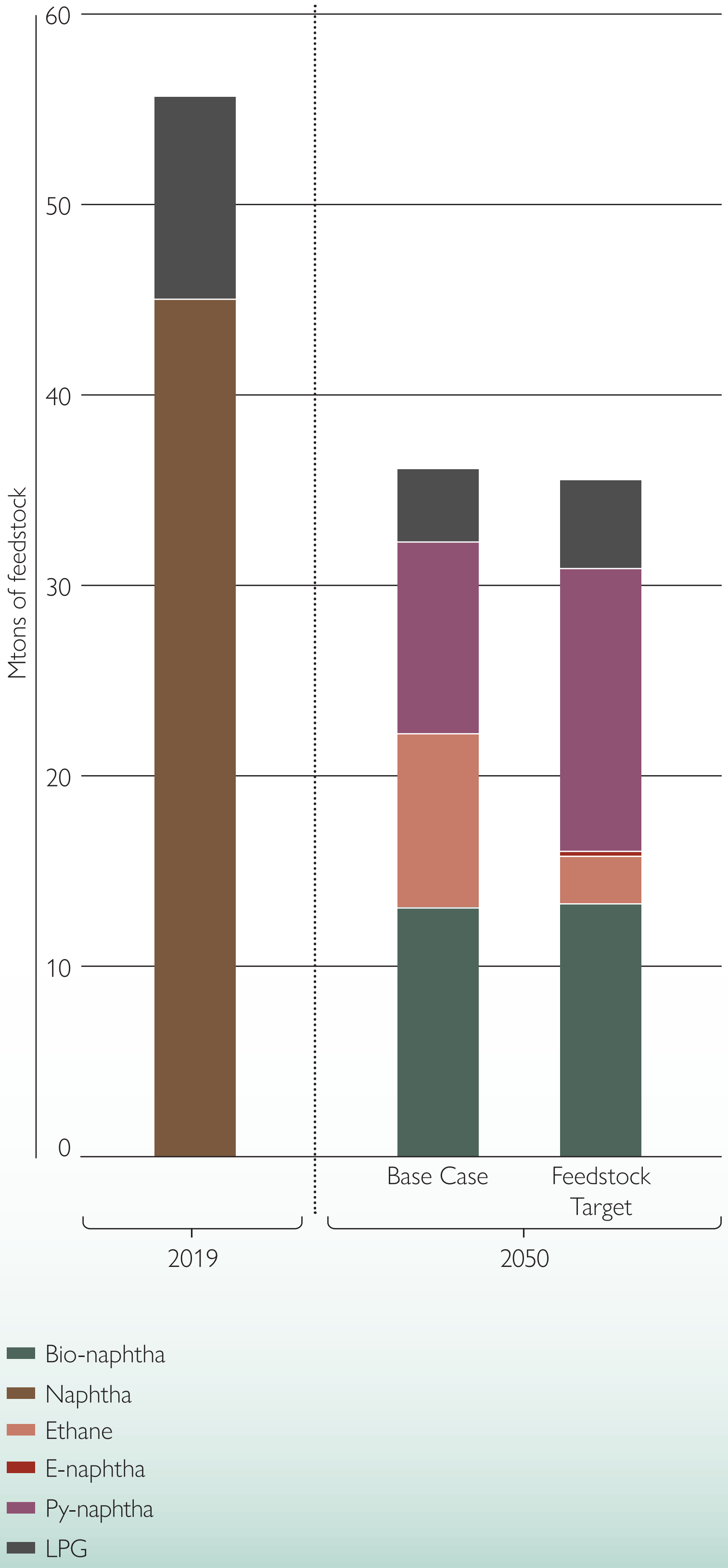
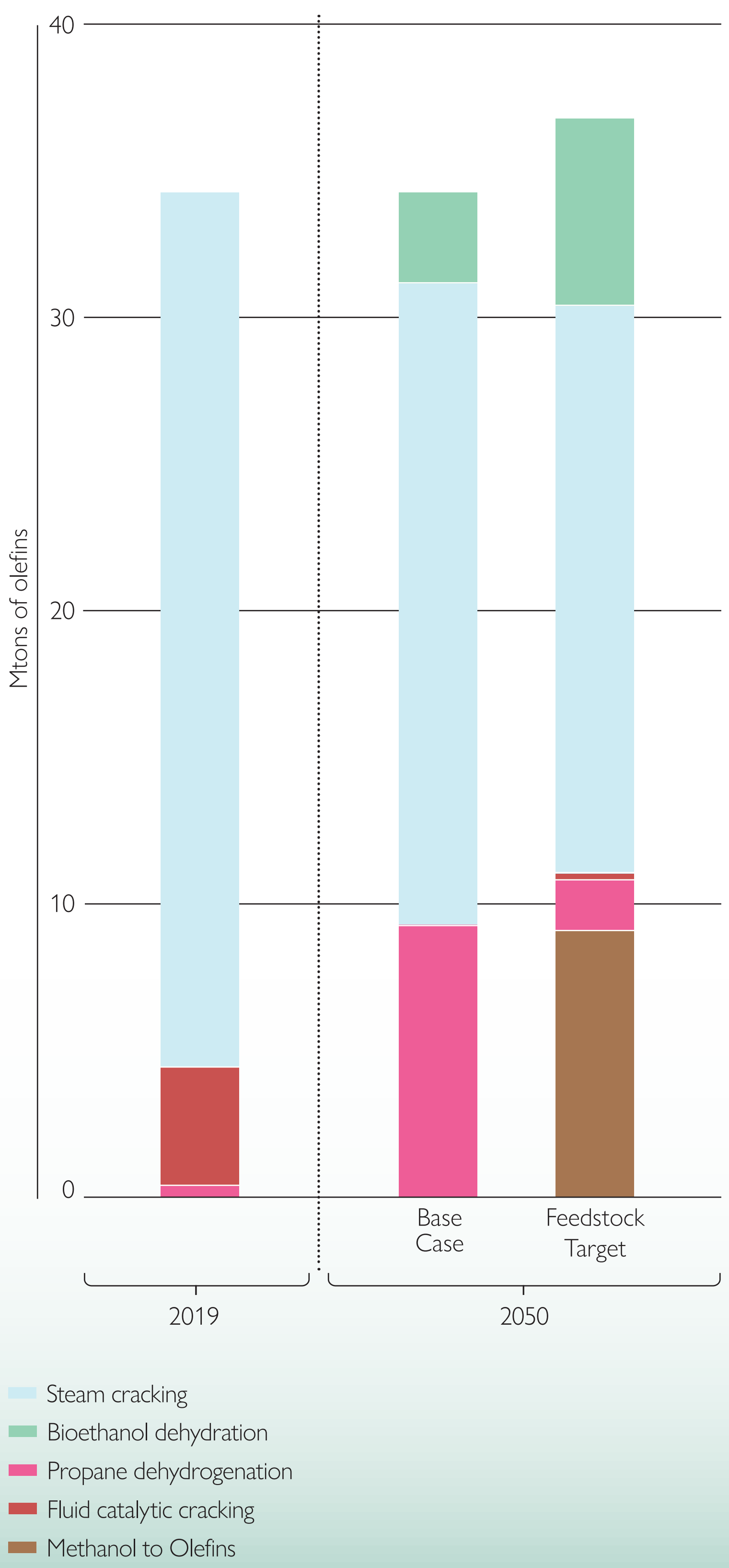


Chart 55 shows the evolution of olefins production by route in the “Feedstock Target” scenario. In 2050, almost half of the total olefins production stems from technologies alternative to steam cracking; moreover, propane dehydrogenation represents a much smaller share of propylene production. Both are partially replaced by **bioethanol dehydrogenation** and the **methanol-based** production. The methanol-to-olefins route was initially not selected by the model in the “Base Case” scenario.

Chart 55

Olefins production by technology – “Base Case” versus “Feedstock Target” scenario



Impact on feedstock demand

The feedstock consumption by mass, as shown in Chart 56, highlights the additional biomass and recycled feedstock that is required to achieve the 83% alternative feedstock target in 2050. **Biomass consumption** between 2019 and 2050 increased by more than 63% in the "Feedstock Target" scenario compared to the consumption during the same period in the "Base Case". The volume of **end-of-life polymers** that are used as feedstock increased by **87%** performing the same comparison. The increase is mainly driven by the deployment of chemical recycling in the form of mixed plastic waste gasification. **Captured CO_2** also emerges as one of the solutions, which replaces virgin materials as a circular source of feedstock.

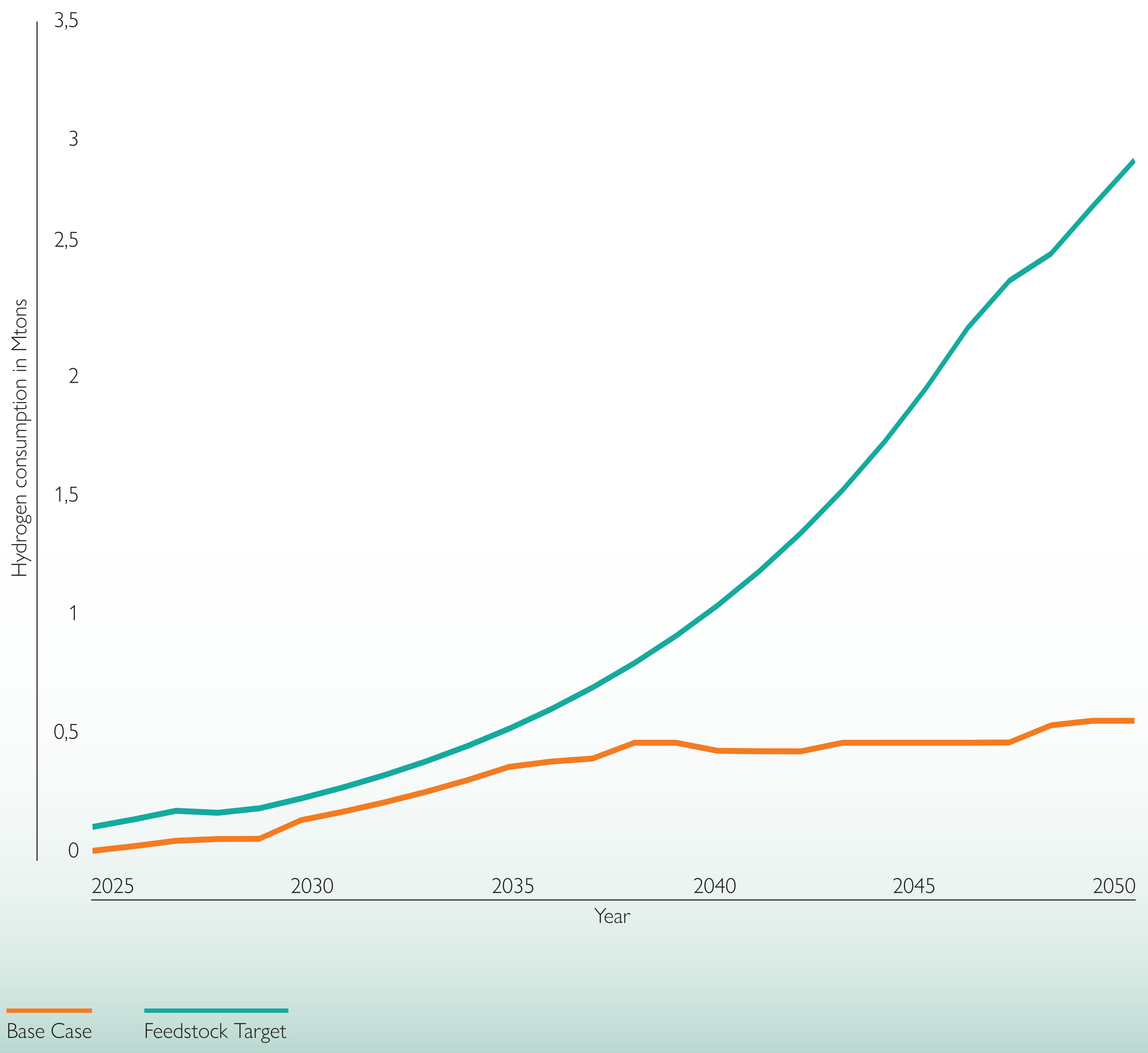
Chart 56

Carbon-based feedstock and hydrogen consumption – "Base Case" versus "Feedstock Target" scenario

The process of using captured CO$_2$ as feedstock is known as CCU, which requires hydrogen as another source feedstock in the case of methanol production. In the “Feedstock Target” scenario, the volume of **hydrogen consumption** for CCU (which is mostly self-produced) increases rapidly post-2030, going above **3Mtons** of hydrogen per year in 2050 as shown in Chart 57.

Chart 57

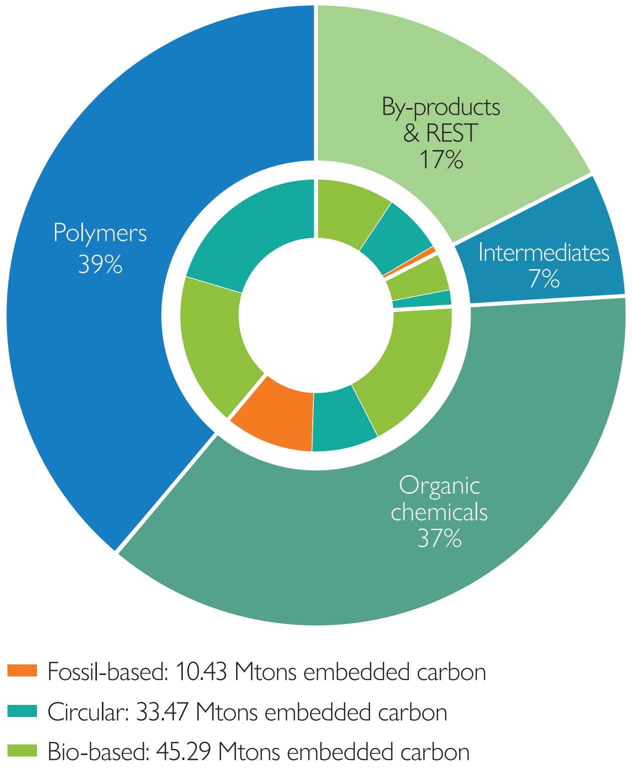
Hydrogen consumption for CCU technologies – “Base Case” versus “Feedstock Target” scenario



To achieve the alternative feedstock target that has been set for 2050, circular feedstock, which includes recycled materials and CO$_2$, is used mainly in **organic chemicals and polymer production.**

Chart 58

Embedded carbon by product category in the “Feedstock Target” scenario in 2050

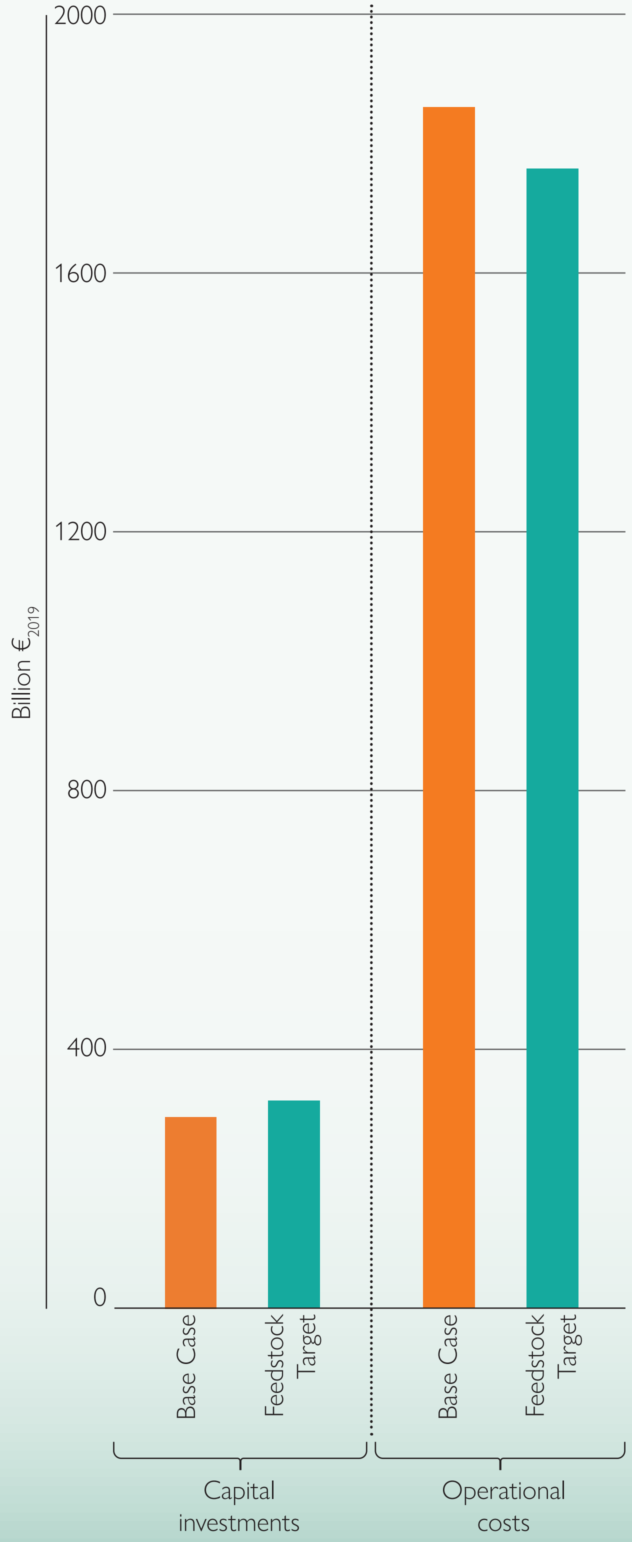


Impact on costs

To achieve the alternative feedstock target, additional investments in chemical recycling and biomass conversion are needed. As shown in Chart 59, the total cumulative **capital cost** up to 2050 in the “Feedstock Target” scenario is **11.6%** higher than the investments made in the “Base Case” scenario. Based on the cost assumption for fossil-based feedstock, which increases in line with the European Commission projections, the total cumulative **operational costs** are lower by almost **7%.** This means that if alternative sources of carbon are abundant and competitive, higher investment costs could be offset by lower operational costs.

Chart 59

Cumulative costs of GHG abatement and circularity solutions in 2050 – “Base Case” versus “Feedstock Target” scenario



Section 10.3

A renewable target for hydrogen

Hydrogen is both a final product and feedstock for the chemical industry as it is used to produce ammonia and methanol. Most of the hydrogen production is currently done through **steam methane reforming** of fossil-based natural gas. Alternative production technologies include **alkaline electrolysis, methane pyrolysis and autothermal reforming.**

The RED has set targets for RFNBOs mandating a minimum share of hydrogen from RFNBOs in the industry. This target is set at 42% in 2030 and 60% in 2035[51]. The following targets for hydrogen production from RFNBOs have been added to the "Base Case" scenario. The results will be shown in the "RED H_2 Targets" scenario.

Changes in assumptions

Since the power sector is modelled through exogenous parameters that are "yearly availability", "GHG intensity" and "price", renewable electricity is not differentiated as a separate source of energy. Due to this lack of differentiation in the model, the RFNBO hydrogen targets have been set for hydrogen produced through electrolysis knowing that the GHG intensity of electricity is assumed to decrease and reach near-zero in 2040. The industry players could choose to either produce hydrogen or purchase it from a hydrogen market. The volumes of hydrogen that are purchased from the market are assumed to be part of the RFNBO hydrogen that is used to set the RED targets in this scenario. The 2030 and 2035 targets have been set for the hydrogen that is used for **ammonia production** in the chemical industry.

The assumptions of the "RED H_2 Targets" are identical to the "Base Case", except an increase in the yearly availability of electricity from 300 TWh to **1.000 TWh,** allowing the model to source enough electricity to produce hydrogen through electrolysis.

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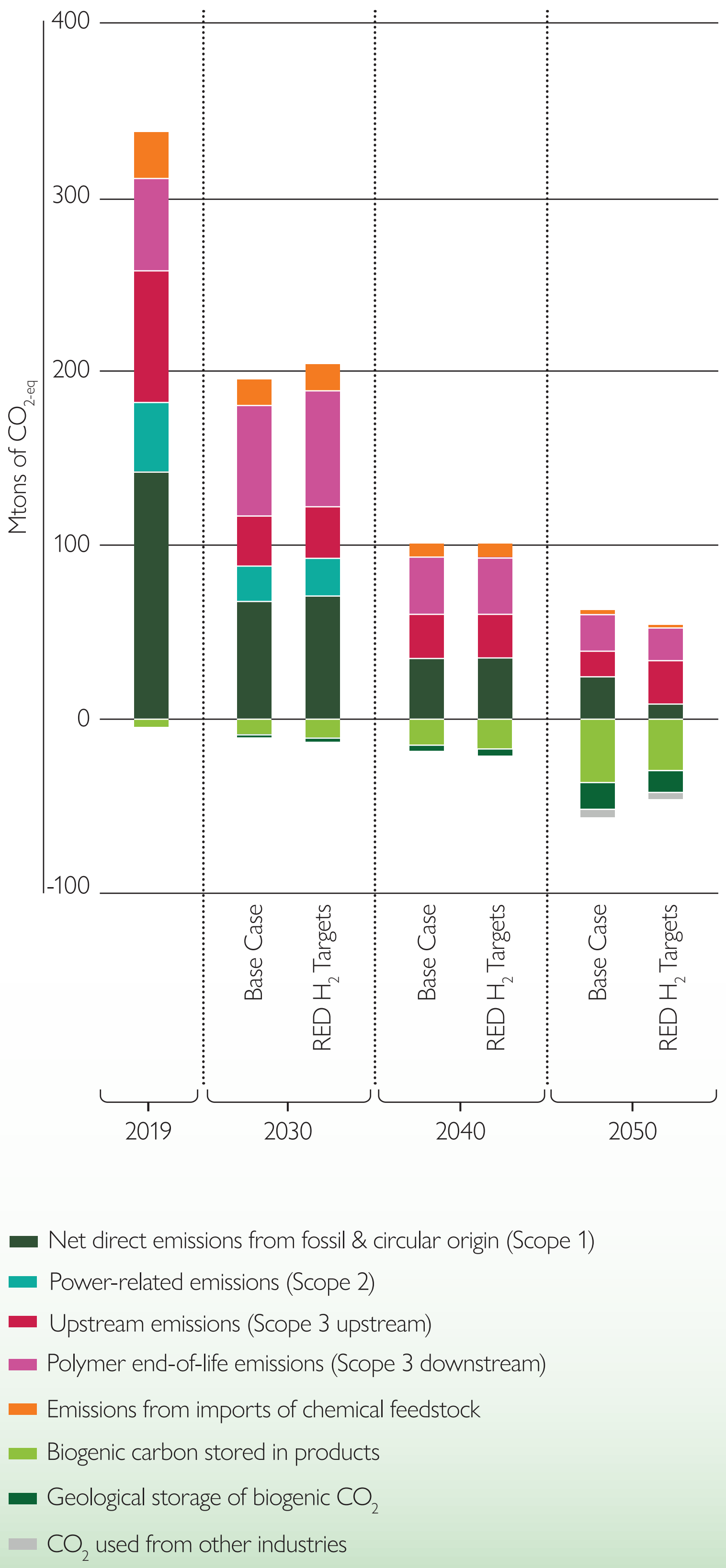
[51] European Commission. Renewable Energy Directive. Renewable Energy Directive (europa.eu)

Impact on the abatement pathway

The implementation of the RFNBO hydrogen targets results in higher **electricity consumption** in 2030, and consequently higher scope 2 emissions in the "RED H_2 Targets" scenario, compared to the "Base Case" as shown in Chart 60. By 2050, the direct emissions decrease to a lower level when implementing the hydrogen targets as steam methane reforming is replaced by alkaline electrolysis. As the GHG intensity of the electricity supply is zero in 2050, the total **residual emissions** are lower in "RED H_2 Targets" compared to the "Base Case" scenario, requiring **less negative emissions.**

Chart 60

GHG emissions per scope – "Base Case" versus "RED H_2 Targets" scenario

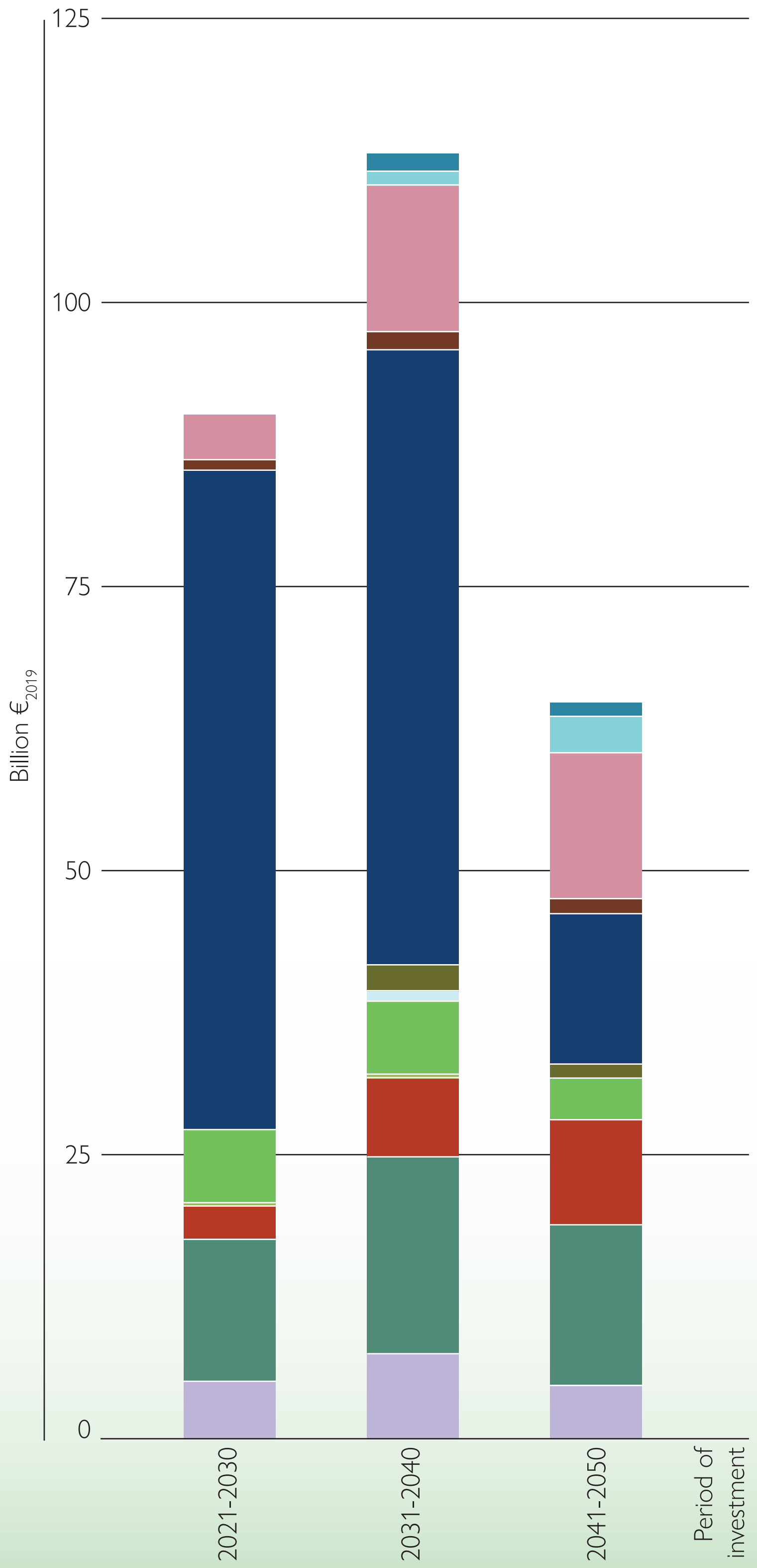


Impact on technology deployment

The introduction of the renewable hydrogen targets implies a major scale up between 2020 and 2040 as the investment in **electrolysers** constitutes **62% and 48%** of the total investments made in the 2020s and the 2030s respectively. Compared to the "Base Case" scenario, total capital investments in alternative technologies in the period between 2021 and 2030 would increase by more than **90%.**

Chart 61

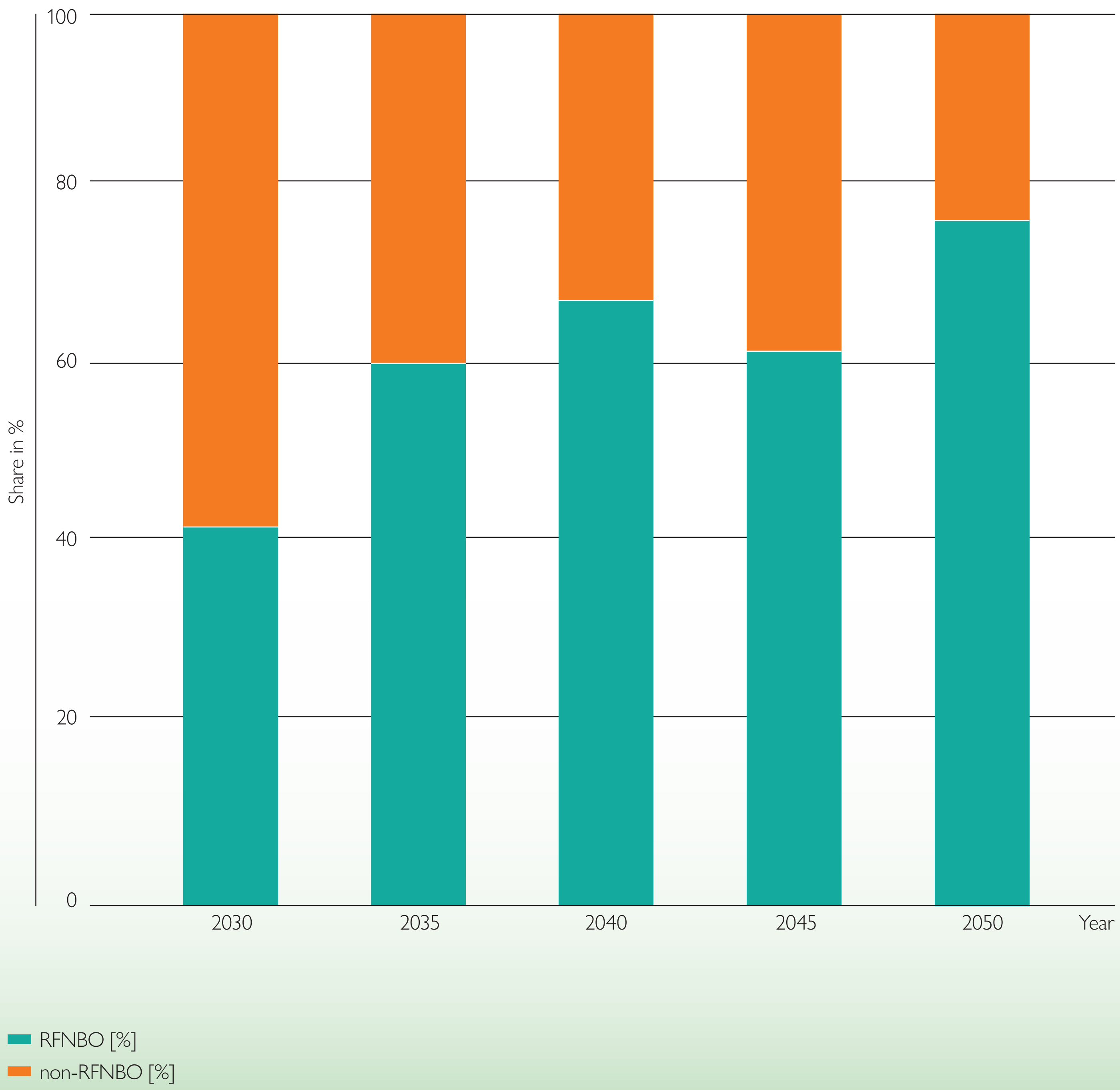
Capital investment going to new technologies in the "RED H_2 Targets" scenario



The minimum targets that have been set for renewable hydrogen in 2030 and 2035 are exceeded in 2050 to reach **76.8%** as shown in Chart 62. The main driver for this increase after 2040 is the assumption that the GHG intensity would be close to zero after that year, which encourages the increase in deployment of electrolysers.

Chart 62

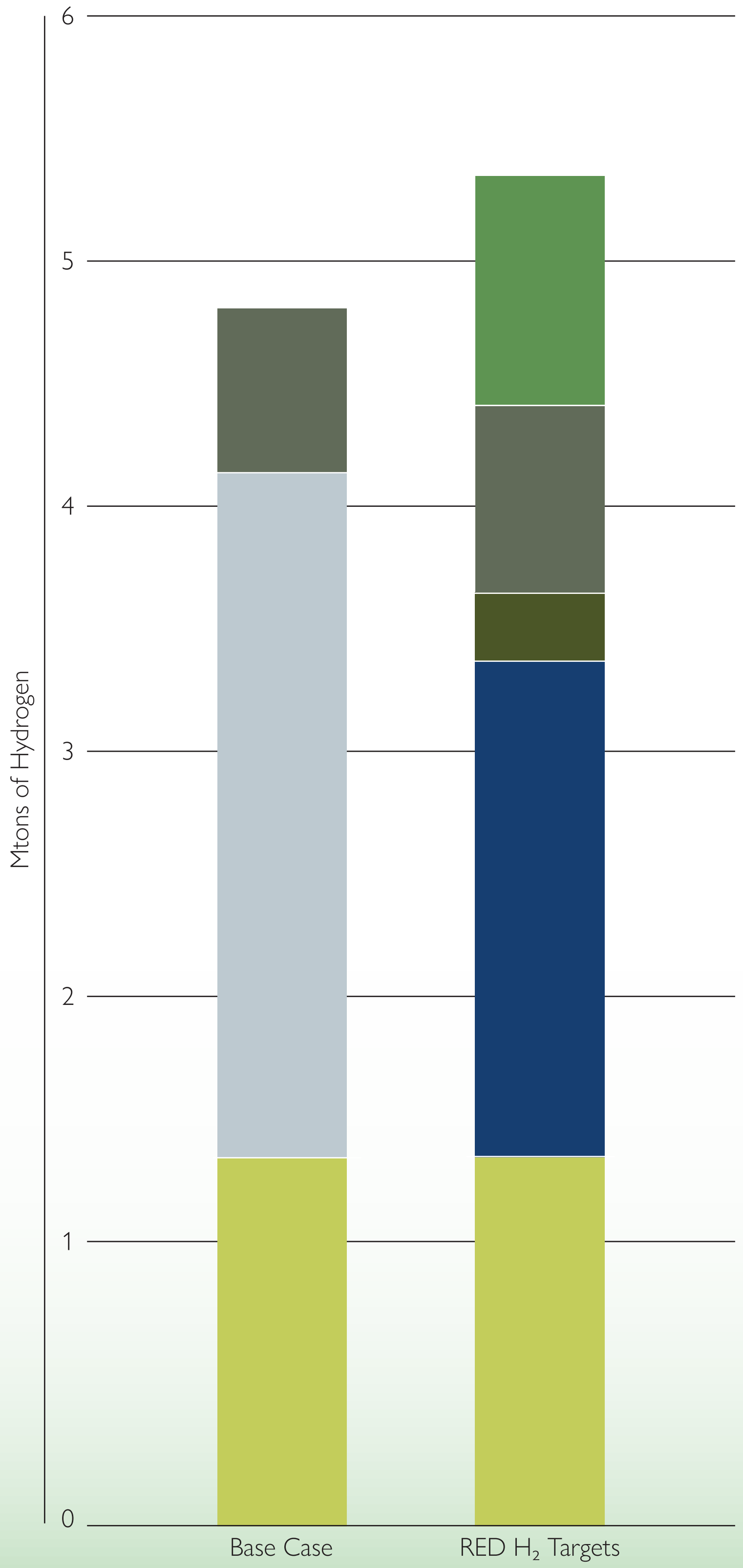
Share of RFNBO hydrogen used in ammonia production in the "RED H_2 Targets" scenario



Reflecting the higher share of renewable hydrogen compared to the "Base Case" scenario, methane pyrolysis is not selected by the model for the production of hydrogen in 2050. It is mostly substituted by **alkaline electrolysis,** which reaches **40.8%** in 2050, as well as SMR and pyrolysis of biomethane.

Chart 63

Hydrogen production by technology – "Base Case" versus "RED H_2 Targets" scenario in 2050

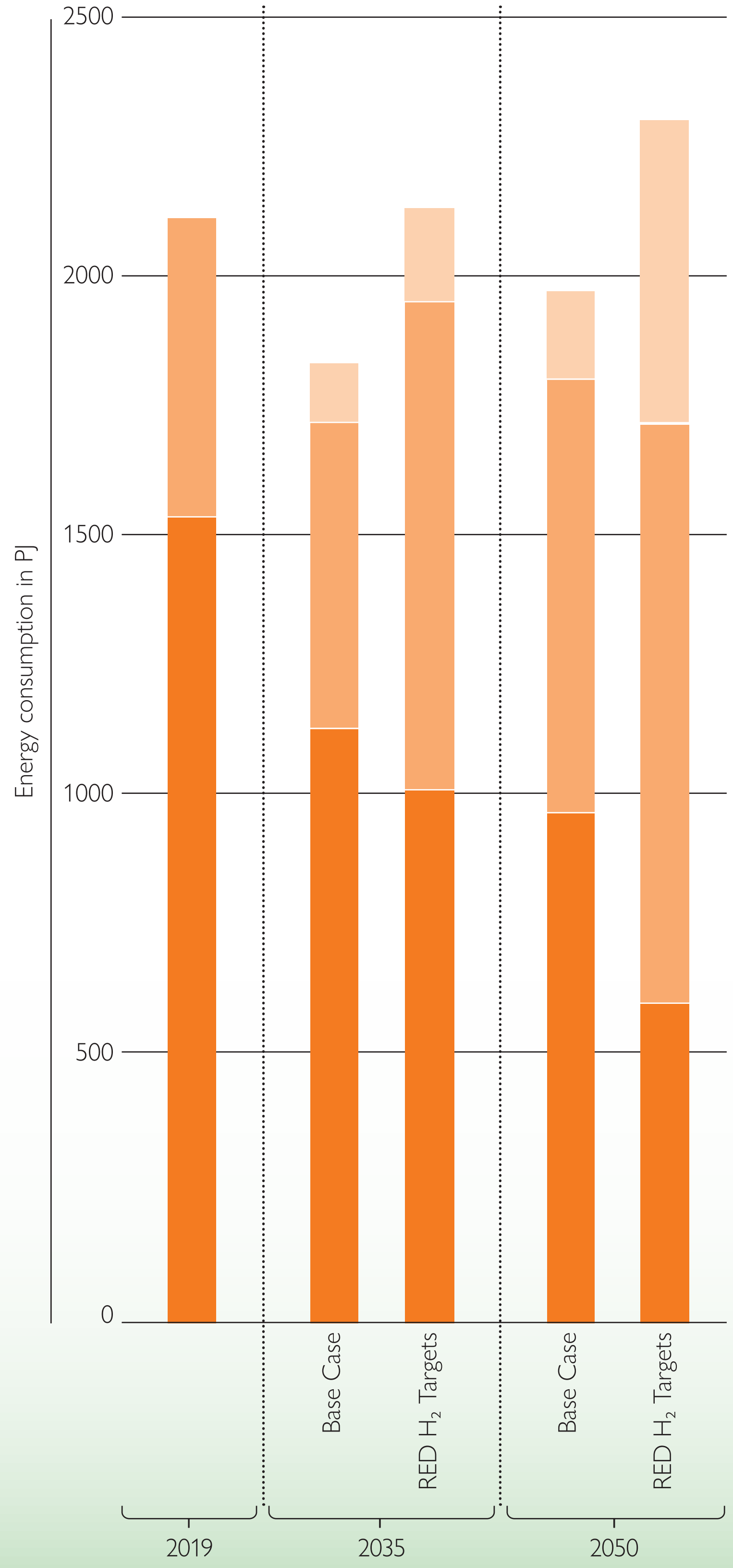


Impact on energy demand

Final energy consumption increases by **12% and 14%** in the "RED H_2 Targets" scenario compared to the "Base Case" in 2035 and 2050 respectively. This increase is due to the additional consumption of **electricity** for the production of hydrogen, with the total electricity consumption reaching 497 TWh in the 2050 in the "RED H_2 Targets" scenario. The share of electrification from the final energy consumption also increases to reach **78.8%** in 2050 in the "RED H_2 Targets" scenario compared to 54.2% in the "Base Case".

Chart 64

Final energy consumption by energy vector – "Base Case" versus "RED H_2 Targets" scenario

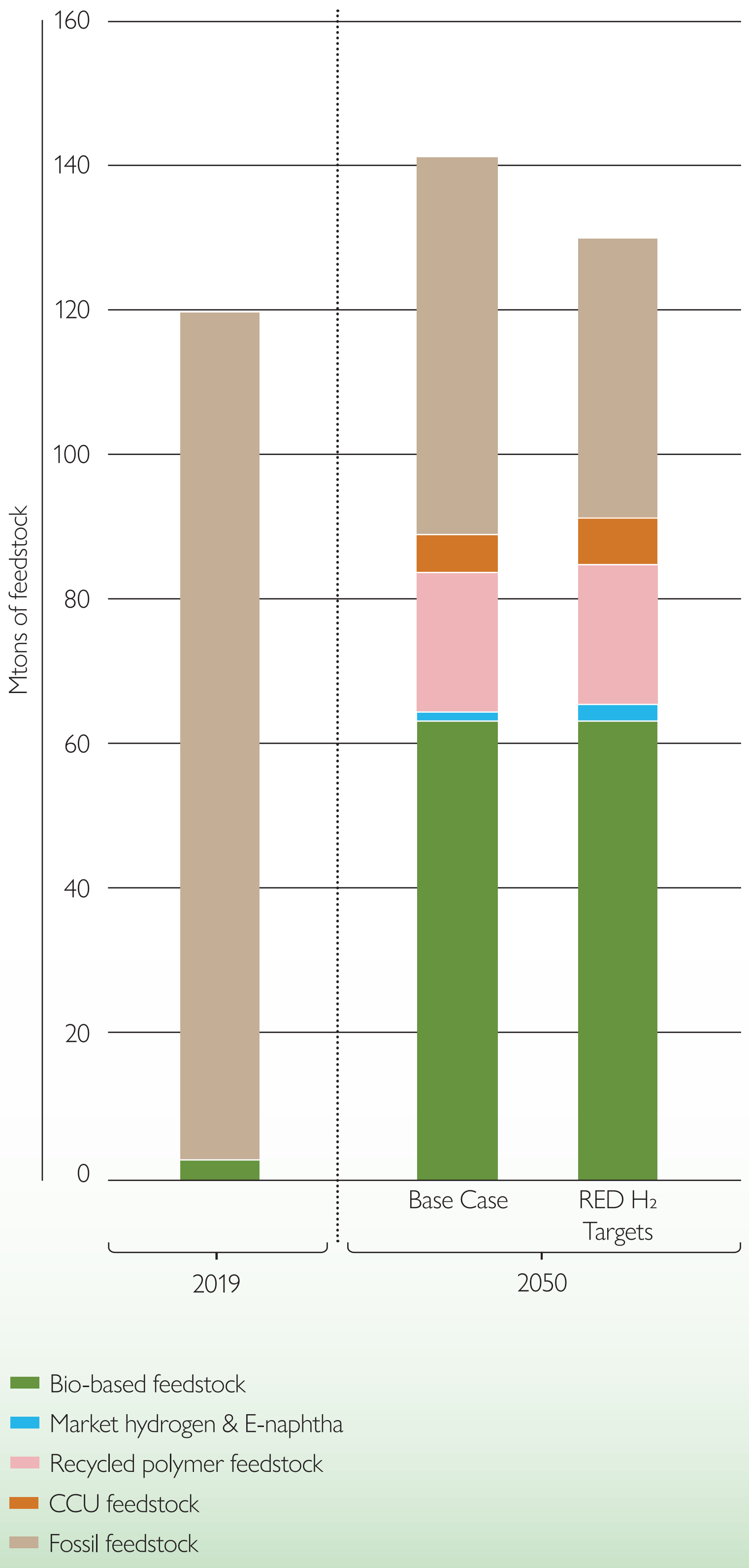


Impact on feedstock demand

The consumption of **fossil-based feedstock** in 2050 decreases in the “RED H_2 Targets” scenario compared to the “Base Case” due to the lower reliance on natural gas as a source of feedstock for the production of hydrogen. The total amount of carbon-based feedstock consumption also **decreases** as the consumption of fossil natural gas is replaced by water and electricity for hydrogen production.

Chart 65

Carbon-based feedstock and hydrogen consumption – “Base Case” versus “RED H_2 Targets” scenario

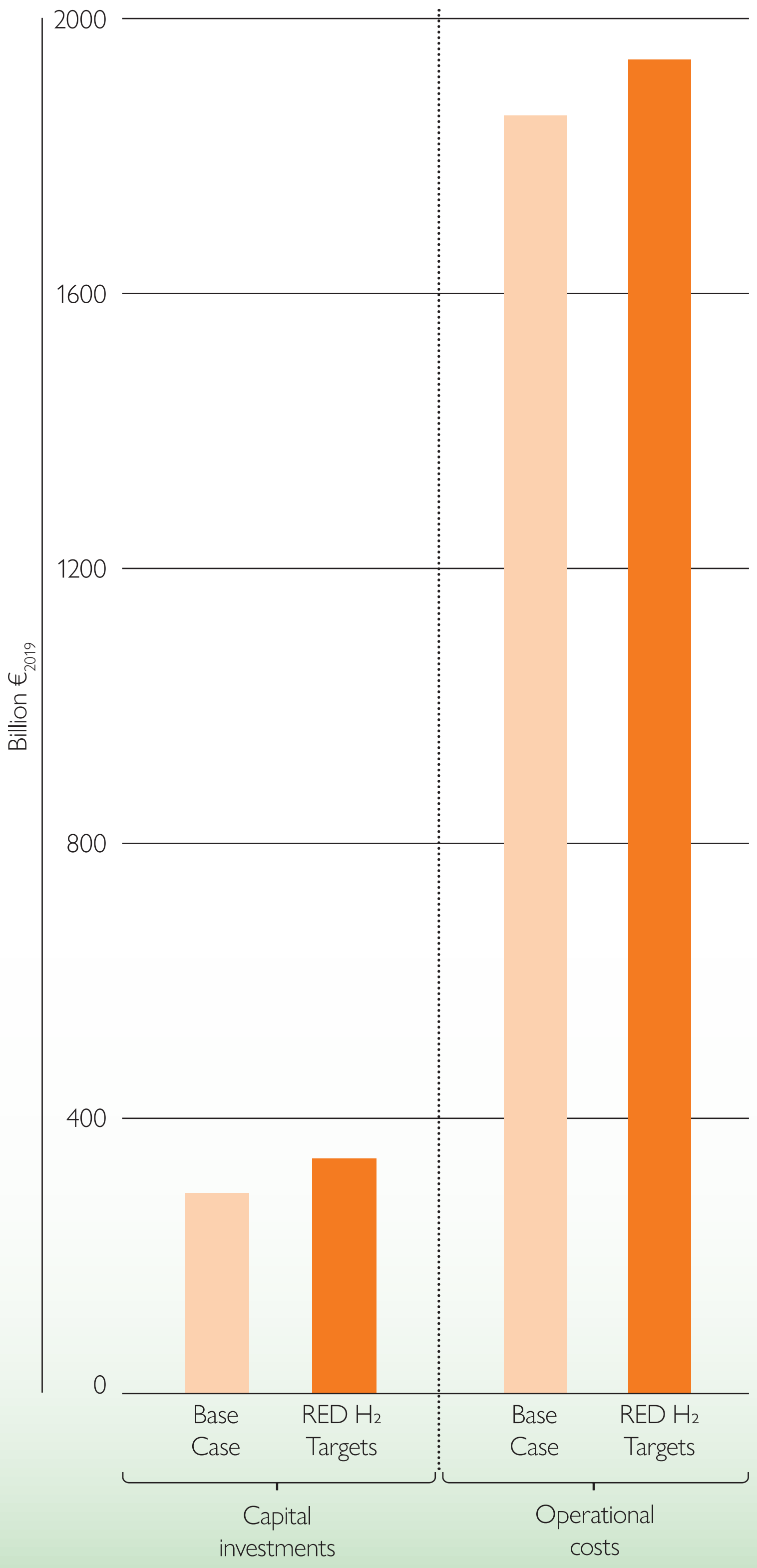


Impact on costs

Additional capital and operational costs are needed to reach the renewable hydrogen targets. The cumulative **capital investment** over the modelling period increases by **17.3%** and the cumulative **operational costs** increase by **4.8%** compared to the “Base Case”. The increase in operational costs is mainly driven by the cost of electricity that is required to produce the hydrogen.

Chart 66

Cumulative costs of GHG abatement and circularity solutions in 2050 – “Base Case” versus “RED H_2 Targets” scenario



Section 10.4

Summary and comparison

Abatement pathways

The implementation of different policies and emission targets drives the model to find new solutions meeting the new constraints that have been introduced. The evolution of total net emissions across all scopes are presented in Chart 67.

The $S1^{iC2050}$ and $S3^{iC2050}$ scenarios are the most differentiated, reflecting the stringency of the caps cap on direct emissions in 2040. The two other scenarios ("Feedstock Target" and "RED H_2 targets") do not vary significantly compared to the "Base Case".

Chart 67

Total net GHG emissions between 2019 and 2050 – Comparison between policy scenarios

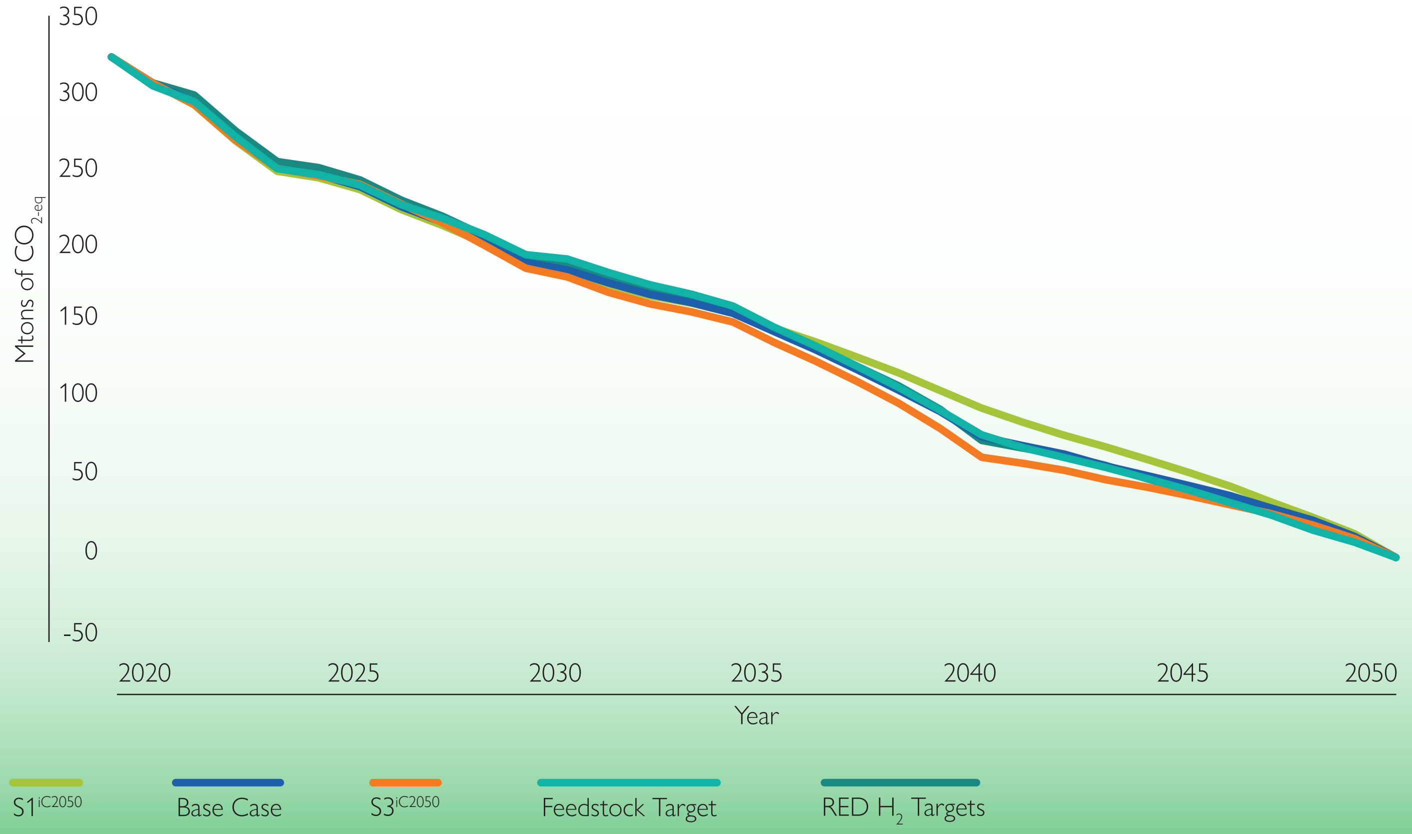


Table 6 shows the detailed comparison of the "Base Case" scenario and the policy scenarios by emission scope. Although all scenarios achieve climate neutrality in the same year, the gross remaining emissions and compensation through negative emissions vary significantly. The **$S3^{iC2050}$** results in the **highest direct and polymer end-of-life emissions,** which are neutralised by a significantly higher amount of carbon removals. The implementation of a higher emission reduction target in 2040 with limited availability of electricity and carbon capture technologies leads to a greater reliance on biomass as a solution for negative emissions. The deployment of bio-based solutions starts in the 2030's, and those technologies stay operational until 2050 as the model is able to achieve the climate neutrality target in 2050 without replacing those technologies. The higher intake of biomass feedstock reduces the need to decrease the gross emissions further as the remaining emissions are compensated.

The **"RED H_2 Targets"** scenario achieves the **lowest amount of residual emissions,** and therefore relies the least on negative emission to achieve climate neutrality in 2050. The higher availability of electricity, which allows shifting hydrogen production towards alkaline electrolysis reduces direct emissions by 41% in 2050, compared to the "Base Case".

Table 6

Emissions per scope across policy scenarios in 2050 in Mtons of $CO_{2\text{-eq}}$

Emission scope	Base Case	$S1^{ic2050}$	$S3^{ic2050}$	Feedstock Target	RED H_2 Targets
Net Direct Emissions from Fossil & Circular Origin	19	21	25	23	12
Scope 2 Emissions	0	0	0	0	0
Upstream Emissions	19	19	23	24	18
Polymer EoL Emissions	19	19	29	17	19
Emissions from Imports	1	1	1	1	1
Biogenic C Stored in Products	-35	-35	-51	-39	-32
Geological Storage of Biogenic CO_2	-19	-21	-25	-23	-12
CO_2 Used from Other Industries	-4	-5	-2	-4	-6

Table 7

Residual and negative emissions in 2050 across policy scenarios

	“Base Case”	$S1^{iC2050}$	**$S3^{iC2050}$**	“Feedstock Targets”	**“RED H_2 Targets”**
Residual emissions [Mtons of $CO_{2\text{-eq}}$]	58	59.9	**77.7**	65.8	**50**
Negative emissions [Mtons of $CO_{2\text{-eq}}$]	-58	-59.9	**-77.7**	-65.8	**-50**

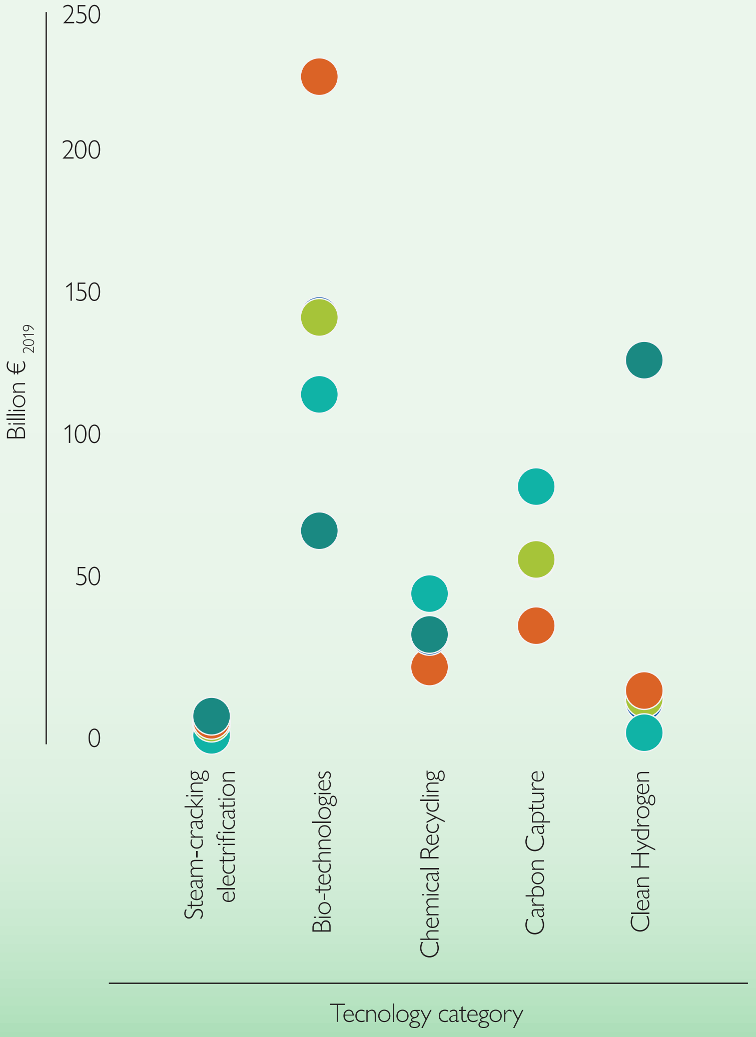
Technology deployment

In line with the above finding, the introduction of a higher emission target in 2040 in the $S3^{iC2050}$ scenario drives higher investments into bio-based solutions as shown in Chart 68. It also results in the lowest level of investments into chemical recycling technologies, as the industry needs to perform better on scope 1 emissions, due to the higher emission reduction targets.

The “RED H_2 Targets” scenario results in the lowest investments in bio-technologies compared to the other scenarios since the utilisation of biomethane for hydrogen production is replaced by electrolysis.

Chart 68

Cumulative investments by technology category across policy scenarios in 2050

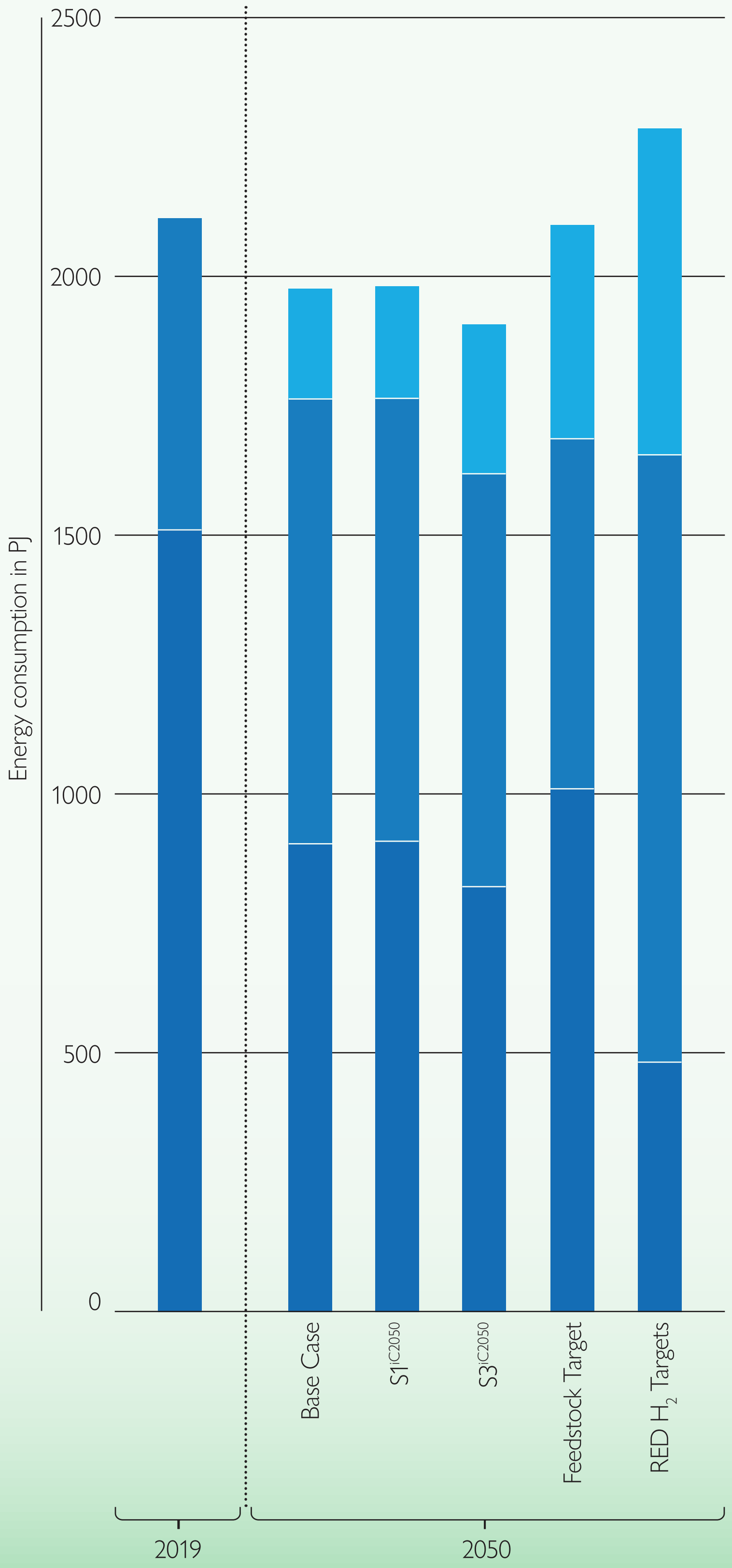


Energy demand

As shown in Chart 69, final energy consumption in 2050 slightly decreases in the **$S3^{iC2050}$ scenario,** compared to the “Base Case”. This is mainly due to lower hydrogen production and limited access to decarbonised electricity and to biomass, combined with a more ambitious abatement pathway. Energy consumption increases most in the **“RED H_2 Targets”** scenario as electrification of processes and heating occurs more rapidly. The production of hydrogen through electrolysis is the main contributor to the increase in direct electricity consumption.

Chart 69

Final energy consumption across policy scenario in 2050

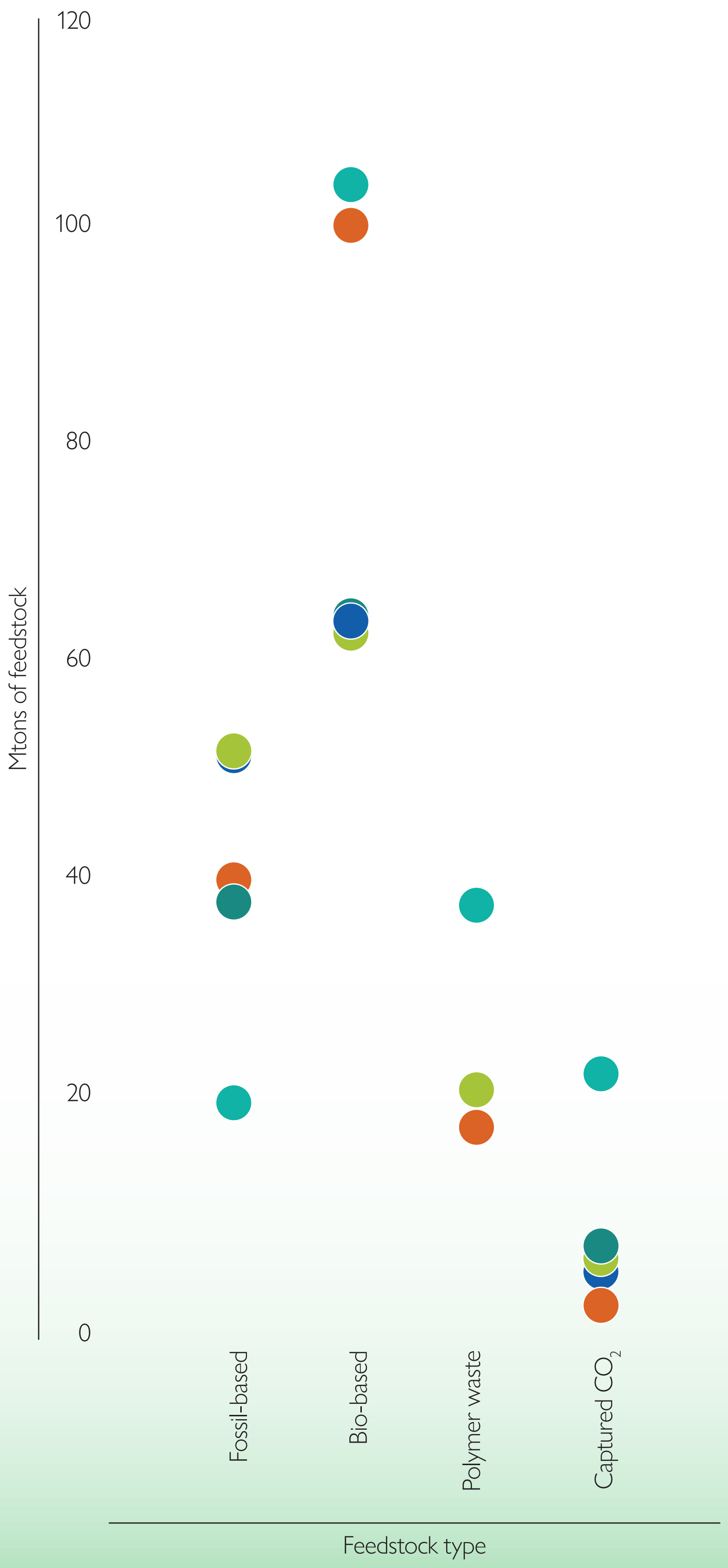


Feedstock demand

Feedstock consumption across policy scenarios in 2050 is presented in Chart 70. The consumption of bio-based feedstock is directly correlated with the **investments in bio-technologies.** The **"Feedstock Targets"** scenario consumes by far the most feedstock from polymer waste and captured CO_2, while consuming the least fossil-based feedstock.

Chart 70

Feedstock consumption by source across policy scenarios in 2050



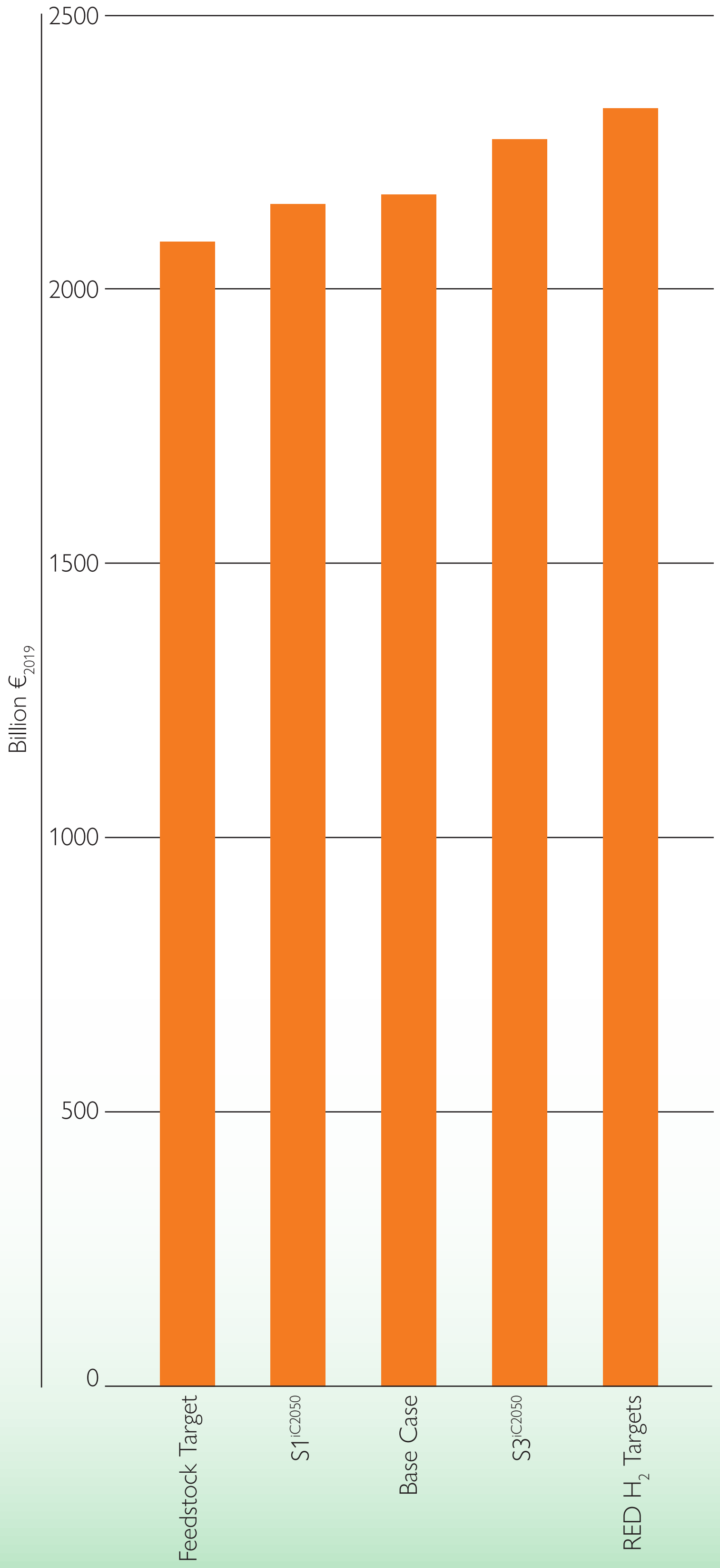
Costs

The sum of the **net present capital** and **operational costs** across policy and emission target scenarios is presented in Chart 71. The **"RED H_2 Targets"** scenario is the most costly due to significant investments in hydrogen production from electrolysers and the additional operational costs from electricity use. The S3^{iC2050} scenario ranks second, with the higher emission reduction target in 2040 driving the model to invest into less mature technologies, making the overall pathway less cost-effective.

The **"Feedstock Target"** scenario has the lowest NPC on the other hand, because the **enabling conditions** are assumed to be all available for this scenario to be feasible. The increase in electricity availability, developments in CO_2 capture technologies and infrastructure, additional sustainable biomass available, and developments in chemical recycling all contribute to achieving the lowest NPC, even though high sustainable non-fossil carbon targets are set between 2030 and 2050.

Chart 71

Total Net Present Cost across policy scenarios



Section 11

“What if?”

The “Base Case” scenario has been developed to explore the future of the EU chemical industry based on available references and official sources. The assumptions of the “Base Case” scenario include a large degree of uncertainty, which makes its materialisation highly improbable. In this section of the report, assumptions are challenged with a series of “what if” and “what if not” sensitivities. The purpose of those sensitivities is to explore **hypothetical futures,** taking a more or less optimistic view regarding the future **enabling framework** for the chemical sector’s transformation. The “what if” and “what if not” sensitivities will explore four categories of abatement solutions: electrification, biomass, recycling, and carbon capture.

Section 11.1

The role of electrons

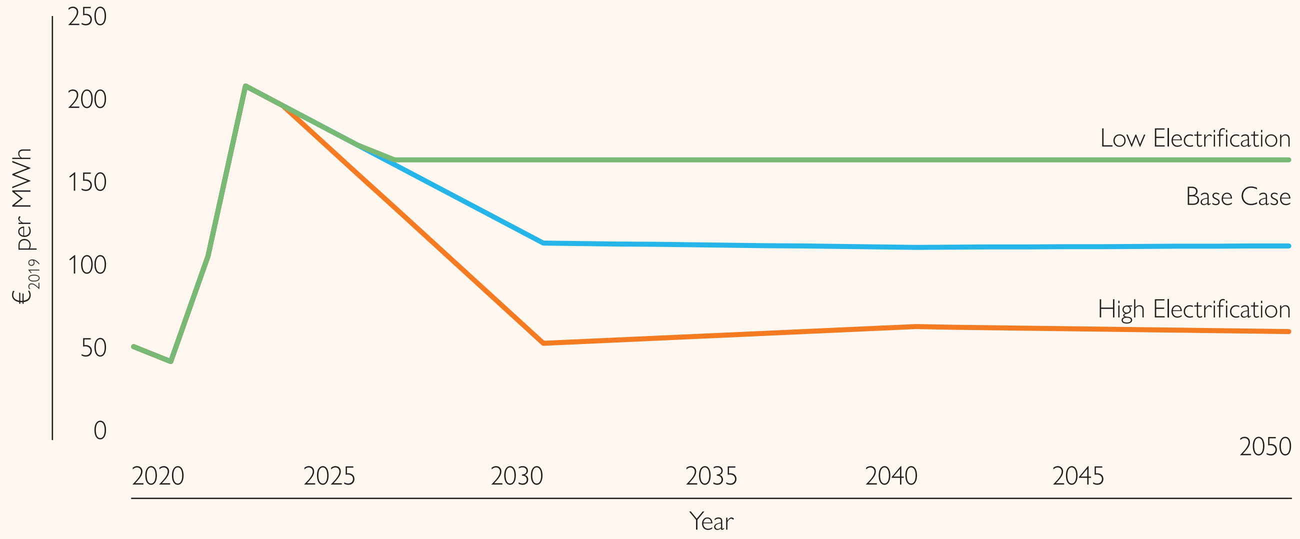
Changes in assumptions

In the “Base Case” scenario, electricity is assumed to have limited availability within the chemical industry, with a maximum limit of 300 TWh per year and a price reaching 109€/MWh in 2050. Those parameters could be replaced by alternative assumptions on the availability of electricity and future prices.

Regarding the price of electricity, we first adopted an optimistic view, performing a “High Electrification” sensitivity analysis, where, we have used the 2022 TYNDP Scenario Report[52]. In this report, the electricity price trajectory stabilises at a **€57/MWh** post-2030, which is almost half the price assumed in the “Base Case” scenario. Taking a more pessimistic approach with a “Low Electrification” sensitivity analysis, we have mirrored the same price variation in a negative way, increasing it by 48% in 2050. The electricity price assumptions for the three scenarios are reported in Chart 72.

Chart 72

Assumptions on electricity price – “Base Case” versus “Low” and “High electrification”



For the second key parameter i.e. availability, we have assumed in the “High Electrification” sensitivity analysis that access to electricity is almost unconstrained, with a cap set at **1,000 TWh.** In the “Low Electrification” analysis, a test has been performed to determine the lower limit for electricity availability that would yield a feasible solution, in combination with the other “Base Case” assumptions. Under **250 TWh** available in 2050 (which is 50% higher than electricity consumption in the chemical industry in 2019), the model is unable to define a feasible pathway towards climate-neutrality.

The changes in assumptions that we have used for the sensitivity, are presented in Table 8.

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[52] Source: ENTSO-E, ENTSOG. (2022). TYNDP 2022. Scenario report. TYNDP 2022 Scenario Report | Version. April 2022 (entsos-tyndp-scenarios.eu)

Table 8

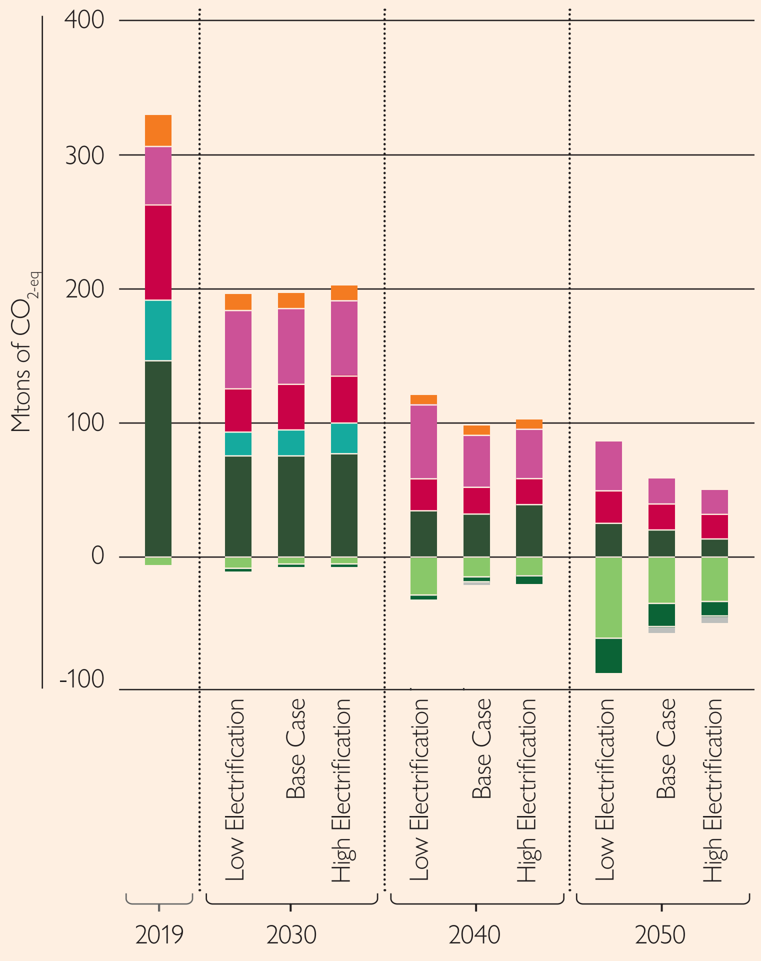
Assumptions on electricity price, electricity availability and deployment of electrified steam cracking – “Base Case” versus “Low” and “High electrification”

Scenario	Electricity price in $€_{2019}$ /MWh	Availability	Electrified steam cracker availability
“Base Case”	109	300 TWh per year	From 2035
“High Electrification”	57	1,000 TWh per year	From 2030
“Low Electrification”	161	250 TWh per year	From 2035

Constraining access to electricity and increasing the price have a clear negative effect on absolute residual emissions across all scopes. Increasing it does result in additional abatements, but not in a symmetric way. Constrained access to electricity also increases the industry's reliance on biomass and carbon capture, resulting in a higher amount of compensations. Under the “High Electrification” sensitivity analysis, scope 2 emissions in 2030 are higher due to the increased reliance on the electricity sector, which is not yet climate-neutral.

Chart 73

GHG emissions per scope – “Base Case” versus “Low” and “High electrification”

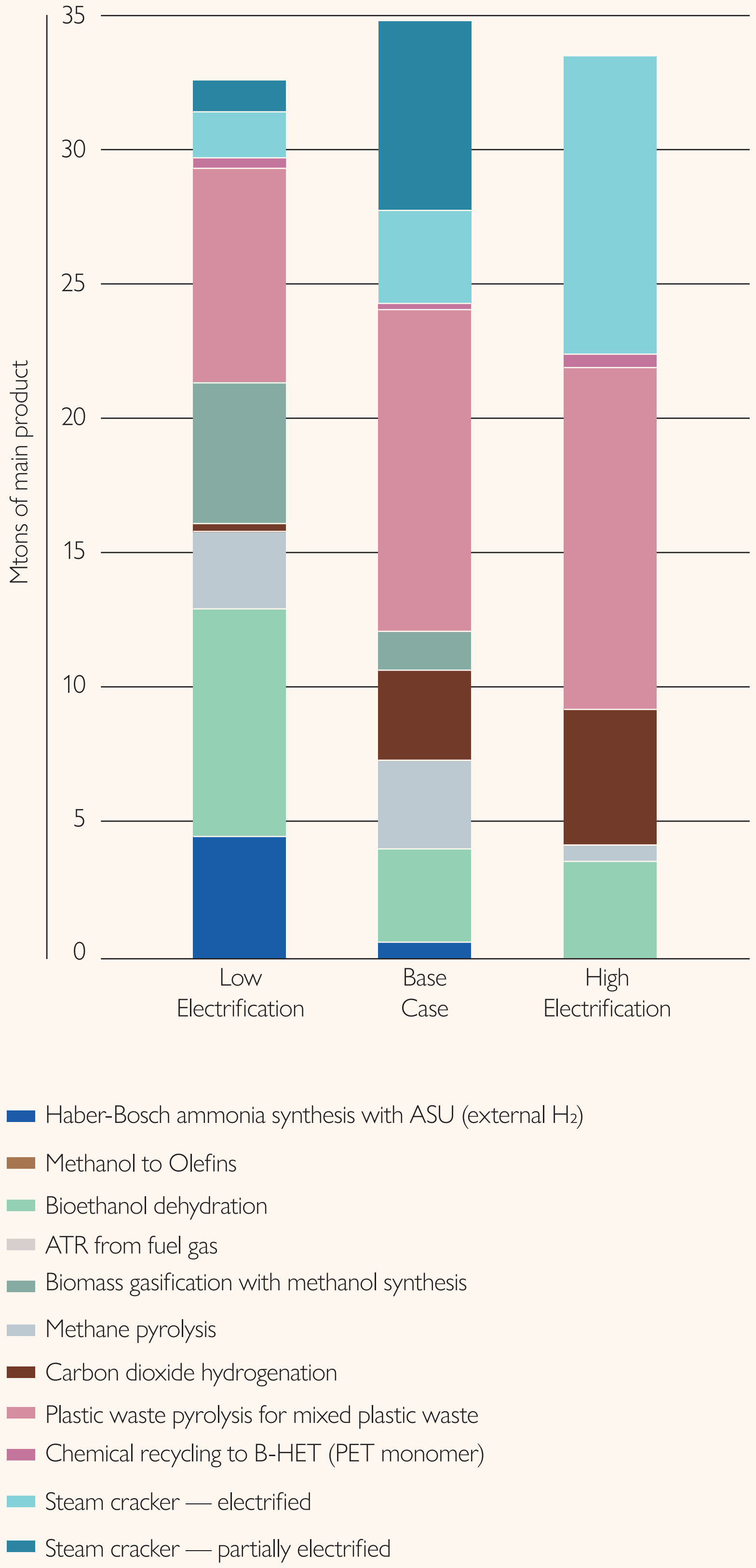


Impact on technology deployment

The cumulative production capacity of alternative technologies in 2050 is shown in Chart 74. The decrease in electricity availability drives the deployment of bio-technologies such as bioethanol dehydration and biomass gasification with methanol synthesis. With increasing electricity availability, the technology mix shifts towards electrification of processes, mainly **steam crackers.**

Chart 74

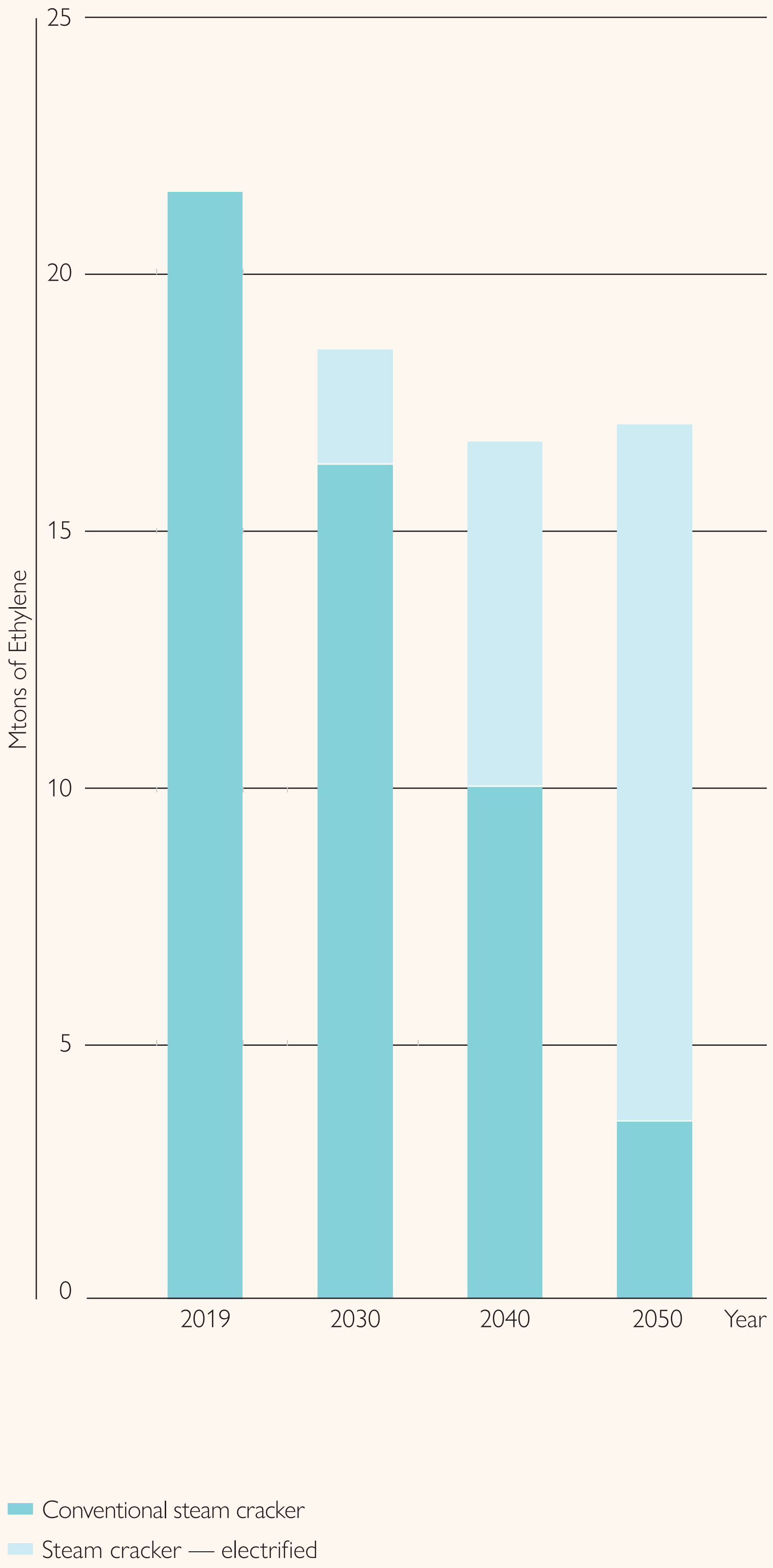
Cumulative capacity for new technologies in 2050 – "Base Case" versus "Low" and "High Electrification"



Direct electrification of steam cracking emerges as the main solution for reducing the emissions from olefin production under "High Electrification" analysis, with **79%** of the total steam cracking capacity being electrified in 2050. Despite electricity being restricted to the maximum in the "Low Electrification" sensitivity, electrified steam cracking still stands out as a solution as shown in Chart 74, underlining its **criticality** for achieving climate-neutrality.

Chart 75

Electrification of steam cracking capacity – "High Electrification"

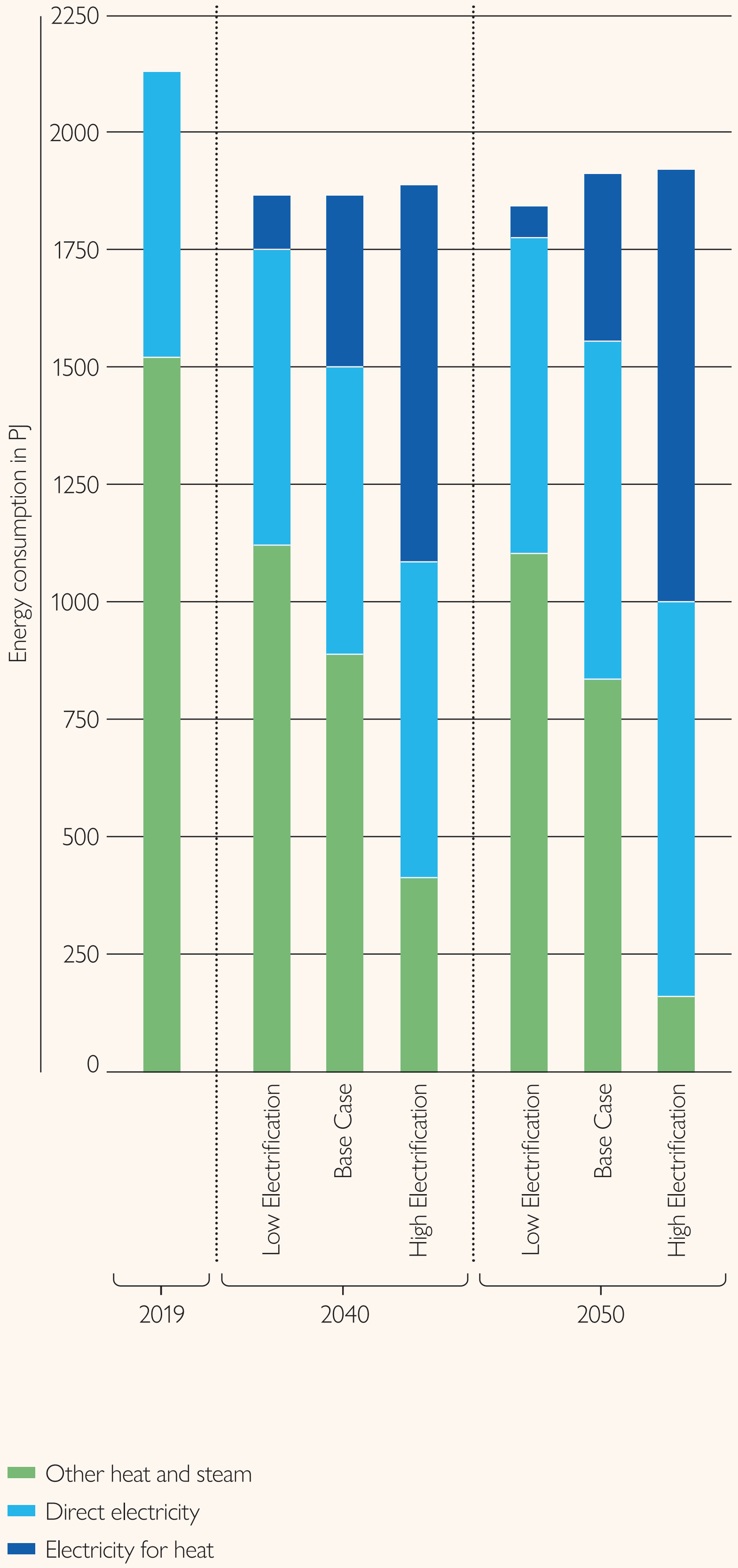


Impact on energy demand

The volume of consumed electricity in the 2050 FED increases between 250 TWh, which is the maximum available in in the “Low Electrification” analysis, and **503 TWh,** reaching up to 91.5% of the total demand. However, the full amount of electricity that is available to the sector under the “High Electrification” analysis remains largely **untapped,** with almost half of the 1,000 TWh available in 2050 being consumed by the sector.

Chart 76

Final energy consumption by energy vector – “Base Case” versus “Low” and “High electrification”



The additional electricity consumed is mostly directed towards **heat generation** as shown in Chart 77. Chart 78 shows the evolution of electricity consumption by use category in the "Base Case" and electrification sensitivities. The increase in consumption of electricity in organics production is mainly due to the **electrification of steam crackers.**

Electricity in boilers competes directly with **biomethane** as a source of heat. In the “High Electrification” analysis, electricity fully substitutes biomethane boilers and only a residual share of the heat demand is met by integrated fuel gas and natural gas furnaces. The excess fuel gas that is not used for heat generation within the steam cracker is re-used for the production of hydrogen or valorised as presented in Figure 15 of Annex 1. Restricted access to electricity, on the other hand, drives up significantly the demand for biomass and leaves a higher share of heat supply relying on biomethane as a fuel.

Chart 77

Installed heat capacity – “Base Case” versus “Low” and “High electrification” in 2050

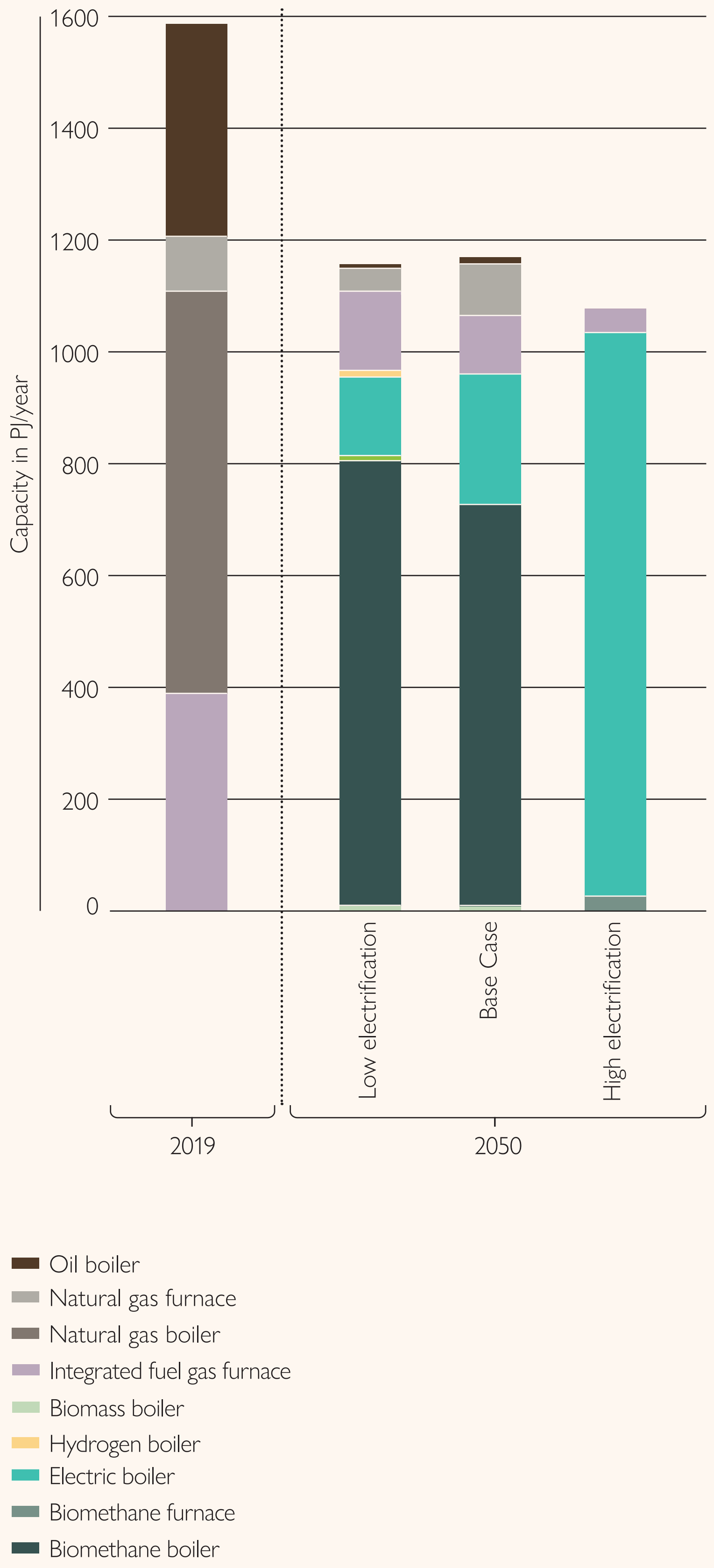
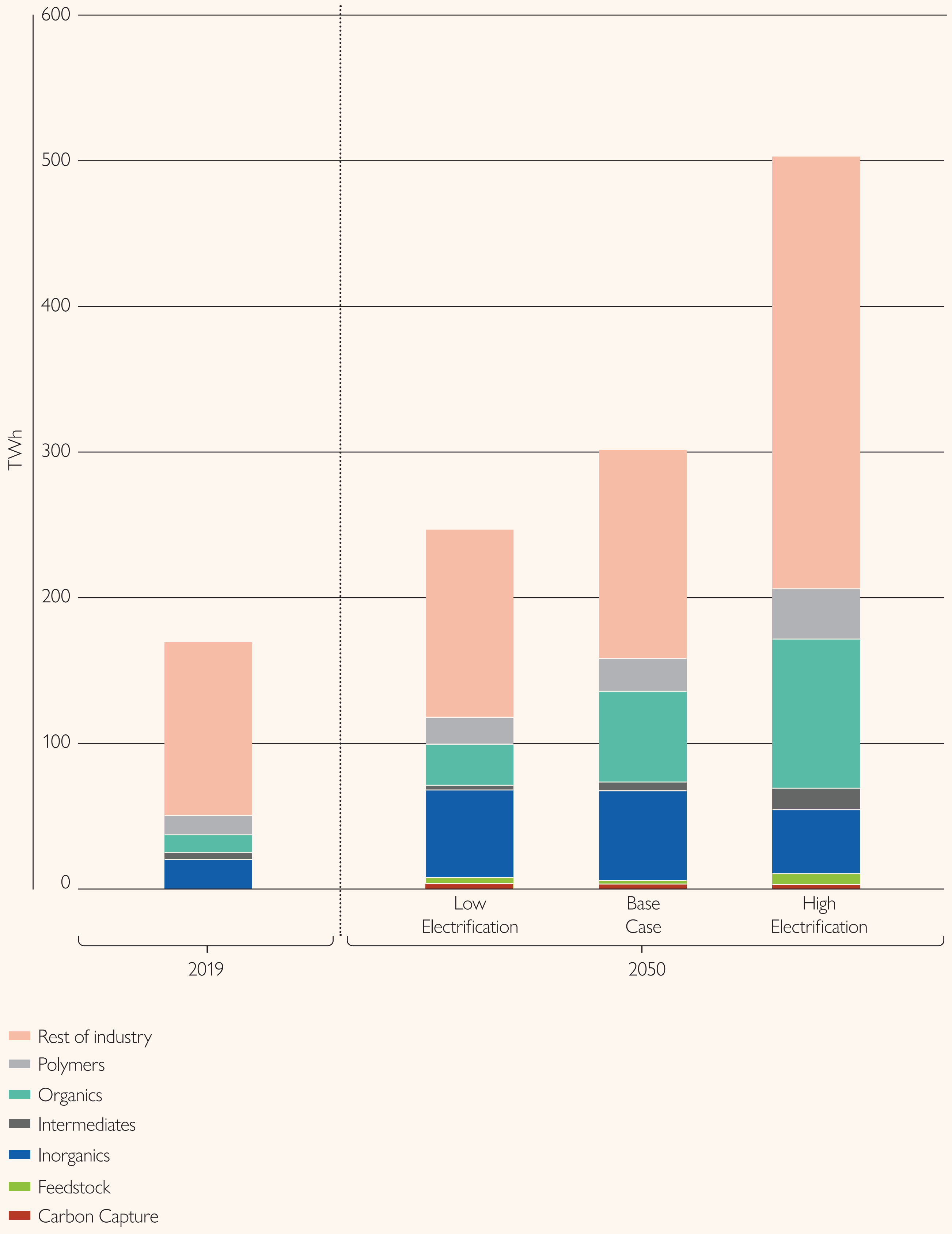


Chart 78

Breakdown of electricity consumption in 2050 – "Base Case" versus "Low" and "High Electrification"

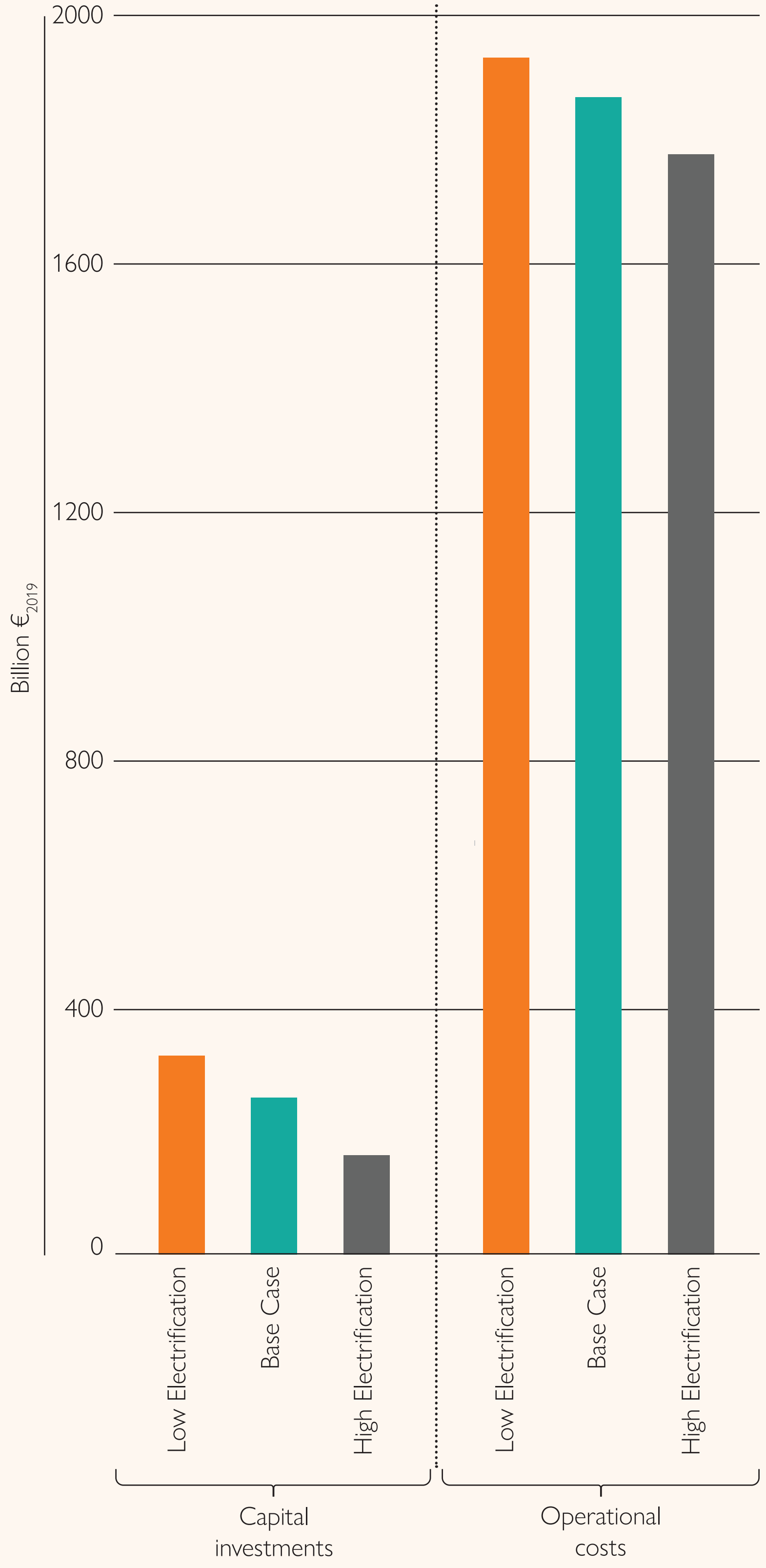


Impact on costs

Limited availability of affordable electricity in the future would impose **significantly higher** costs on the chemical sector to achieve climate-neutrality. This is not only attributable to operational costs and the increased cost of electricity, but also to capital costs. **Capital investments** are **64% higher** in the "Low Electrification" versus the "High Electrification" analysis, since technological options are restricted.

Chart 79

Cumulative costs of GHG abatement and circularity solutions in 2050 – "Base Case" versus "Low" and "High electrification"



Section 11.2

Switching to bio-molecules

Changes in assumptions

In this section, we are focusing on the physical availability of sustainable biomass in order to test the impact of a more or less favourable environment for the chemical industry.

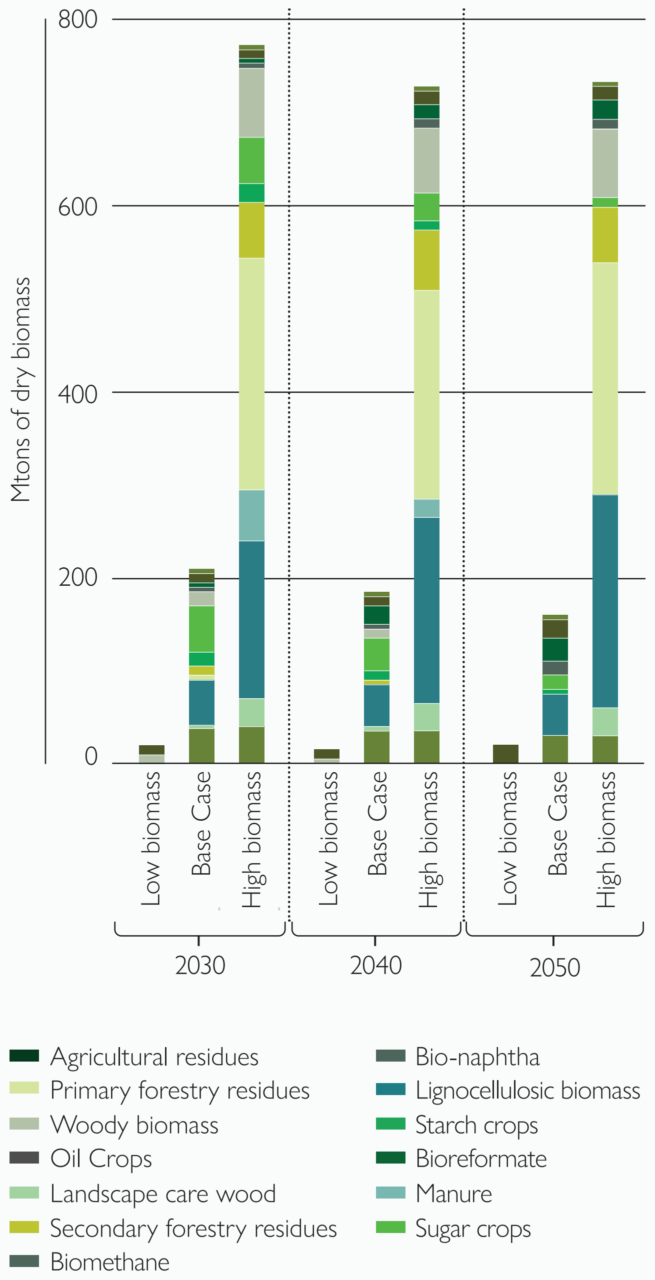
We first assumed a greater availability of biomass under a "High Biomass" sensitivity analysis. The new assumptions are derived from the "High Scenario" in the CE DELFT analysis (see Annex 5), except for woody biomass and agricultural residues.

Looking at the opposite direction, the "Low Biomass" sensitivity analysis considers that **no biomass** is available to the chemical industry as a source of **feedstock** due to competition with energy generation. As a result the model can only direct biogenic feedstock to biochemistry value chains or use biogenic CO_2 captured from energy production. This is in line with the PRIMES modelling results that supported the 2040 climate target's Impact Assessment[53]. In order to avoid running into **infeasibility** issues (i.e. the model cannot find a pathway to climate-neutrality by 2050), the electricity availability has been increased to **1,000 TWh.** The ability to source biomethane as a fuel for heat generation has also been increased.

The changes in biomass availability assumptions that we have used for the sensitivity, are presented in Chart 80.

Chart 80

Assumptions on biomass availability – "Base Case" versus "Low" and "High Biomass"

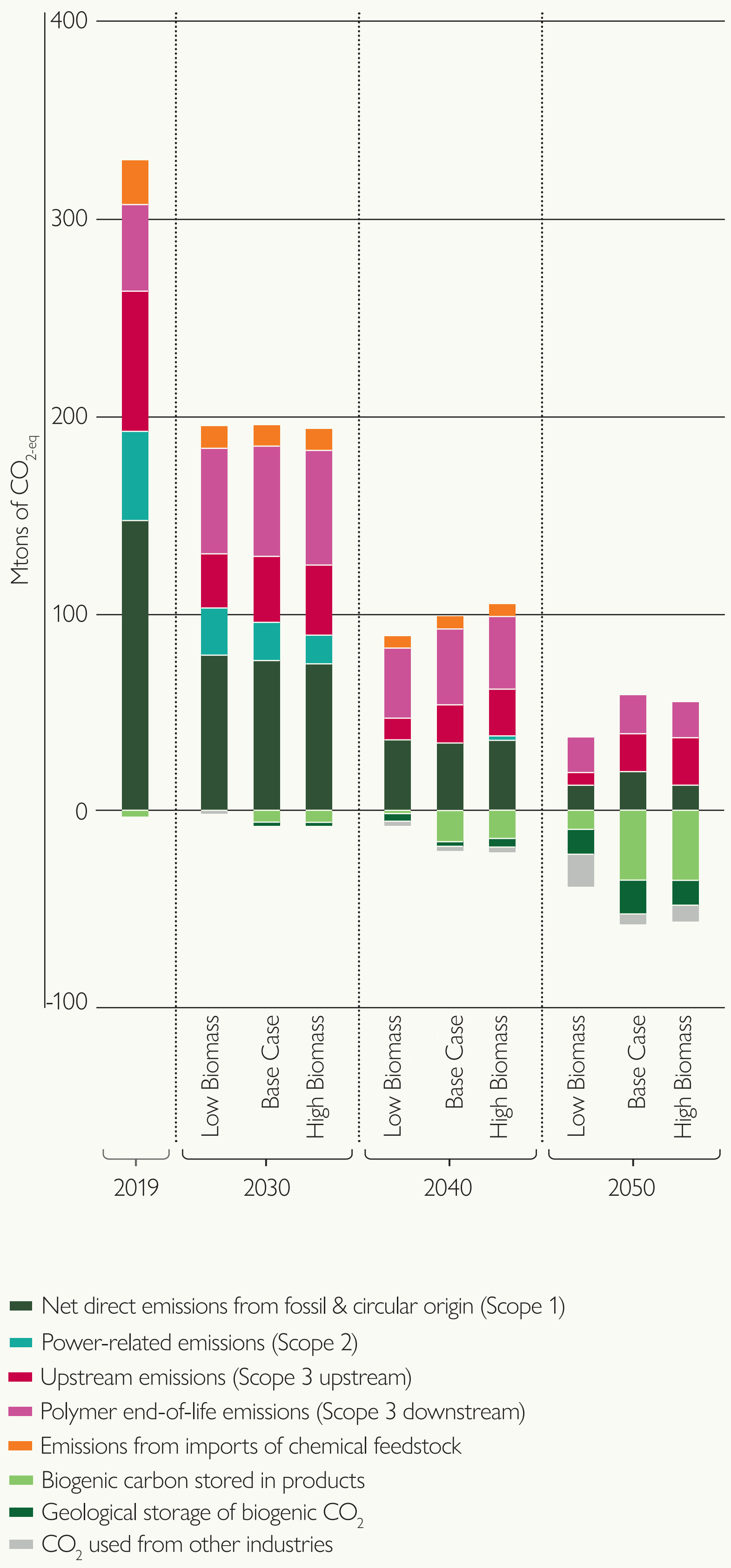


Impact on the abatement pathway

Drastically limiting access to bio-based feedstock reduces the role of negative emissions in the achievement of the climate-neutrality target, although the use of biomass for energy generation would still allow the model to achieve **negative emissions** by capturing and storing bio-based CO_2. Absolute **residual emissions** therefore reach their lowest point in the "Low Biomass" analysis results. Increasing the availability of biomass only has a marginal impact on the industry's emission's profile but it does result in lower fossil-based scope 1 emissions in 2050.

Chart 81

GHG emissions per scope – "Base Case" versus "Low" and "High Biomass"



[53] Source: European Commission. (2024). Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society Impact Assessment Report Part III. resource.html (europa.eu). Figure 51

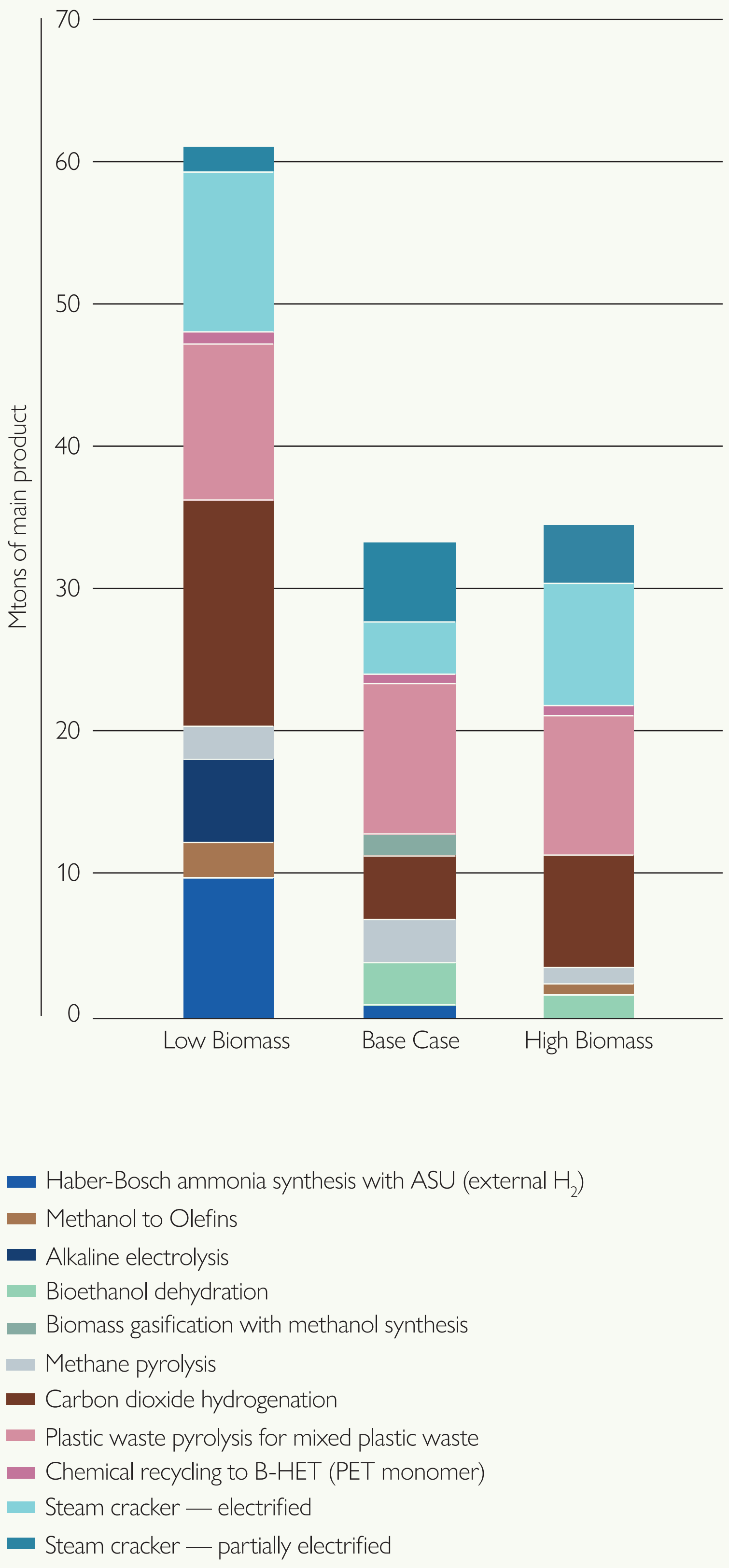
Impact on technology deployment

Increasing the availability of biomass does not fundamentally change the technology mix, except for **electrified steam cracking,** which is deployed on a bigger scale compared to the "Base Case". This occurs as explained previously, because the model has more solutions for heat generation. The model allocates the finite electricity available for direct electrification of the steam cracker while the additional biomass replaces electricity for heat generation.

The picture looks radically different though, when significantly constraining access to biogenic feedstock, requiring much bigger investments into alternative technologies, as shown in Chart 82. Most of these additional investments are related to the **valorisation of captured CO_2** as a new source of carbon including carbon dioxide hydrogenation and hydrogen production from electrolysis.

Chart 82

Cumulative capacity for new production technology in 2050 – "Base Case" versus "Low" and "High Biomass"

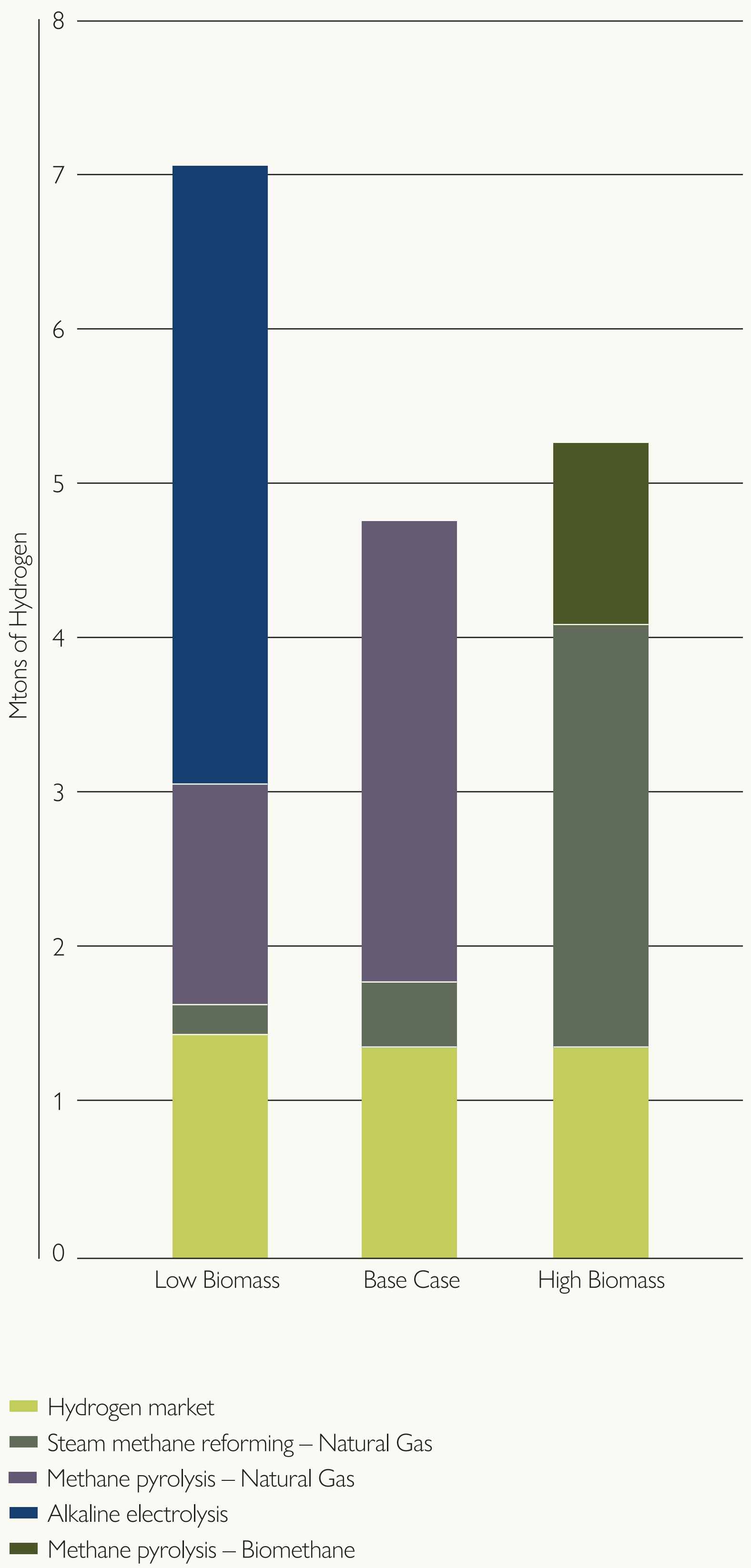


As shown in Chart 83, total **hydrogen** production increases when constraining access to biomass as feedstock and therefore incentivising CO_2 utilisation technologies. Due to the increase in electricity availability in the "Low Biomass" analysis, alkaline electrolysis, which was not present in the "Base Case" scenario results, emerges as the main production method for hydrogen. The hydrogen market supplies around one third of total hydrogen demand in the "Base Case" and "Low" and "High Biomass" analysis, while production is done through SMR and methane pyrolysis.

When, on the contrary, biomass availability is increased, SMR of biomethane is substituted by **biomethane pyrolysis,** while SMR of natural gas increases. In the 'High Biomass' analysis, the additional woody biomass enables the model to allocate some of it for heat generation. This frees up part of the yearly available electricity, which was previously used for heating, and reallocates it to methane pyrolysis (methane pyrolysis consumes more electricity compared to SMR). The storage of biogenic carbon in products and capture of biogenic CO_2 results in negative emissions which allows keeping capacities of steam methane reforming of natural gas in the "High Biomass" analysis.

Chart 83

Hydrogen production by technology in 2050 – "Base Case" versus "Low" and "High Biomass"

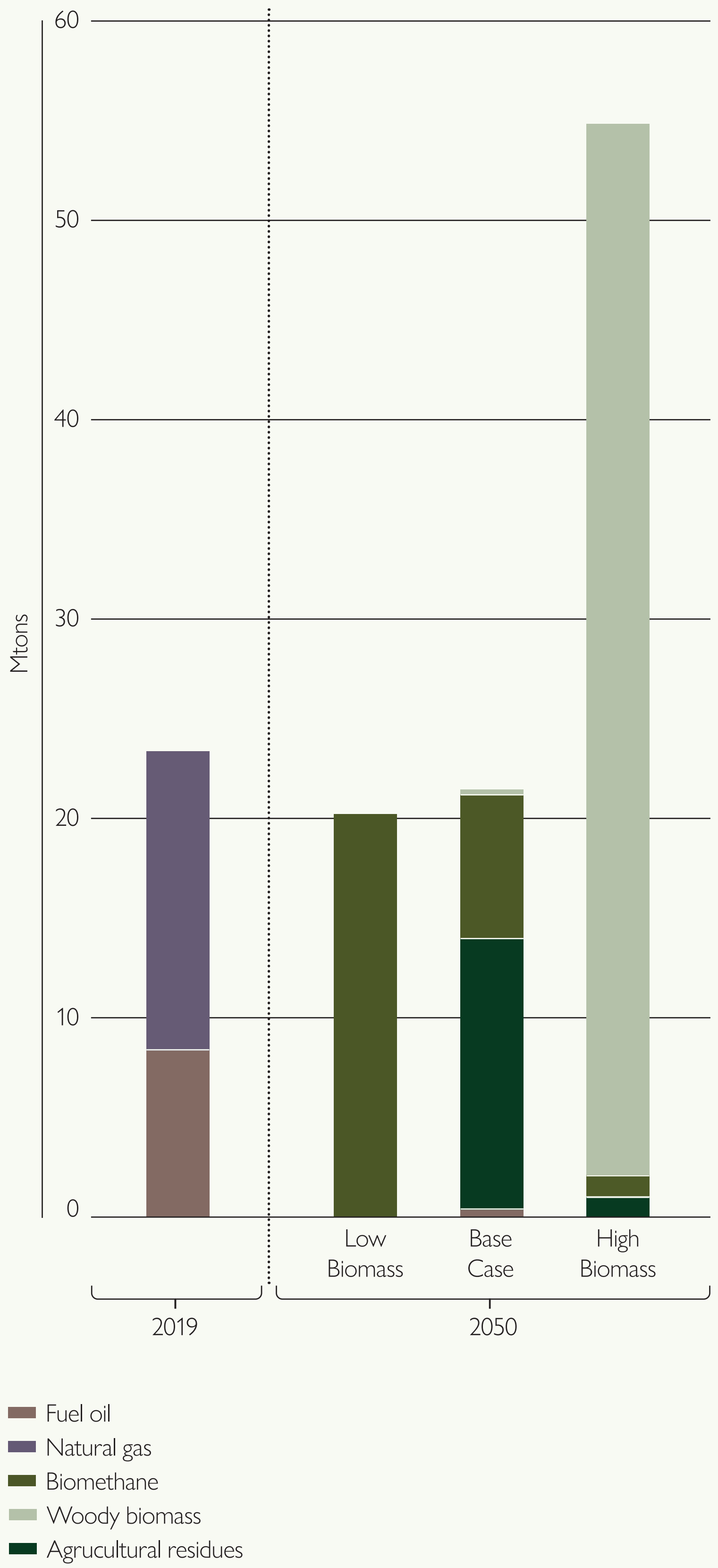


Impact on energy demand

Woody biomass becomes the main source of fuel for heat generation when increasing the availability of bio-based materials, while it is totally absent in 2050 when the availability is lower. When available, woody biomass is selected as a more cost effective fuel for heat generation compared to biomethane. The use of biomass boilers within the model accounts for emission-neutral heat generation with the possibility of capturing the CO_2 emissions and storing them to account for emission removal. In the "Low Biomass" analysis, where the use of **agricultural residues** for biomethane production is not possible within the industry's perimeter, biomethane from the market largely dominates for heat production. In the "Base Case" scenario, the availability of agricultural residues does allow producing biomethane through biomass gasification, which is used as a fuel alongside the biomethane supply from the market.

Chart 84

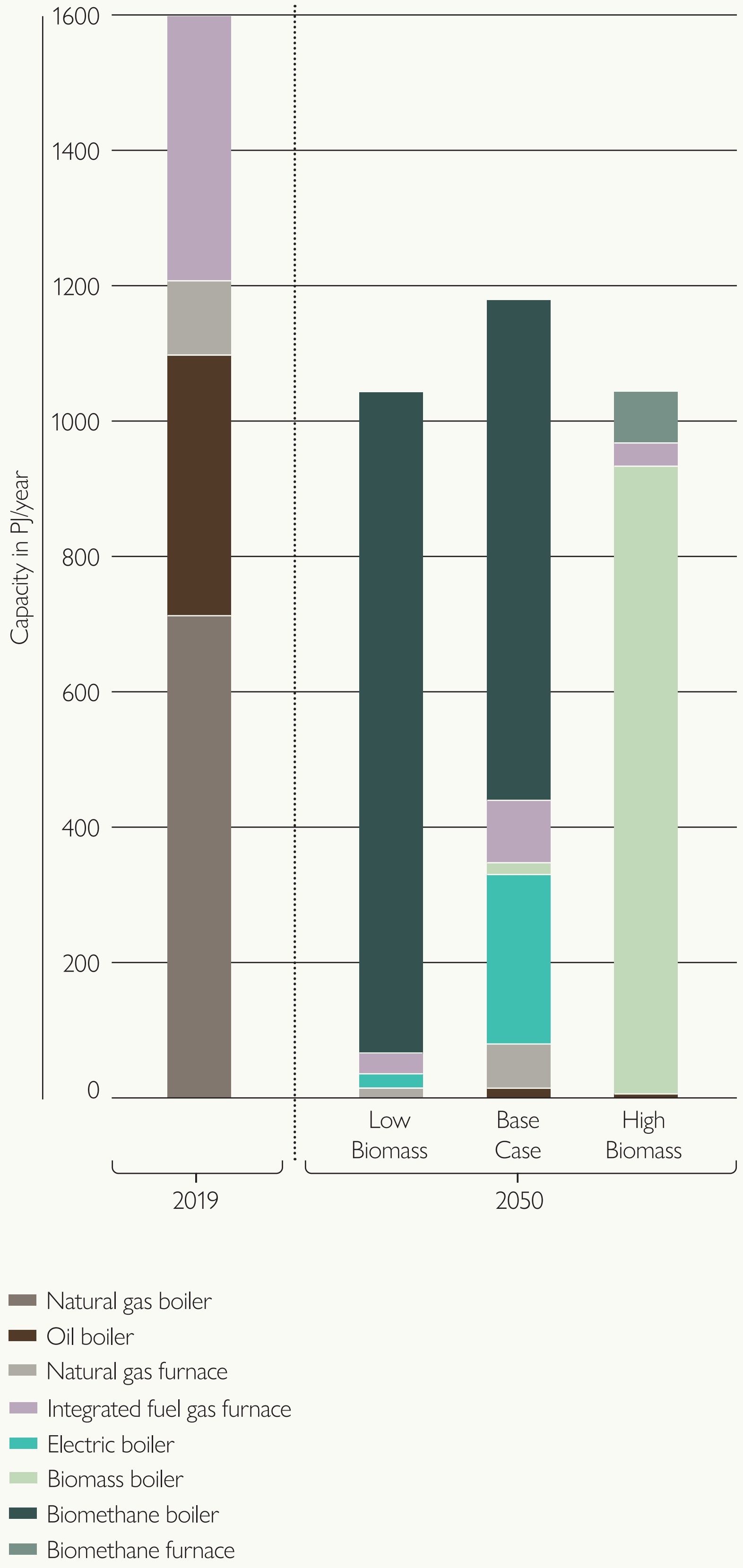
Fuel consumption by source – "Base Case" versus "Low" and "High Biomass"



Electric boilers are not (significantly) deployed for heat generation in either of the sensitivity analyses. In the "Low Biomass" case, even though electricity availability has been increased, this electricity is directed towards the **electrification of processes** and hydrogen production for **CCU,** as feedstock switching is limited in this scenario. In the "High Biomass" analysis, the availability of woody biomass as a source of fuel for biomass boilers leads the model into investing in biomass heat generation.

Chart 85

Installed heat capacity – "Base Case" versus "Low" and "High Biomass"

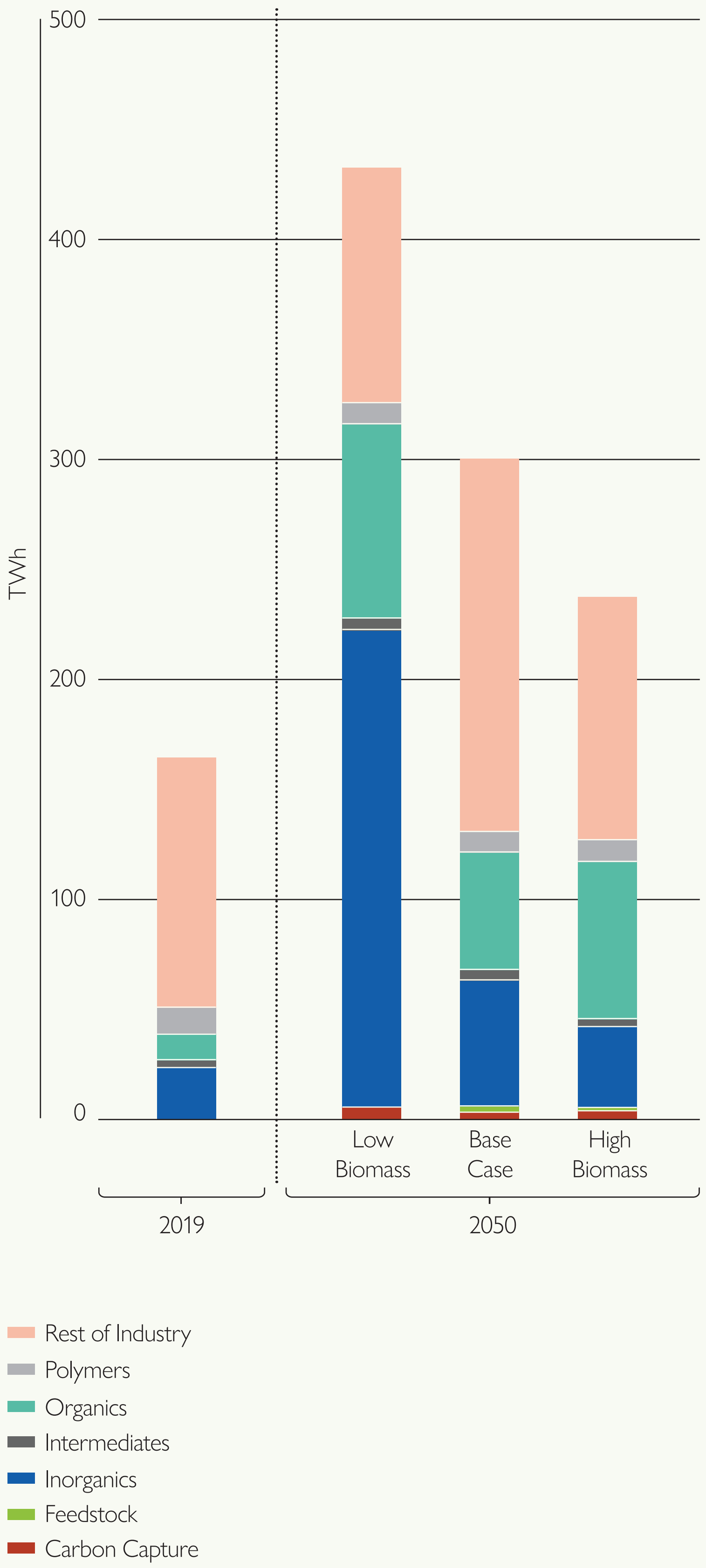


The increased use of biomass as an energy and heat source when increasing biomass availability, comes at the expense of electricity consumption, which “only” reaches **230 TWh** in 2050. This means that the model does not consume all of the 300 TWh that are available. Due to less electricity being allocated for heat generation, electrification of processes and steam cracking plays a greater role, mainly driven by organics production.

Under the “Low Biomass” approach, electricity consumption grows up to more than **500 TWh** in 2050, which is still half of the total availability. More than half of this consumption is linked to the production of inorganics, mainly hydrogen through electrolysis. Electrification of processes for the production of organics also increases compared to the “Base Case” scenario, while only small amounts of electricity are used for heat generation.

Chart 86

Breakdown of electricity consumption – “Base Case” versus “Low” and “High Biomass”



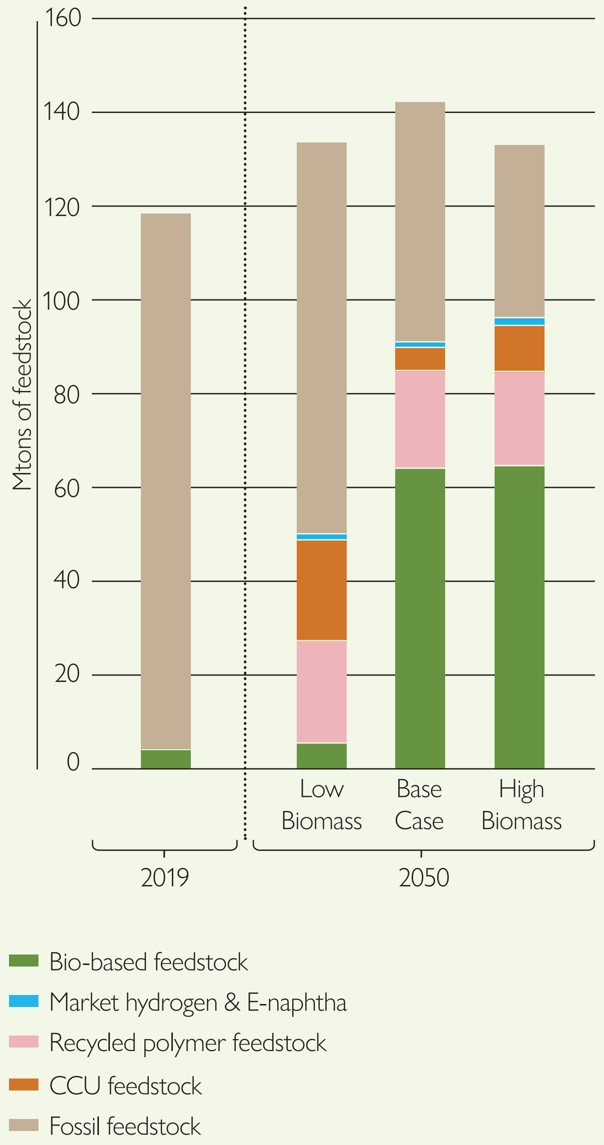
Impact on feedstock demand

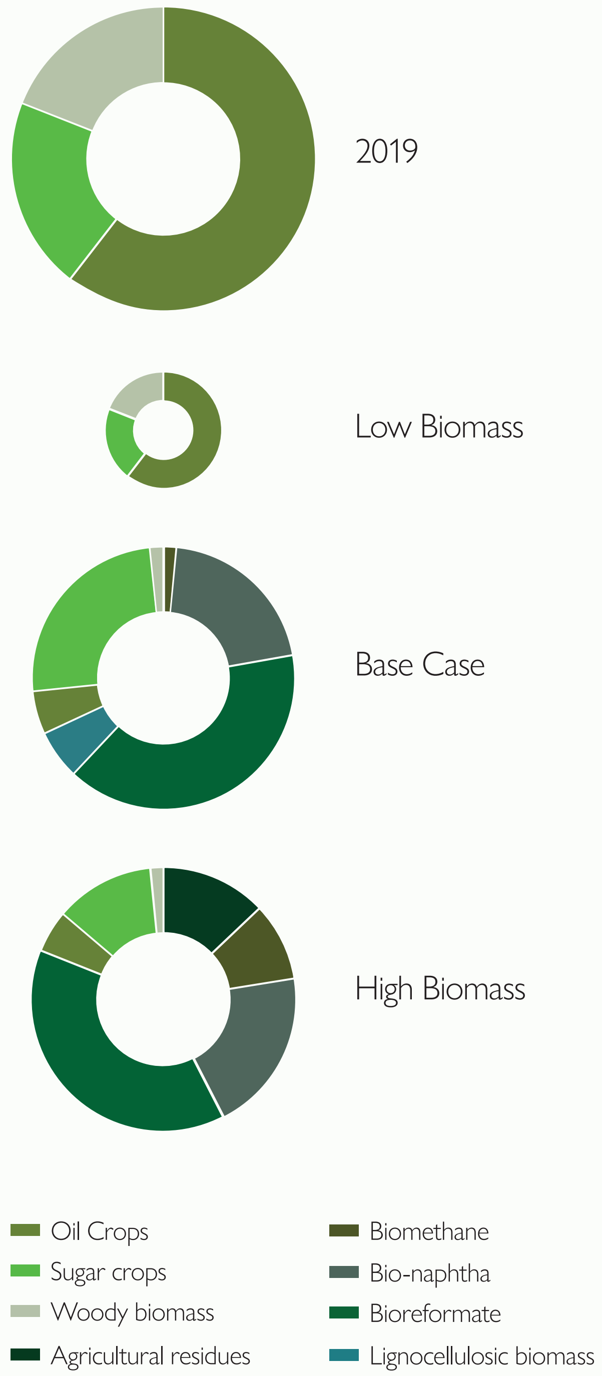
Fossil-based feedstock emerges as the main source of carbon feedstock in the “Low Biomass” sensitivity analysis, reaching more than 50% of the total feedstock consumption in 2050. In order to compensate for the significantly limited volumes of biogenic feedstock. Captured CO_2 (from the chemical industry or from other industries) ultimately becomes a solution that is picked up by the model, while the volumes of recycled feedstock remain stable.

On the other hand, the amount of bio-based feedstock that is consumed does not significantly vary when increasing biomass availability, compared to the “Base Case”. However the bio-based share from total feedstock consumption increases as fossil feedstock consumption decreased. This is because the higher availability of **different sources** of biomass allows the model to allocate resources more efficiently to meet demand and the 20% sustainable non-fossil target for carbon within the industry.

Chart 87

Carbon-based feedstock and hydrogen consumption – “Base Case” versus “Low” and “High Biomass”





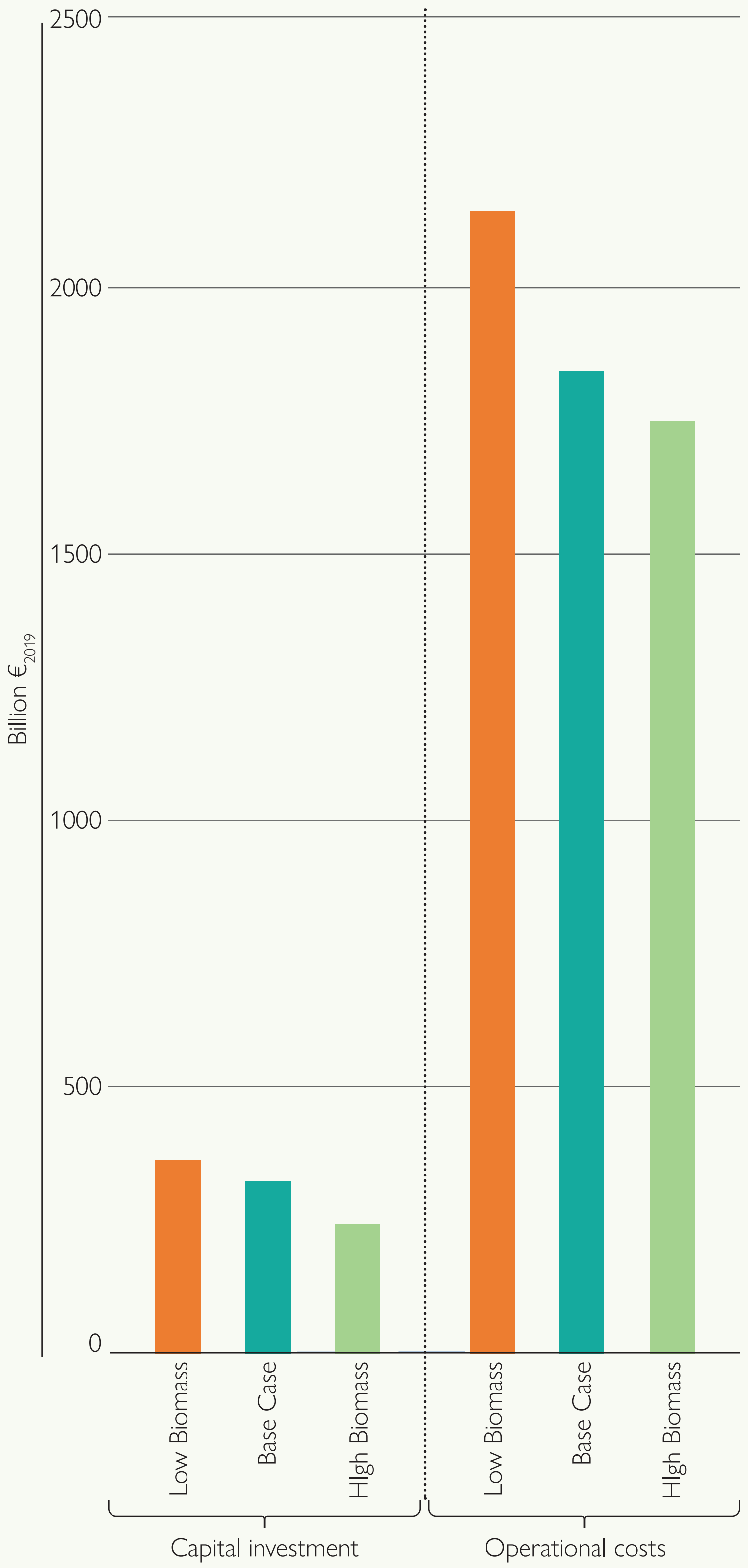
Impact on costs

Capital investments and operational costs decrease with the increasing availability of biomass as feedstock and energy sources for the industry. When on the contrary, strict constraints on biomass availability are imposed, the **operational costs** increase by **15%** compared to the "Base Case" and **21.3%** compared to a future where biomass is abundantly available. The **capital investments** decrease by **32.5%** in the "High Biomass" analysis when compared to the "Low Biomass" as deployment of alternative technologies is higher in the later due to the limited ability for feedstock switching and lower compensation through negative emissions.

In general this shows that biomass can – depending of prices – be an economically attractive solution for the industry (e.g. versus electricity), also because it gives more flexibility for the industry to use **carbon removal** for reaching climate-neutrality.

Chart 88

Cumulative costs of GHG abatement and circularity solutions in 2050 – "Base Case" versus "Low" and "High Biomass"



Section 11.3

Untapping the potential of chemical recycling

Changes in assumptions

Both chemical and mechanical recycling contribute to the reduction of virgin **raw material consumption** and prevent the **loss of embedded carbon** into landfill or into the atmosphere, due to incineration. In the following section, the impacts of increasing or decreasing the enabling conditions for chemical and mechanical recycling will be explored focusing on technology and policy developments (landfill ban). On the one hand, we will assume an increase in **mechanical recycling** volumes and improvement in **chemical recycling technologies.** On the opposite side, we will assume that mechanical recycling is not improving beyond current shares and that chemical recycling is deploying at a lower rate. The assumptions of the "High" and "Low Recycling" analyses are summarised inTable 9.

Table 9

Assumptions on recycling of waste – "Base Case" versus "Low" and "High Recycling"

Scenario	Mechanical recycling (2019 till 2050)	Yield for pyrolysis of mixed plastic waste[54]	Deployment rate of chemical recycling technologies	Landfill ban implemented after 2030
"Base Case"	194Mtons	50% cracker feedstock yield	12%	Yes
"High Recycling"	267Mtons	70% cracker feedstock yield	30%	Yes
"Low Recycling"	149Mtons	50% cracker feedstock yield	6%	No

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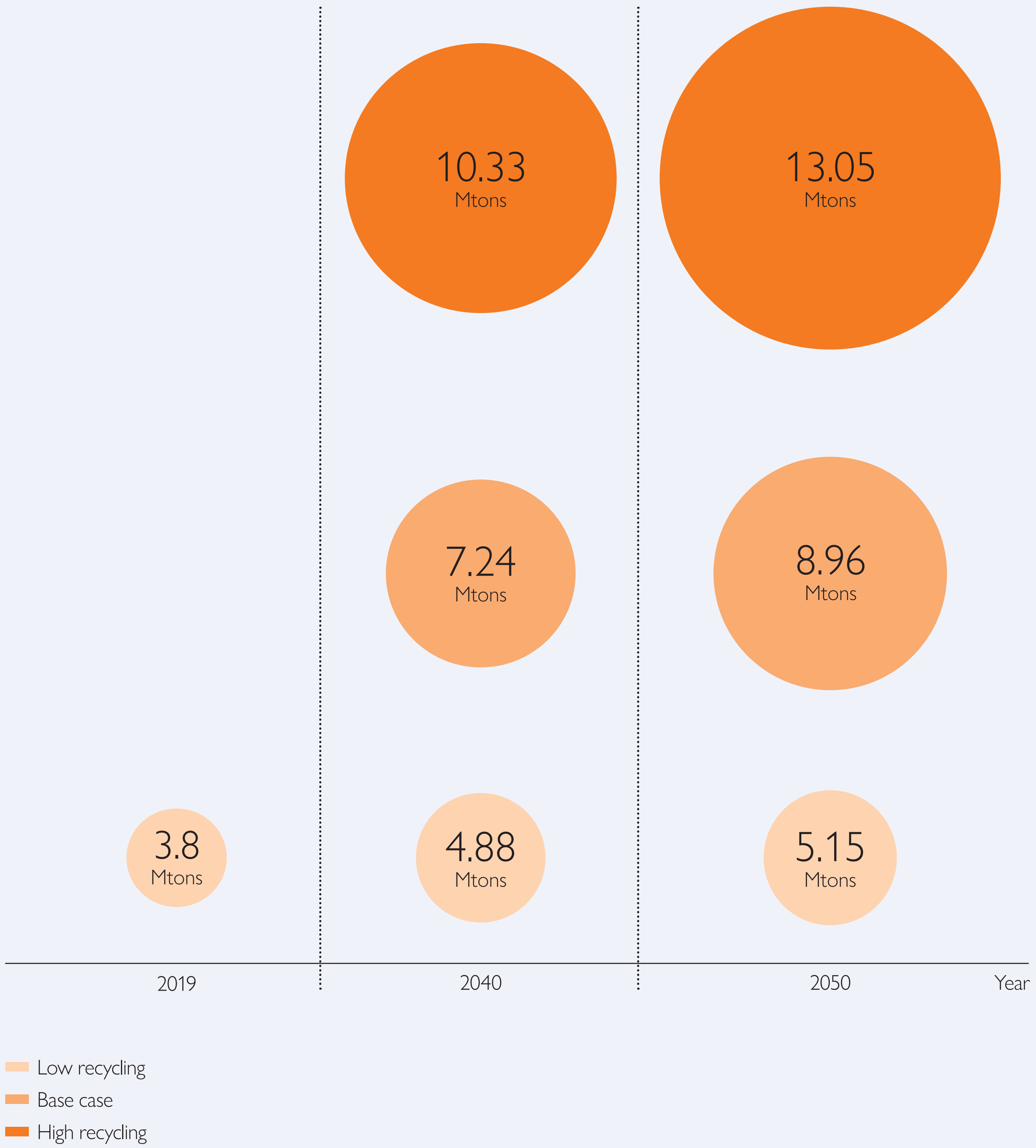
[54] The share of py-naphtha output to mixed plastic waste input of pyrolysis. The py-naphtha is the share of pyrolysis oil that can be used as feedstock to the steam cracker in iC2050.

The mechanical recycling trajectories that has been assumed in the “Low” and “High recycling” analyses for the total polymers are shown in Chart 89.

Chart 89

Assumptions of volumes of mechanical recycling of polymers – “Base Case” versus “Low” and “High Recycling” in Mtons of recycled polymers

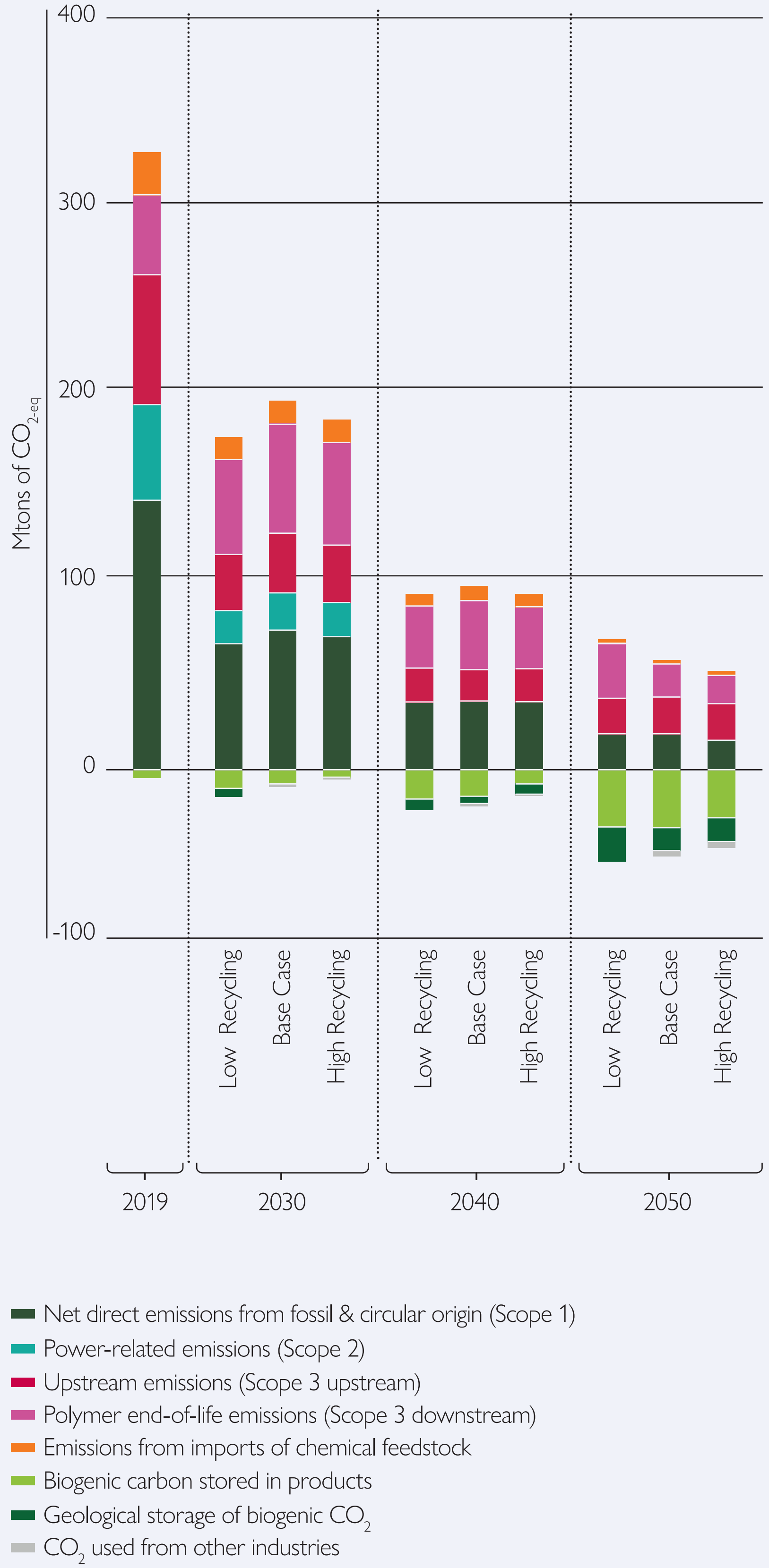


Impact on the abatement pathway

The total net emissions depending on the levels of recycling are shown in Chart 90. The “Low Recycling” results diverge from the “Base Case” scenario and “High Recycling” analysis in 2030 because there is **no landfill ban.** This allows disposing managed waste into landfills post-2030. After 2040, highly favourable conditions for waste recycling (high recycling) lead to slightly lower net emissions.

Chart 90

GHG emissions per scope – “Base Case” versus “Low” and “High Recycling”



Impact on the deployment of chemical recycling

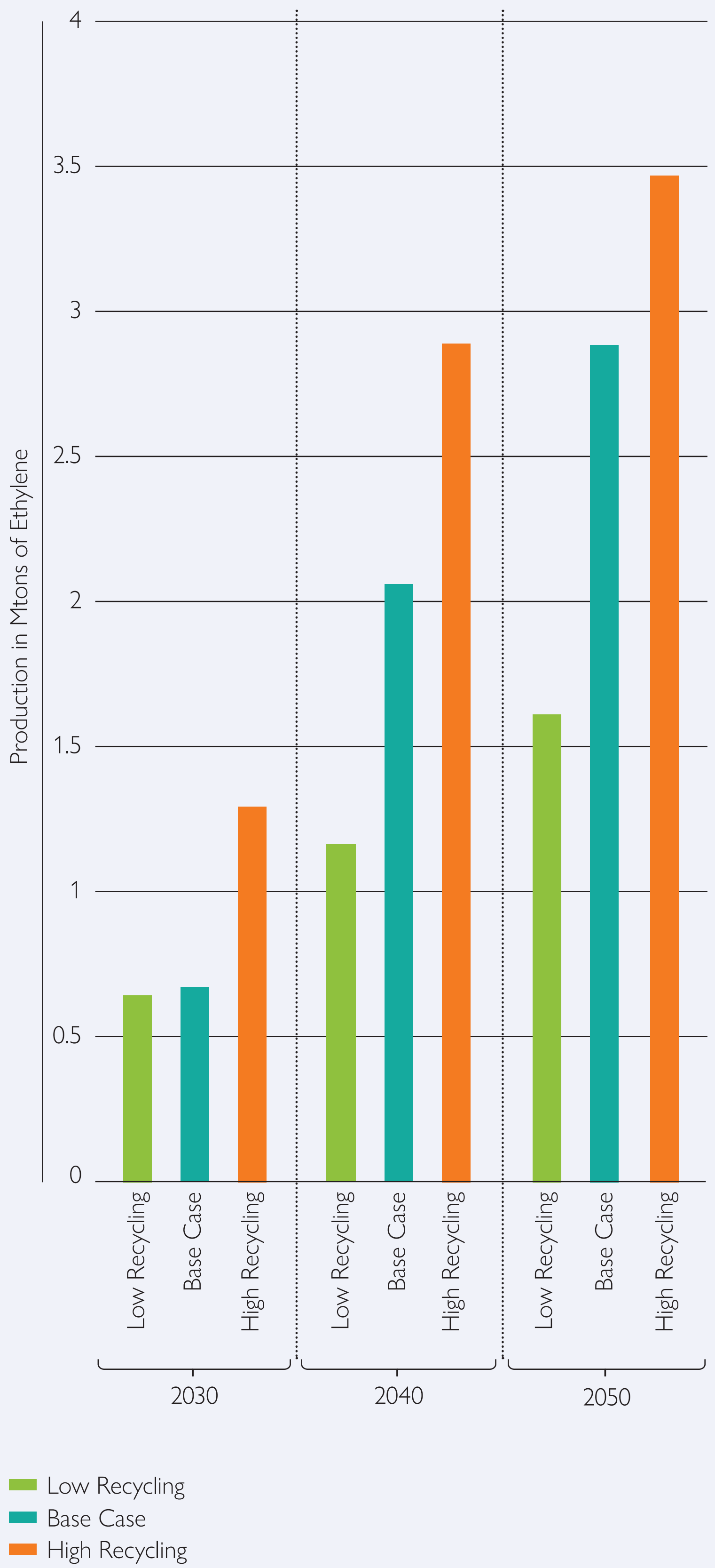
The main chemical recycling technology that is deployed in the "Base Case" scenario and "High Recycling" analysis is **mixed plastic waste pyrolysis.** The output of this process provides a feedstock share that can be used as an input for steam crackers. The GHG emissions resulting from pyrolysis are accounted under scope 1 emissions of the sector, while reductions in emissions related to waste combustion are reported under scope 3.

The comparison of ethylene production from py-naphtha is shown in Chart 91. The sustainable non-fossil embedded carbon target of 20% is one of the key drivers for pyrolysis of mixed plastic waste.

Other chemical recycling technologies such as mixed plastic waste gasification, polystyrene pyrolysis and PET recycling to B-HET do not play a role, since they come at a higher NPC. In specific scenarios such as the "Feedstock Target" scenario, mixed plastic waste gasification and PET recycling to H-PET are deployed in addition to mixed plastic waste pyrolysis to achieve the higher sustainable non-fossil carbon targets.

Chart 91

Ethylene production from pyrolysis naphtha – "Base Case" versus "Low" and "High Recycling"



Circular polymers

Fossil-based production decreases in all scenarios presented in Chart 92. When assuming highly favourable conditions for waste recycling ("High Recycling" analysis), waste recycling supplies **half of the polymer production** in 2050, compared to **38.5%** in the "Base Case" scenario and **22%** "Low Recycling" analysis. In the "Low Recycling" analysis, recycled polymers are partly substituted by bio-based polymers.

Chart 92

Carbon embedded in polymers by type of carbon source

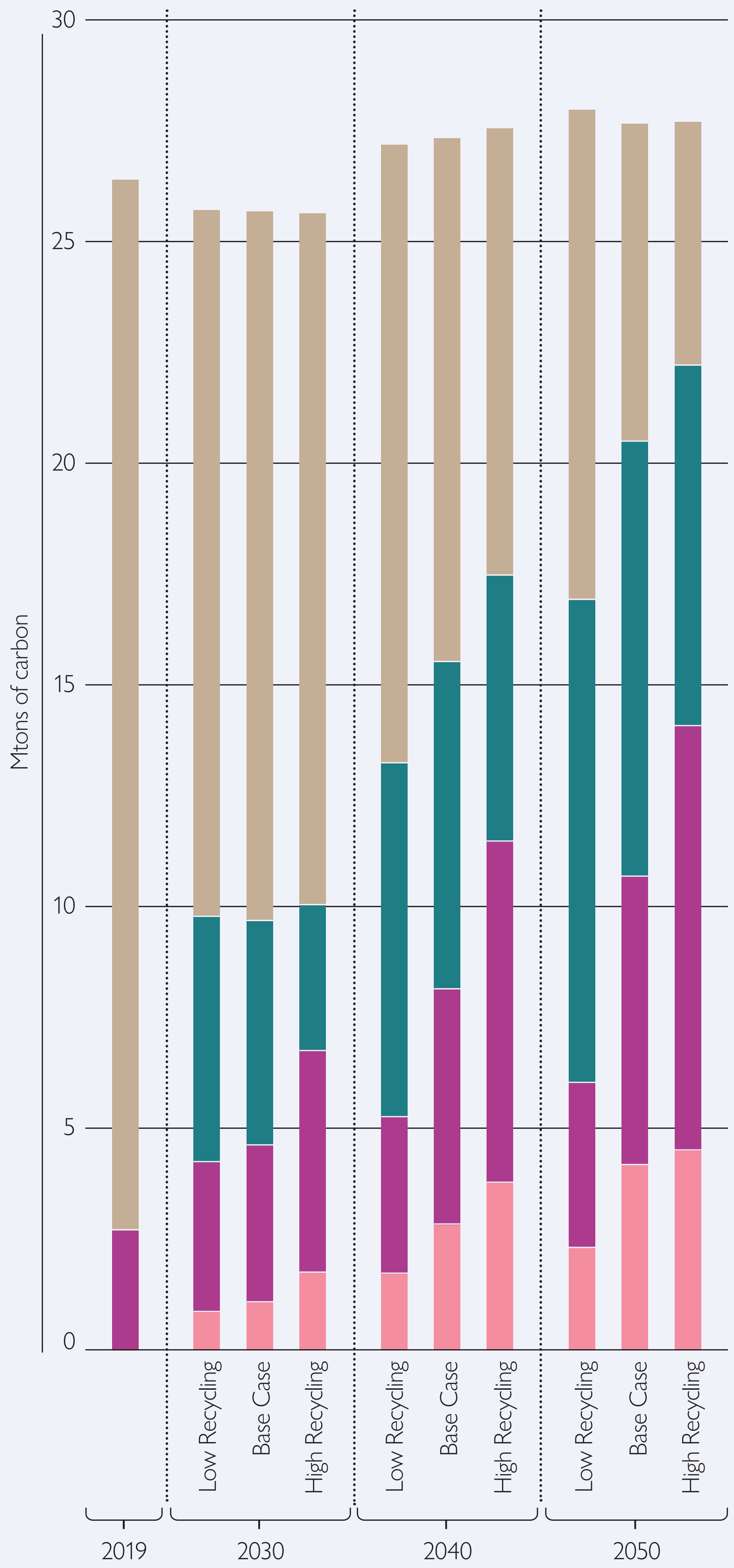


Chart 93

Carbon-based feedstock and hydrogen consumption – “Base Case” versus “Low” and “High Recycling”

Impact on feedstock demand

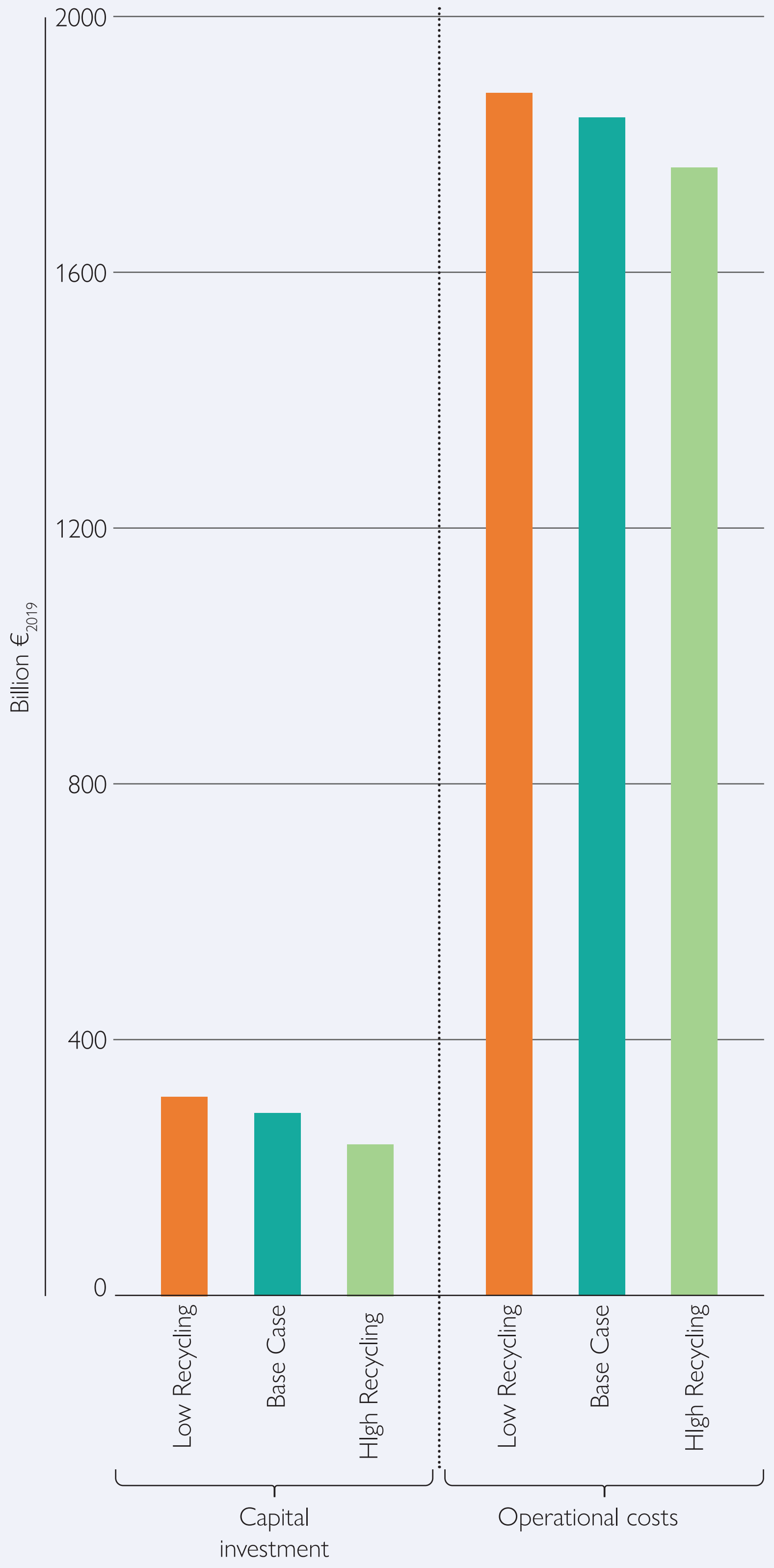
The comparison of feedstock consumption in 2050 between the “Base Case” and the “Low Recycling” and “High Recycling” analyses is presented in Chart 93. The total amount of feedstock consumed in the “Low Recycling” analysis is equal to that of the “Base Case”, but with a higher share of fossil feedstock. With limited recycling ability, the model relies less on recycled polymers and CO_2 as a feedstock source. In the “High Recycling” analysis, the **total amount of feedstock** consumed is lower as the increase in mechanical recycling reduces the need for virgin raw materials.

Impact on costs

The capital investments and operational costs shown in decrease in the "High Recycling" analysis since a higher share of the chemical demand is met by mechanical recycling, whose costs are assumed to be separated from the chemical sector costs in iC2050. The increase in **mechanical recycling** reduces the monomer demand and thus their production in the model.

Chart 94

Cumulative costs of GHG abatement and circularity solutions in 2050 – "Base Case" versus "Low" and "High Recycling"



Section 11.4

Carbon capture

Changes in assumptions

The development of CO_2 capture technologies is dependent on technological, economic, societal and regulatory developments. The **acceptance** of carbon capture as one of the possible solutions for emission abatement is a driver for accelerating the technology's deployment. Another important aspect is the development of the necessary **infrastructure** to handle the captured CO_2 whether it would be stored or utilised. Efficient CO_2 transportation networks along with sufficient storage injection capacity would allow a greater deployment of carbon capture. Development in the areas that have been mentioned is not guaranteed as the future holds a level of uncertainty. In this section, two opposite scenarios for CO_2 capture will be compared.

We have adopted on the one hand an optimistic view, where **deployment rates** of CO_2 capture technologies are higher, **technology costs** are lower, and **transport distances** are lower. An increase in the **methanol processes' deployment** rate has been implemented to allow CO_2 utilisation technologies to be deployed more rapidly. On the opposite end, we considered the impact of lower deployment rates, higher technology costs, and longer transport distances. The assumptions of the "High" and "Low Carbon Capture" analyses are summarised in Table 10.

Table 10

Assumptions on carbon capture, transport and storage; Assumptions on methanol processes deployment rate – "Base Case" versus "Low" and "High Carbon Capture"

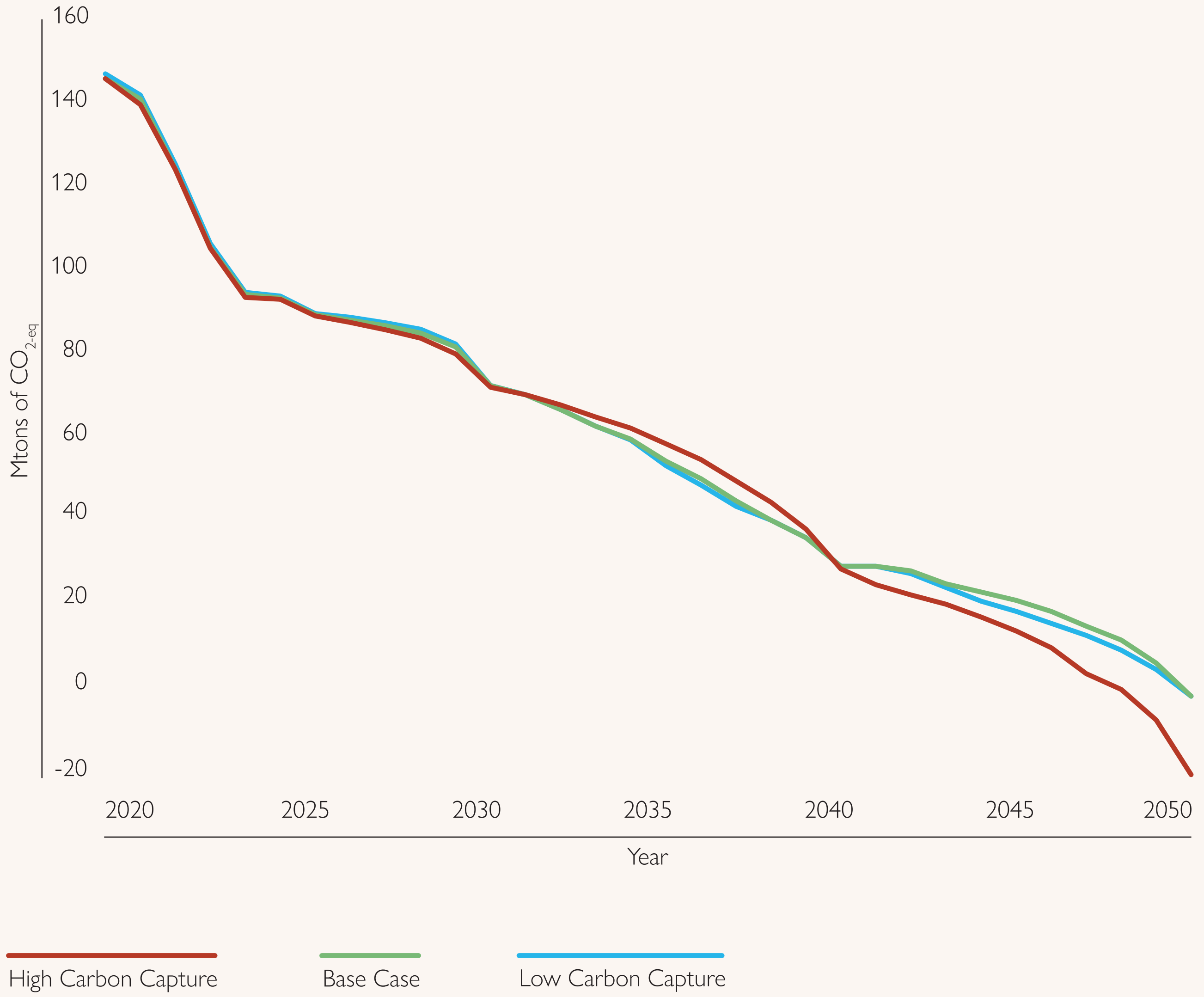
Scenario	Deployment rate of carbon capture technologies	Methanol processes' deployment rate	CO_2 Transport distances	Costs in 2050 – M€/Mton of capacity	CO_2 storage injection capacity in 2050 [Mtons CO_2]
"Base Case"	9%	10%	Inland: 700 km CCU other indus.: 125 km	PCE – High purity: 137 PCE – Low purity: 306.13	250
"High Carbon Capture"	18%	30%	Inland: 500 km CCU other indus.: 100 km	PCE – High purity: 30.594 PCE – Low purity: 188.96	250
"Low Carbon Capture"	8.5%	10%	Inland: 1000 km CCU other indus.: 150 km	PCE – High purity: 137 PCE – Low purity: 306.13	20

Impact on the abatement pathway

The **net scope 1 emissions** of the chemical sector across scenarios are presented in Chart 95. The "High Carbon Capture" results show higher net emissions compared to the other two scenarios before 2040 as the higher deployment rates allow the model to abate emissions more rapidly later on during the period. After 2040, CO_2 capture continues to abate direct emissions especially in the "High Carbon Capture" analysis since capturing and storing CO_2 of biogenic origin would allow compensating for the remaining gross emissions across other scopes.

Chart 95

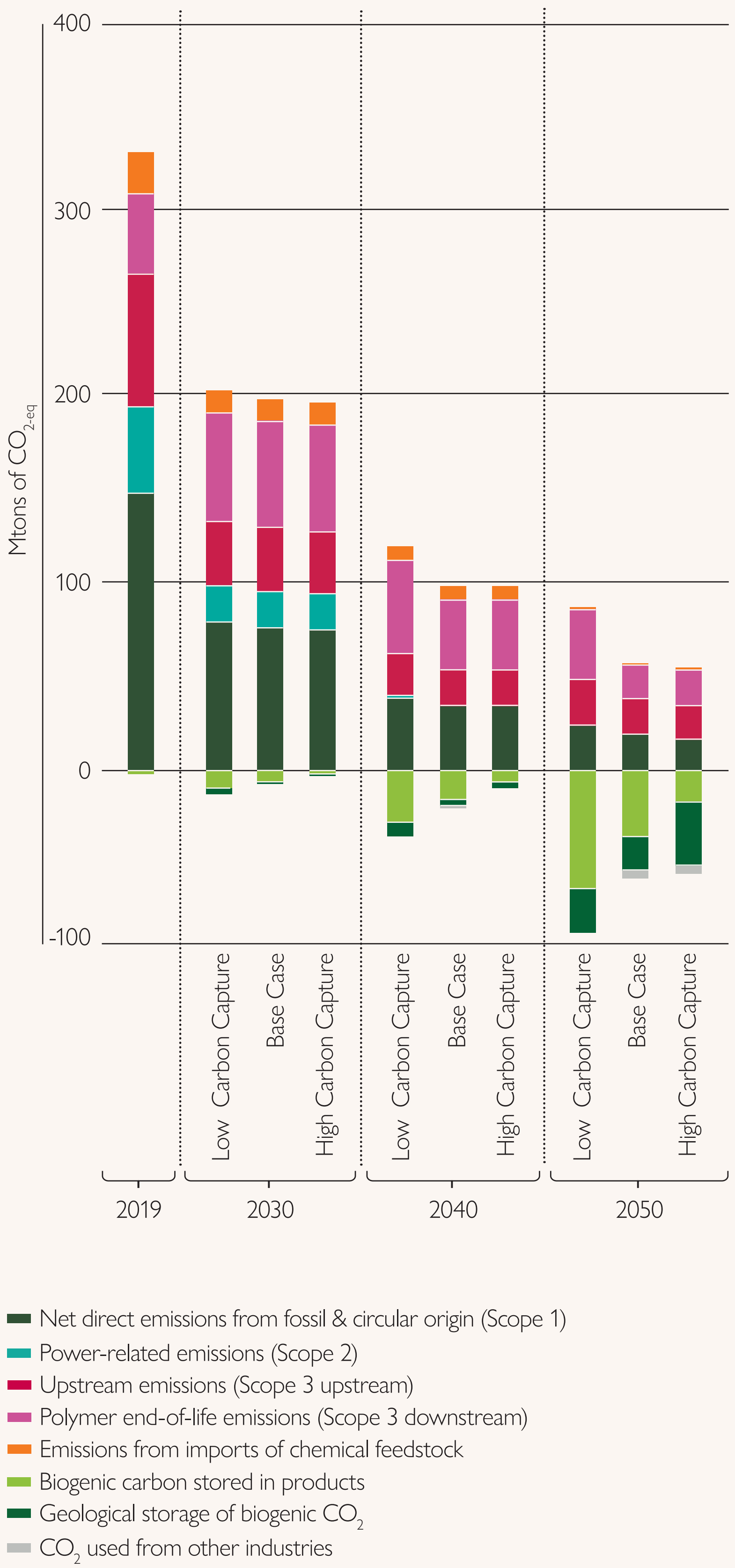
Net direct emissions between 2019 and 2050 – "Base Case" versus "Low" and "High Carbon Capture"



As shown in Chart 96, absolute emissions decrease with the increase in CO_2 capture, reducing the need for negative emissions. The increased deployment of carbon capture technologies allows transporting higher amounts of biogenic CO_2 to mineral storage locations, hence increasing the **negative emissions** compensation by geological storage of biogenic CO_2.

Chart 96

GHG emissions per scope – "Base Case" versus "Low" and "High Carbon Capture"

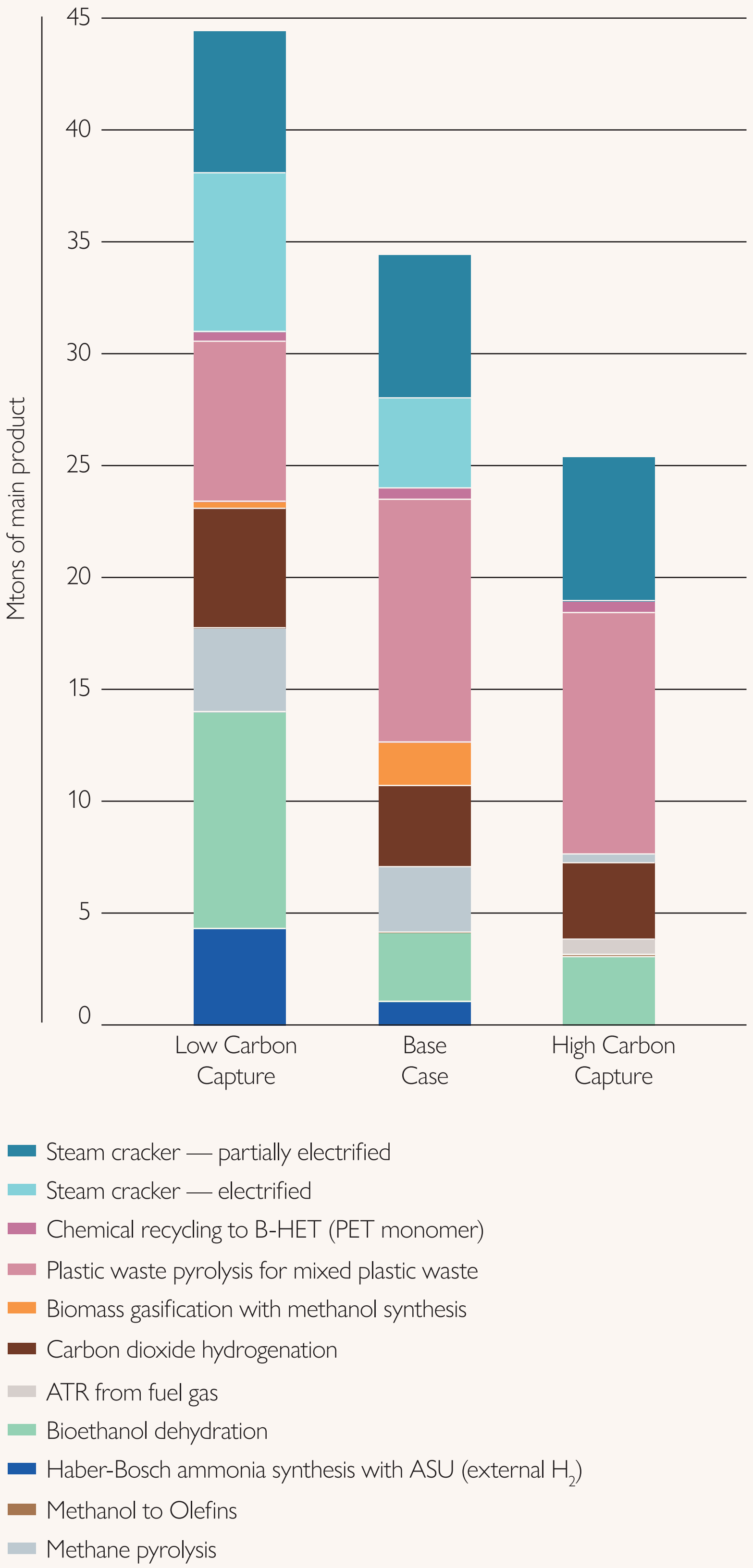


Impact on technology deployment

The higher availability of CO_2 capture technologies and infrastructure results in a **lower deployment** of alternative production processes as shown in Chart 97. Having large access to a carbon capture infrastructure allows the model to keep operating some of the traditional technologies and to manage emissions directly at the end of the pipe. In a more constrained environment ("Low Carbon Capture" analysis), the deployed production capacities are bigger and more diverse, because solutions need to be found upstream.

Chart 97

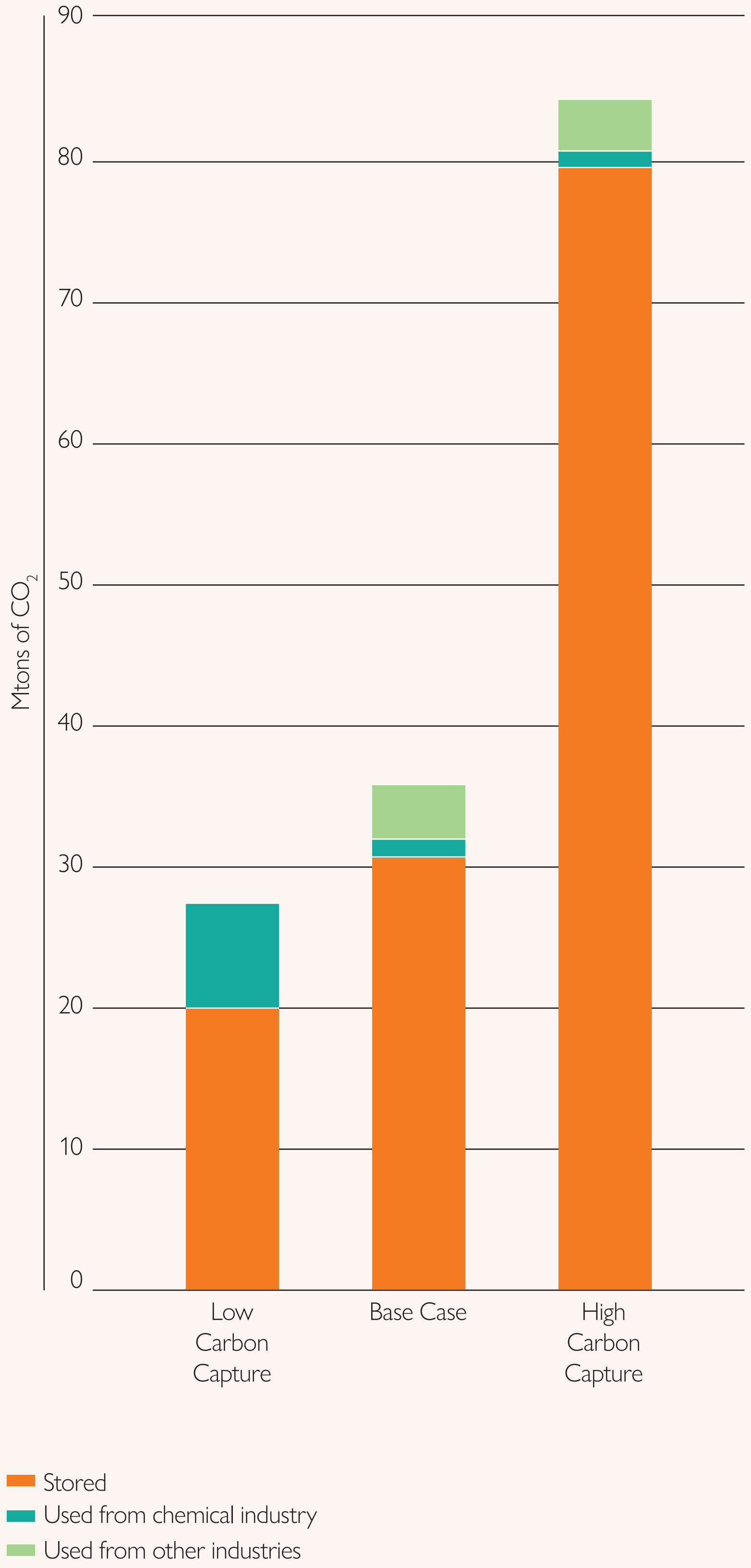
Cumulative capacity for new production technologies – "Base Case" versus "Low" and "High Carbon Capture" in 2050



As shown in Chart 98, releasing the constraints around carbon capture leads to **more than a doubling of captured volumes.** Most of the captured CO_2 across the compared scenarios in 2050 is stored **underground.** Based on the limited capacity for CO_2 transportation in the "Low Carbon Capture" analysis, the CO_2 usage from other industries would not be present in 2050.

Chart 98

Total CO_2 captured for storage or usage – "Base Case" versus "Low" and "High Carbon Capture" in 2050

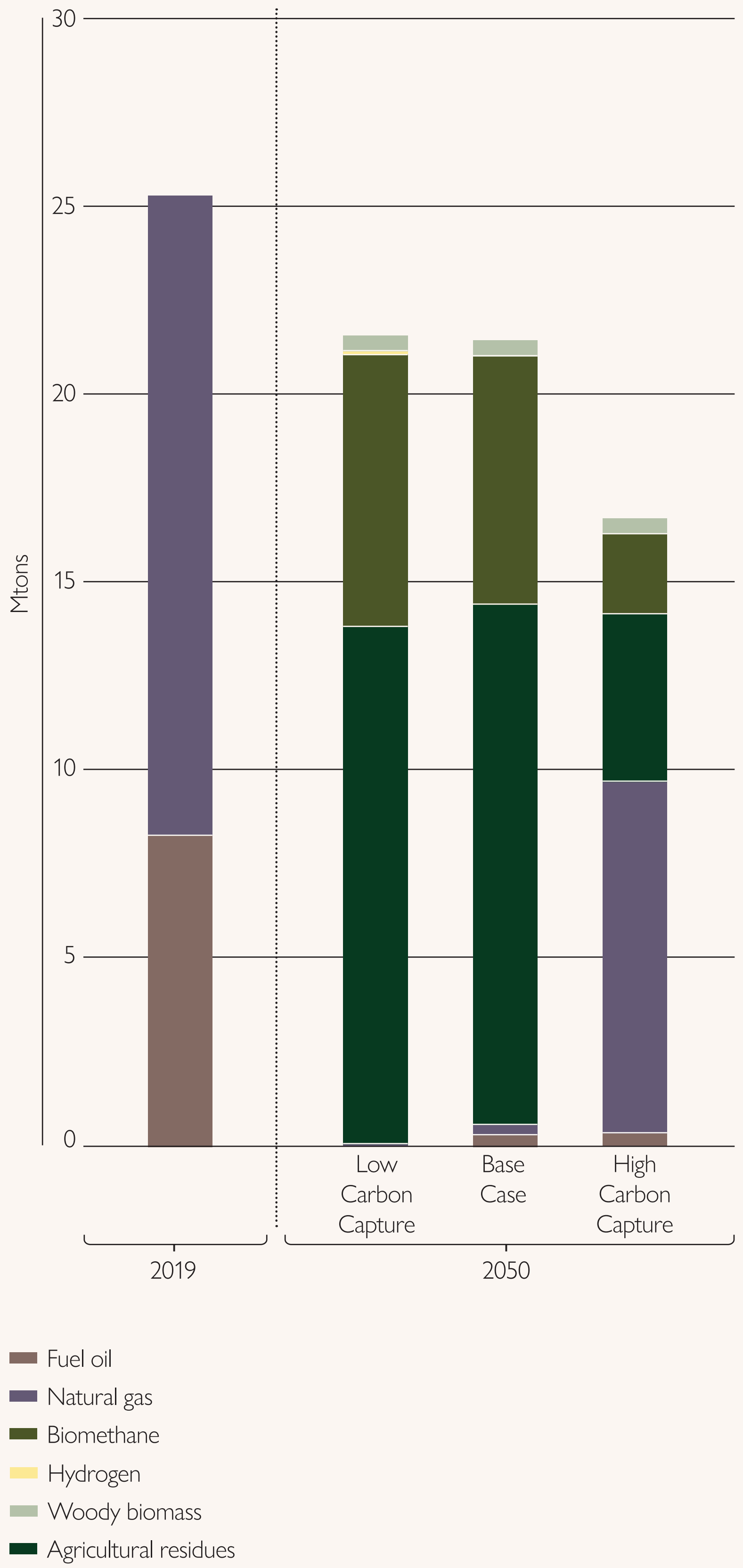


Impact on energy demand

As shown in Chart 99, constraining access to CO_2 capture technologies and infrastructure ("Low Carbon Capture" analysis) does not lead to significant changes in the industry's **fuel mix.** Increasing such access however, does lead to a high residual amount of **fossil-based energy (58%)** in the total fuel consumption in 2050. However, the total fuel purchase is lower since a higher amount of fuel gas from steam crackers is used for heat generation.

Chart 99

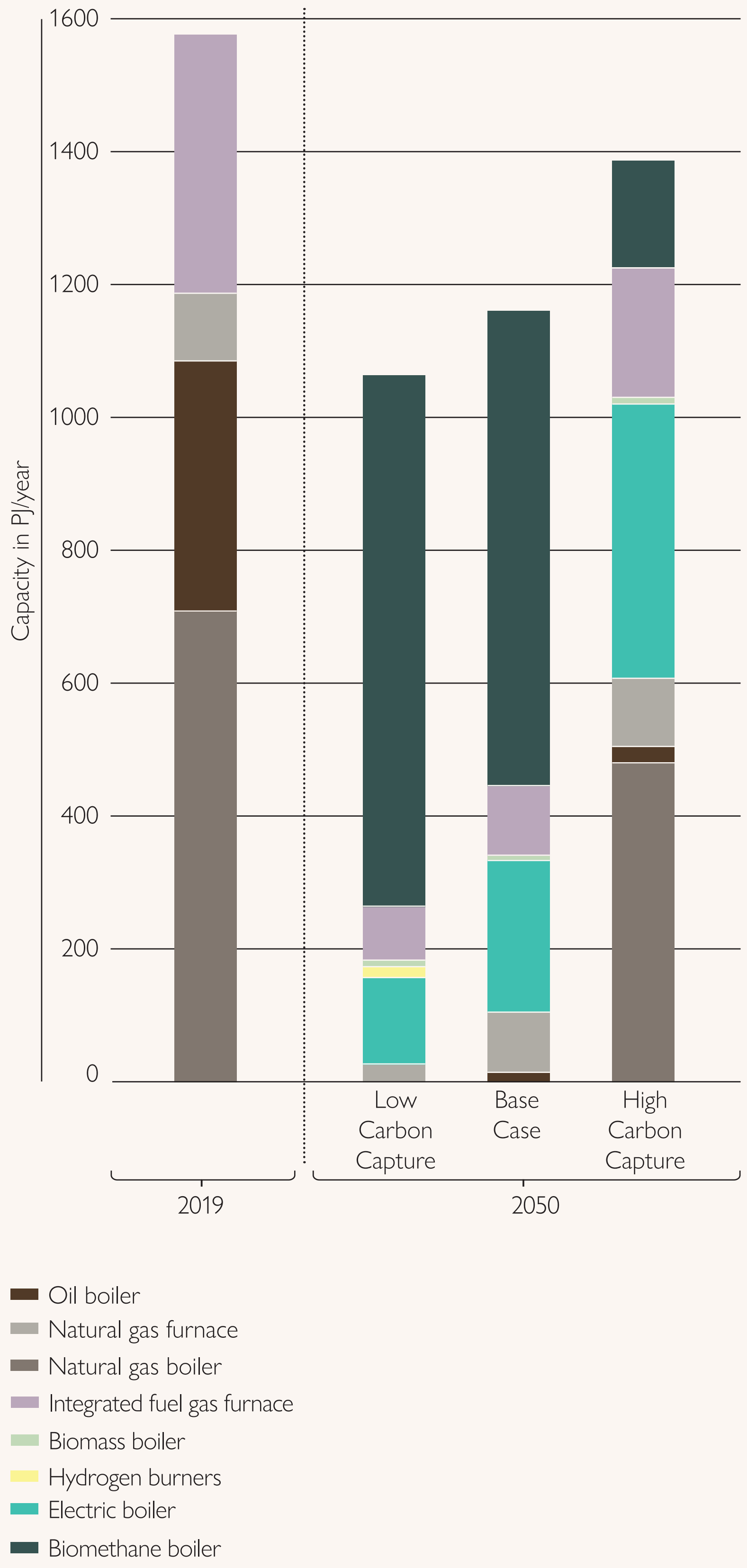
Fuel consumption by source – "Base Case" versus "Low" and "High Carbon Capture"



As shown in Chart 100, increasing the availability of CO_2 capture technologies and infrastructure does not only lead to a higher share of fossil-based heat capacity but also a higher deployment of **electric boilers.** This is because the reduction in electricity consumption for direct electrification of processes can be allocated for heat generation.

Chart 100

Installed heat capacity – "Base Case" versus "Low" and "High Carbon Capture"

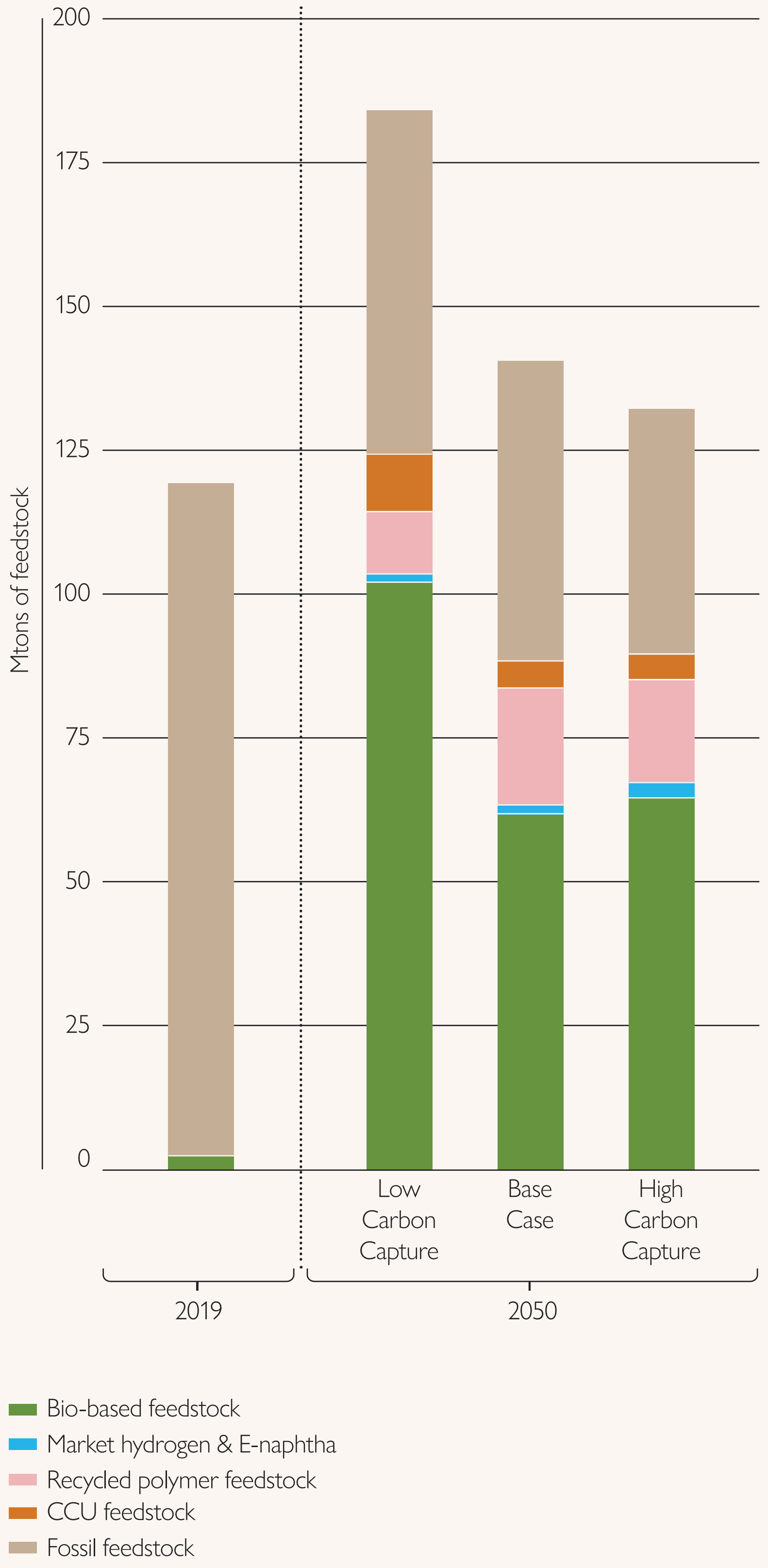


Impact on feedstock demand

In a constrained environment ("Low Carbon Capture" analysis), the total feedstock consumption increases as shown in Chart 101. The increase in bio-based feedstock consumption is mainly driven by the switch from steam cracking to **bioethanol dehydration** due to the limit CO_2 capture capacity. Since the direct emissions from chemical recycling cannot be captured to the same extent as the other scenarios, the use of **recycling polymer feedstock** decreases and the intake of virgin **fossil feedstock and** $\mathbf{CO_2}$ increases.

Chart 101

Carbon-based feedstock and hydrogen consumption – "Base Case" versus "Low" and "High Carbon Capture"

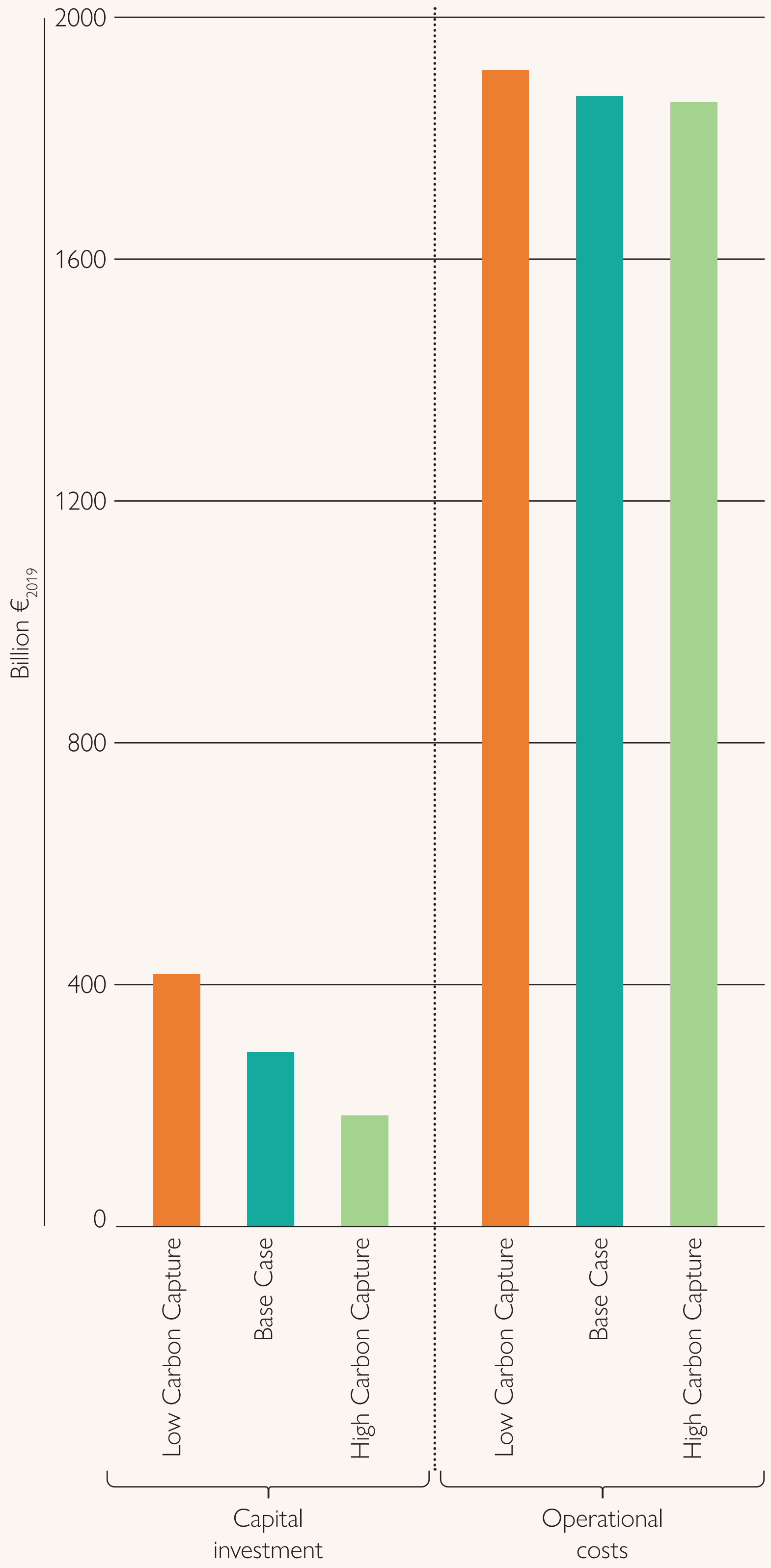


Cost

While changes in conditions regarding access to carbon capture technologies and infrastructure have a major on the amount of capital investment needed, releasing these condition have almost no effect on operational costs. The capital investments are 27% and 69% higher in the "Low Carbon Capture" analysis compared to the "Base Case" and "High Carbon Capture" respectively. The increase in the deployment of carbon capture technologies results in lower deployment of alternative production technologies.

Chart 102

Cumulative costs of GHG abatement and circularity solutions in 2050 – "Base Case" versus "Low" and "High Carbon Capture"



Section 11.5

Summary and comparison

Abatement pathways

Table 11 shows a comparison of the "Base Case" scenario and the "what if?" sensitivity analyses for each type of emissions, looking both at residual emissions and negative emissions in 2050.

Ensuring ample access to biomass and decarbonised electricity is the most efficient solution to abate **direct emissions.** When increasing access to sustainable biomass, direct emissions are reduced as the use of bio-based feedstock results in net-zero process emissions. Under the "Low Electrification" analysis, residual scope 1 emissions stay at their highest point in 2050, due to the greater reliance on conventional production and heat generation technologies.

A massive deployment of carbon capture technologies and infrastructure, or bio-based solutions, lead to higher amounts of **upstream scope 3 emissions** but increases the potential for negative emissions. When limiting access to electricity ("Low Electrification"), fuels become a more attractive source of heat generation, which leads to an increase in scope 3 upstream emissions. Even in the case of restrained access to biomass ("Low Biomass"), upstream emissions are relatively low as we assume that the intensity of fossil-based refinery production goes down in line with the IEA NZE scenario[55].

End-of-life emissions naturally reach their lowest point when recycling technologies are deployed to their maximum (on the reverse side, "Low Recycling" results also show low end-of-life emissions but this is only due to the ban on landfill, which has been removed). Having less access to electricity and CO_2 capture limits the ability of shifting end-of-life emissions to scope 1 through chemical recycling, which leads to higher gross polymer end-of-life emissions in both scenarios compared to the "Base Case" and other "What if" analyses.

The scenarios and analyses with more carbon capture (e.g. "High Carbon Capture") result in the highest amount of **emission removal** through the capture and **geological storage** of biogenic CO_2, while the low electrification, recycling and carbon capture analyses have the highest amount of negative compensation through storage of biogenic carbon **in chemical products.**

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[55] International Energy Agency. (2023). The oil and gas industry in net zero transitions. International Energy Agency. https://www.iea.org/reports/the-oil-and-gas-industry-in-net-zero-transitions

Table 11

Emissions per scope across "what if" analyses in 2050 in Mtons of $CO_{2\text{-eq}}$

Emission scope	Base Case	Low Electrification	High Electrification	Low Biomass	High Biomass	Low Carbon Capture	High Carbon Capture	Low Recycling	High Recycling
Net Direct Emissions from Fossil & Circular Origin	19	24	12	13	12	24	16	25	15
Scope 2 Emissions	0	0	0	0	0	0	0	0	0
Upstream Emissions	19	23	18	5	23	24	19	20	18
Polymer end-of-life Emissions	19	37	19	18	19	38	19	17	16
Emissions from Imports	1	1	1	1	1	1	1	1	1
Biogenic C Stored in Products	-35	-61	-33	-8	-35	-63	-17	-37	-30
Geological Storage of Biogenic CO_2	-19	-24	-13	-13	-12	-23	-34	-25	-15
CO_2 Used from Other Industries	-4	-0.4	-5	-16	-8	0	-4	-1	-6

Table 12

Residual and negative emissions in 2050 across "what if" analyses

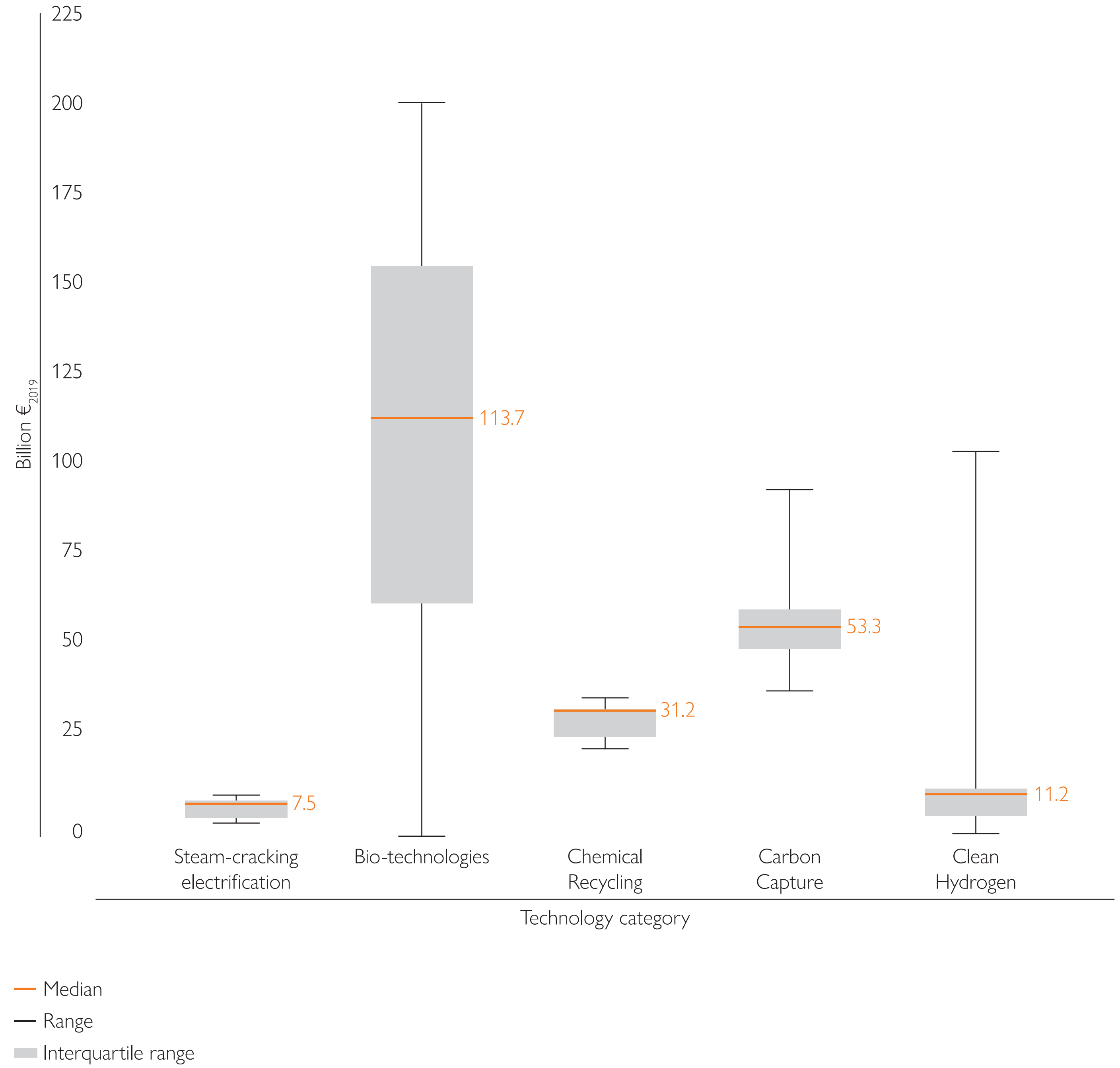
	"Base Case"	"Low Electrification"	"High Electrification"	**"Low Biomass"**	"High Biomass"	**"Low Carbon Capture"**	"High Carbon Capture"	"Low Recycling"	"High Recycling"
Residual emissions [Mtons of $CO_{2\text{-eq}}$]	58	85.6	50.1	**37.2**	55.1	**86.3**	55	63.1	51.1
Negative emissions [Mtons of $CO_{2\text{-eq}}$]	-58	-85.6	-50.1	**-37.2**	-55.1	**-86.3**	-55	-63.1	-51.1

Technology deployment

Chart 103 shows the range of discounted investment per type of technology solution across scenarios and analyses. The **biggest uncertainty** is related to investments into **bio-based technologies,** which include product and feedstock production technologies and exclude heat generation. They range between zero and close to 200 Bio€. The climate-neutrality constraint, along with the alternative embedded carbon target affects the model's choice for investing in bio-based solutions. Most of the results on **clean hydrogen** investments are located at the bottom of the range with the exception of the "Low Biomass" analysis, where the model invests in alkaline electrolysis to produce hydrogen. The role of CO_2 utilisation technologies within the scenarios affects the investments in clean hydrogen investments. Results on steam cracking electrification and chemical recycling are quite consistent across scenarios.

Chart 103

Total cumulative investment in technologies by category across "what if" analyses in 2050

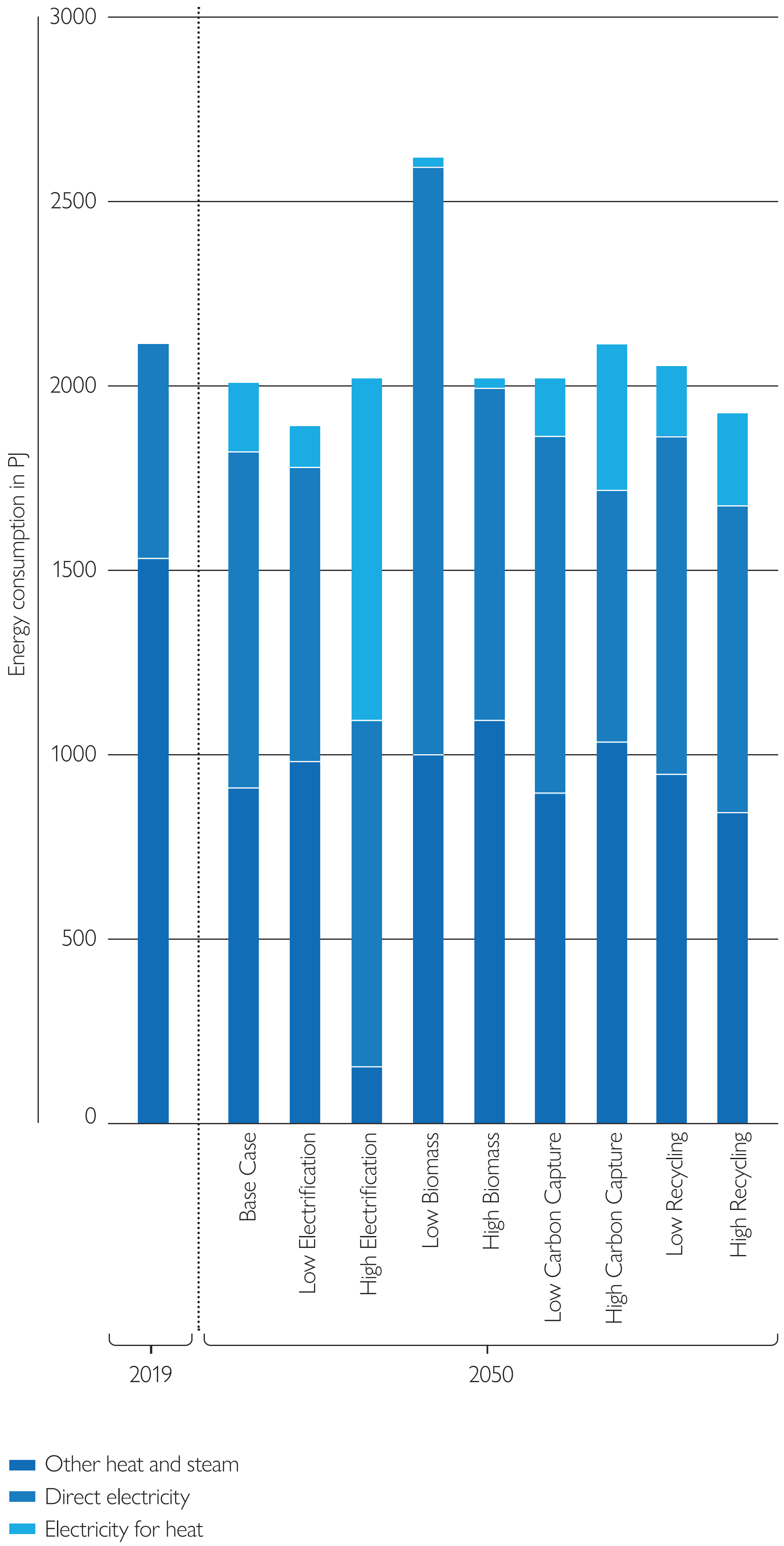


Energy demand

Chart 104 shows the final energy consumption across the "what if" analyses in 2050. The energy consumption in the **"Low Biomass"** analysis increases the most compared to the other cases as the model has limited access to bio-feed which limits the ability of carbon storage within products. Direct electrification is one of the main solutions in the "Low Biomass" analysis. In the "High Electrification" analysis, electrical boilers replace fossil fuel and biomass boilers for heat generation as more than 50% of the consumed electricity is for heating.

Chart 104

Final energy consumption by type across "what if" analyses in 2050

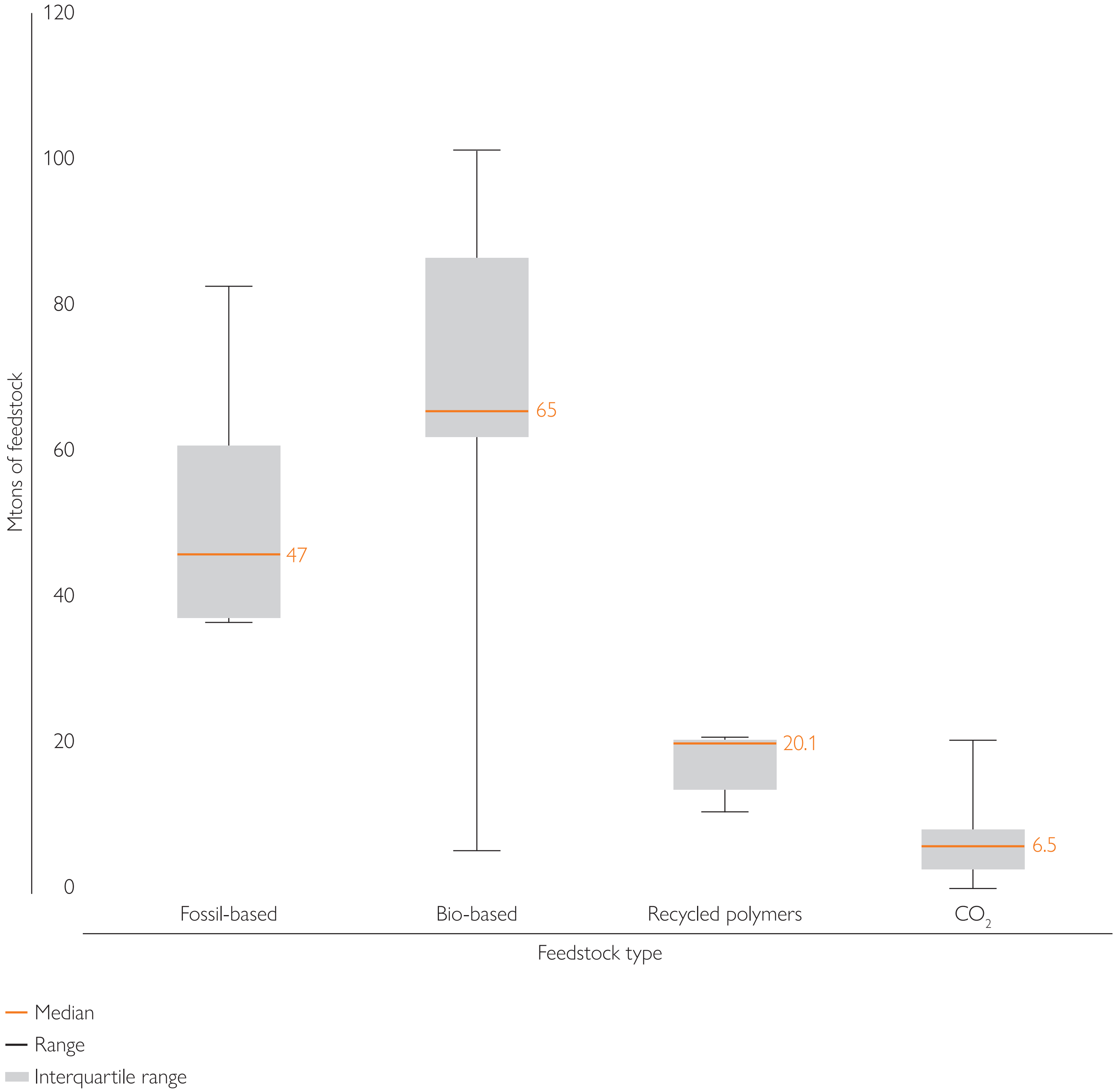


Feedstock demand

Chart 105 shows the range of total feedstock consumption volumes in 2050 across scenarios and analyses. The biggest volumes are **biomass-related** with more than 50% of the scenarios consuming **above 65Mtons** but this is also an area with wide uncertainty as it ranges between 6Mtons and 102Mtons. The volumes of **fossil-based feedstock** range between 37Mtons and 83Mtons, where 50% of the results consumed **more than 47Mtons. Polymer waste and CO_2** represent across scenarios, the **lowest** feedstock volumes. More than half of the scenarios consumed greater than **20Mtons** of recycled polymer waste as a source of feedstock, and **6Mtons** of captured CO_2.

Chart 105

Feedstock consumption volumes by type in 2050 across “what if” analyses

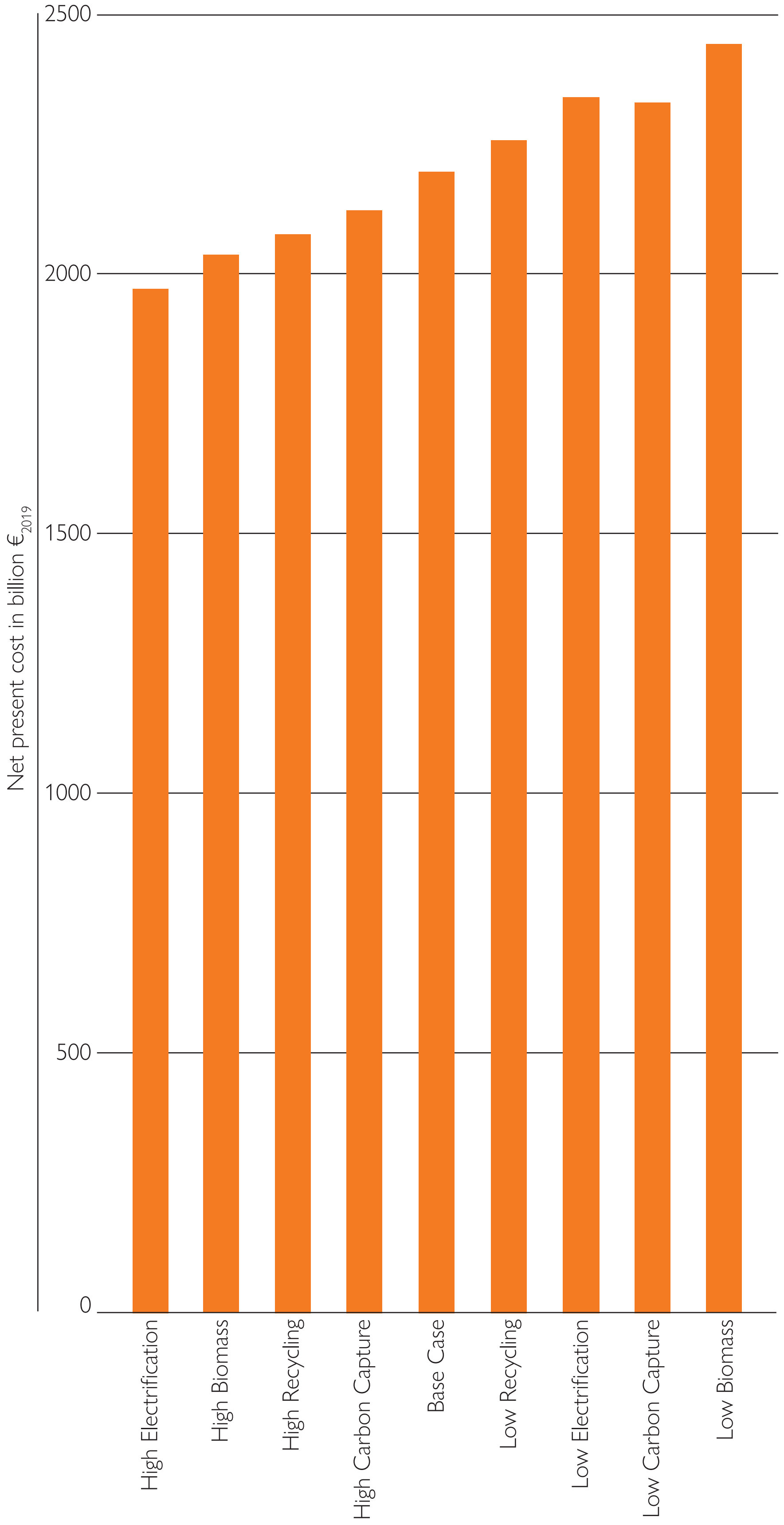


Costs

The total **net present costs** across the “What if” analyses and the “Base Case” scenario are presented in Chart 106. The “Base Case” scenario is at the midpoint of the positive and negative “What if” analyses. Ensuring **high access to clean electricity at a lower price** would yield the lowest NPC as direct electrification of processes and heat generation would be rapidly deployed. The **"Low Biomass"** analysis represents the highest NPC, standing **23.7%** above the lowest NPC in the "High Electrification" analysis. This shows that costs can vary significantly depending on the set of available enabling conditions for achieving climate neutrality.

Chart 106

Total Net Present Cost across scenarios across “what if” analyses



Section 12

Conclusions

A number of technological pathways like electrification, bio-based routes, chemical recycling or carbon capture emerge from our entire analysis, as **backbone solutions** for reaching the climate neutrality and circularity ambitions. **Negative emissions** are also required in all scenarios. How much each solution contributes to the end-result remains primarily a function of availability and relative cost. The chemical industry's pathway to climate-neutrality and circularity is impacted by a **multitude of factors,** both inside and outside the control of chemical companies, especially when looking across the value chain. This creates a **massive uncertainty** around the mix of solutions and costs needed to support the transition, but also underscores the need to ensure access to a **wide range of options.** Abatement solutions work like **communicating vessels:** restricting access to certain technologies, energy or feedstock sources causes a heavier reliance on the remaining options, therefore putting at risk the achievement of climate and circularity targets. The overall cost of the transition for the chemical industry largely depends on the enabling framework and the cost of alternative resources.

Restricted access to electricity for example, either puts at risk the climate-neutrality objective or creates an overreliance on biomass, or requires unrealistic amounts of carbon capture. Restricted access to alternative resources or technologies also leads to an increase in costs including capital costs, as it does not allow the industry to explore **lowest-costs pathways.**

Figure 11 shows the differential between current industry conditions on the one hand, and where the industry needs to be in order to reach its climate and circularity objectives. For each element it shows a minimum and a maximum requirement, to reflect the uncertainty based on the scenarios described in this report.

Despite the electrification of processes, the chemical industry remains a **molecule-based industry,** where carbon plays an essential role. Therefore, access to **biomass** is indispensable in order to substitute fossil molecules. Although polymer waste and captured CO_2 are important complementary solutions, biomass is – based on our assumptions – the easiest and most economically attractive feedstock alternative, because it requires limited adaptation to existing processes. Access to such biomass, especially when respecting sustainability obligations, is however finite. **Geopolitical developments,** notably in relation to Ukraine, will determine the EU's capacity to secure its access to green molecules. The chemical industry will be facing tough competition with other sectors of the economy. Supporting the chemical sector's transition to climate-neutrality and circularity therefore requires bold action from EU decision-makers. Across the EU, crop yields need to increase to their maximum and if not all sectors' demand can be met, resources will have to be **prioritised** towards the applications that can offer the best climate and environmental benefits.

A significant gap can also be observed for **electricity supply,** compared to today. Securing sufficient access to electricity will require to significantly ramp up capacity. By way of illustration, meeting the electricity demand of the "Base Case" scenario would require around **15 nuclear power plants** coming out of the ground[56].

The results of the "Base Case" scenario show that the pursued climate and circularity objectives are already highly ambitious. Increasing the level of climate targets (see the analysis on 2040 targets), circularity (see the analysis on feedstock targets) or setting a renewable hydrogen target, is **an additional stretch.** These new targets can only be met if additional resources (compared to the already massive volumes and capacities) are deployed.

The analysis of alternative feedstock targets also shows the **complex link between circular feedstock and GHG emissions.** The "Feedstock Targets" scenario shows that mandating very high shares of alternative carbon would not be instrumental for reaching the climate-neutrality targets and could even be counterproductive, if the enabling conditions, notably access to clean energy, are not in place. If and when adopting such targets, decision-makers should therefore clearly spell-out the type of environmental benefits that are pursued and underpin their decisions with strong scientific data.

Last but not least, while the **competitiveness** of the chemical industry is not the focus of this report, it will shape and influence the ability of the sector to achieve its transition. The sheer amount of capital and operational budget will need to be financed with higher revenues providing a **return on investments,** otherwise investments will not materialise in Europe. Boosting demand for net zero, low carbon and circular products is therefore essential.

A fundamental assumption at the basis of our scenarios is the fixed amount of production happening in Europe: the model cannot achieve the climate and circularity objectives by closing down capacity and replacing with imports. As we know, reality is different: failing to create the necessary enabling conditions for the chemical sector's transition, will not only weaken climate action but also potentially lead to a deterioration of the EU's economic fabric.

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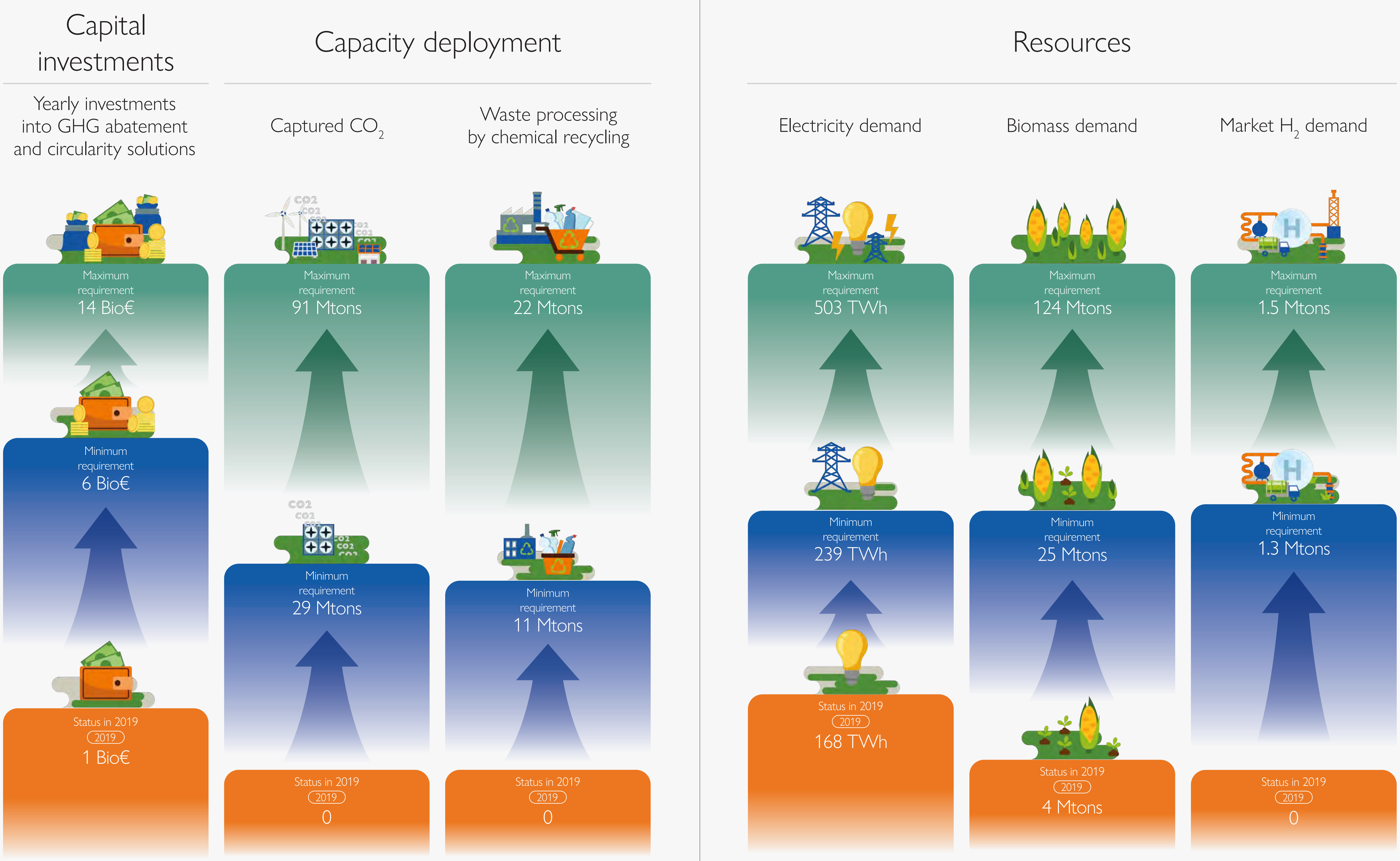
[56] This is assuming a typical nuclear reactor of 1 GW running at full capacity

Figure 11

Key indicators of the transition



Section 13

Acknowledgments

This report and the iC2050 model that it documents, are the result of a massive team effort and have brought together a wide range of expertise.

First, we would like to thank our **Steering Group,** with Mark Williams as our Chair, and Philippe Ducom, Stefan Kothrade and Wim Michiels as members of the Steering Group, and Marco Mensink, as Cefic Director General. As our industry captains, they have given us precious strategic advice as well as an overall sense of direction, under mandate of the Cefic Board of Directors.

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Section 14

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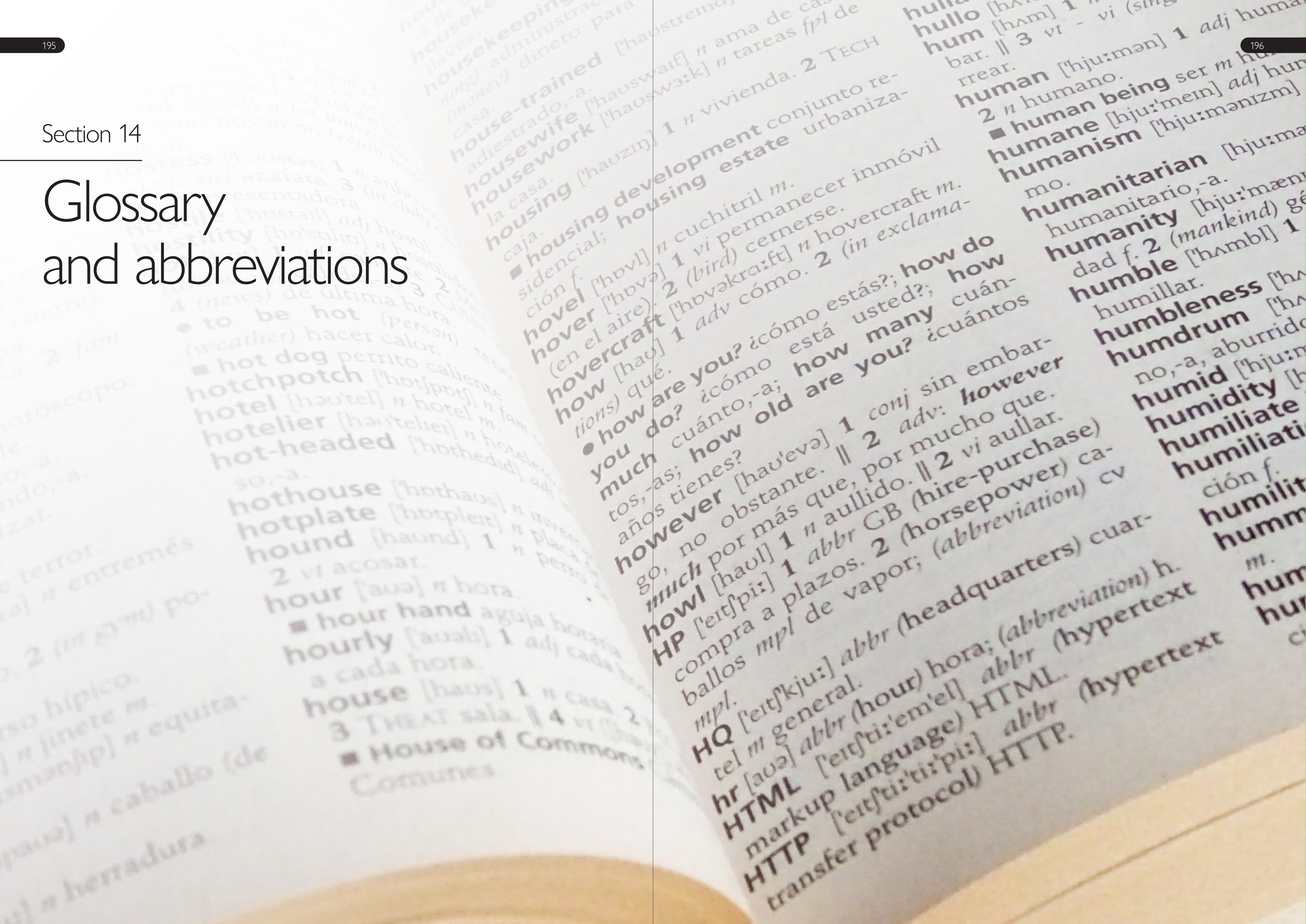
Section 14

Glossary and abbreviations



Glossary

Alternative (low-carbon) feedstock: Alternative feedstock is any feedstock which replaces primary fossil carbon as feedstock for manufacturing processes in the chemical industry.[57]

Biogenic carbon: Biogenic carbon refers to carbon that is sequestered from the atmosphere during biomass growth and may be released back to the atmosphere later due to combustion of the biomass or decomposition (e.g., of food waste).[58]

Capital costs: also known as capital expenses, represent a cost incurred on the purchase of land, buildings, construction and equipment to be used in the production of goods or the rendering of services.[59]

Carbon budget: The area under a greenhouse gas (GHG) emissions trajectory that satisfies assumptions about limits on cumulative emissions estimated to avoid a certain level of global mean surface temperature rise. Carbon budgets may be defined at the global level, national, or sub-national levels.[60]

Carbon dioxide (CO_2): Carbon dioxide is a colourless gas formed during the combustion of any material containing carbon and an important greenhouse gas. Naturally, it makes up 0.04% of the air in the atmosphere. CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.[61]

Carbon removal or Carbon Dioxide Removal: Set of techniques that aim to remove carbon dioxide (CO_2) directly from the atmosphere by either (1) increasing natural sinks for carbon or (2) using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration.[62]

Circular carbon feedstock: circular carbon feedstocks covers sustainable biomass, atmospheric carbon, recycled plastic waste or captured CO_2 whether originating from the chemical sector itself or from another industrial sector.[63]

Circular economy: A systems approach involving industrial processes and economic activities along the whole value chain that are restorative or regenerative by design, aiming for a climate-neutral and resource-efficient economy by maintaining the value of products, materials and resources as long as possible.[64]

CO_2 utilisation: refers to the process of Carbon Capture and Utilisation (CCU). Carbon capture and utilisation refers to a range of applications through which CO_2 is captured and used either directly (i.e. not chemically altered) or indirectly (i.e. transformed) in various products.[65]

Deployment rate: The pace at which new production capacity can be deployed from year to year.

Emissions intensity: The emissions released per unit of activity.[66]

E-naphtha: E-naphtha is a synthetic naphtha made from renewable electricity, water, and carbon dioxide. It is used as a sustainable alternative in petrochemical production and fuel blending.

Energy efficiency: 'energy efficiency' means the ratio of output compared to the input energy that was injected in the process.[67]

Energy intensity: The energy intensity shows how much energy is needed per unit of activity, output, or any other organization-specific metric. The production index of the chemical sector is used as the organization-specific production metric.[68]

Fossil-based carbon: carbon contained in non-renewable raw materials, such as crude oil or natural gas.

Fossil fuel: Carbon-based fuels from fossil hydrocarbon deposits, including coal, peat, oil, and natural gas.[69]

GHG emissions: Emissions of greenhouse gases, such as carbon dioxide, nitrous oxide, methane and fluorinated gases, which absorb infrared radiation contributing to the greenhouse effect.[70]

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[57] Source: : Cefic (2024). List of definitions Cefic Sustainable Development Indicators. List of definitions Cefic Sustainable Development Indicators — cefic.org

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[61] Source: : Cefic (2024). List of definitions Cefic Sustainable Development Indicators. List of definitions Cefic Sustainable Development Indicators — cefic.org

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[63] Source: Cefic. (2021). iC2050 project report – Shining a light on the EU27 chemical sector's journey toward climate-neutrality.

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Intermediates: any chemical substance produced during the conversion of some reactant to a product. Most synthetic processes involve transformation of some readily available and often inexpensive substance to some desired product through a succession of steps. All the substances generated by one step and used for the succeeding step are considered intermediates.[71]

Inorganic compounds: Inorganic compound, any substance in which two or more chemical elements (usually other than carbon) are combined, nearly always in definite proportions. [72]

Organic chemicals: Organic chemicals, or organic compound, indicates any of a large class of chemical compounds in which one or more atoms of carbon are covalently linked to atoms of other elements, most commonly hydrogen, oxygen, or nitrogen.[73]

Geological storage of CO_2: Carbon dioxide capture and geological storage (CCS) consists of the capture of carbon dioxide (CO_2) from industrial installations, its transport to a storage site and its injection into a suitable underground geological formation for the purposes of permanent storage.[74]

Monomers: REACH defines a monomer as a substance which is capable of forming covalent bonds with a sequence of additional like or unlike molecules under the conditions of the relevant polymer-forming reaction used for the particular process.[75]

Net Present Cost: is the total cost of a project or investment over its entire lifespan, expressed in today's euros. It includes all expenses such as initial capital costs, operating and maintenance costs, and any other associated costs, discounted to their present value using a specific discount rate.

Operational costs: also known as operating costs or operating expenses, operational costs represent the ongoing expenses incurred by a business to produce goods or services. Examples of operational costs are the salaries paid to the employees, costs of electricity, etc.[76]

Polymers: A polymer is a substance consisting of molecules characterised by the sequence of one or more types of monomer unit. Such molecules must be distributed over a range of molecular weights. Differences in the molecular weight are primarily attributable to differences in the number of monomer units.[77]

Renewable energy: Any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use.[78]

Scope 1 GHG emissions: are direct greenhouse gas emissions that are from sources owned or controlled by the reporting entity (f.e. a chemical company). (source: IPCC). They can be divided into two types of emission sources: 1. emissions resulting from on-site combustion of fuels to generate energy; 2. emissions directly from production processes.[79]

Scope 2 GHG emissions: emissions of GHG associated with the production of electricity, heat or steam purchased by the reporting entity. [80]

Scope 3 GHG emissions: cover all other indirect emissions, i.e. emissions associated with the extraction and production of purchased materials, fuels, and services, including transport in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, etc.[81]

Substitution Rate: The share of initial capacity (2019) that can be replaced each year by a new capacity.

Technosphere: generally, technosphere denotes the totality of human-made structures, systems and processes. In the context of this report, technosphere refers to the industrial environments.

Weighted average cost of capital: The weighted average cost of capital (WACC) is a financial ratio that measures a company's financing costs. It weighs equity and debt proportionally to its percentage of the total capital structure.[82]

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[72] Source: Encyclopedia Britannica. Inorganic Compound definition. Inorganic compound | Definition & Examples | Britannica

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[82] Source: Jadeja V. (2024). Business Insider. Understanding Weighted average Cost of Capital (WACC). Weighted Average Cost of Capital (WACC) Explained (businessinsider.com)

Abbreviations

Abbreviation	Full name
€$_{2019}$	2019 Euro
ASU	Air Separation Unit
ATR	Auto Thermal Reforming
BAU	Business as usual
B-HET	Bis(2-hydroxyethyl) terephthalate
Bio€	Billion €
Bio-LNG	Bio-liquified natural gas
BTX	Benzene, Toluene and Xylene
CAGR	Compound Annual Growth Rate
CBAM	Carbon Border Adjustment Mechanism
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCR	Continuous Catalytic Reforming
CCU	Carbon Capture and Utilisation
CH_4	Methane
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalent
CRF	Capital Recovery Factor
DSR	Deposit Return Systems
EC	European Commission
EED	Energy Efficiency Directive
EFSA	European Food safety Authority
EoL	End-of-life
EPBD	Energy Performance of Buildings Directive
EPS	Expanded polystyrene
ESPR	Ecodesign for Sustainable Products Regulation
ETS	Emissions Trading System
EU	European Union
EU27	27 member states of the European Union
FCC	Fluid Catalytic Cracking
FED	Final Energy Demand
GAMS	General Algebraic Modeling System
GDP	Gross domestic product
GHG	Greenhouse Gas
H_2	Hydrogen
HDPE	High density polyethylene
HFC	Hydrofluoro Carbon
IEA-NZE	International Energy Agenda – Net Zero Emissions by 2050 Scenario
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
LPG	Liquid Petroleum Gas
MEG	Mono-Ethylene Glycol
Mio€	Million €
MTA	Methanol-To-Aromatics
Mtoe	Million tons of oil equivalent
MTO	Methanol-To-Olefins
Mtons or MT	Million tons
MWh	Megawatt hours
N_2O	Nitrous oxide
NPC	Net Present Cost
NGL	Natural Gas Liquid
ODC	Oxygen-Depolarized Cathode
PCE	Purchase Cost of Equipment
PE	Polyethylene
PET	Polyethylene Terephthalate
PFC	Perfluorocarbon
PJ	Petajoule
PPe	Polypropylene
PPC	Physical Plant Cost
PPWR	Packaging and Packaging Waste regulation
PS	Polystyrene
PTA	Purified Terephthalic Acid
PVC	Polyvinyl Chloride
pygas	Pyrolysis gasoline
RDF	Residue-derived fuel
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
SBTi	Science Base Targets initiative
SMR	Steam Methane Reforming
SUPD	Single Use Plastics Directive
syngas	Synthesis Gas
TRL	Technology Readiness Level
TWh	Terawatt hours
WACC	Weighted Average Cost of Capital
WFD	Waste Framework Directive
wt. %	Percentage by weight

Annex 1

Categories of input parameters

Production volumes

The production volumes are determined by the model based on a set of exogenous parameters that are: product demand, imports, exports, and the share of mechanical recycling for polymers. The following equation presents the calculation of the required production volumes:

$$Production_{t,p} = Demand_{t,p} + Exports_{t,p} - Imports_{t,p} - Mechanical\ Recycling_{t,p}$$

Where "t" is the time period, which is the year in iC2050, and "p" is the product.

The production volumes of final products and intermediates are consistent: a share of the intermediate demand is used as an input for the production of the final product. The model calculates the amount of intermediate product demand for the production of final products based on the defined yields.

Economic parameters

Discount rate

The objective function of iC2050 is to minimise the net present cost of production within the chemical industry. To account for the temporal value of cash flows and reflect inflation, a base year (2019) was assumed, to which future costs and benefits are discounted.

Weighted Average Cost of Capital (WACC)

Investments in new capacities are annualised over the economic lifetime of the project based on the WACC. This parameter takes into account the average of the costs of equity and debt for an investing company. As iC2050 is a sectoral model, an average value for WACC is assumed across different technologies.

Substitution and deployment rates

The substitution and deployment rates are introduced within the model to allow for a gradual deployment of new technologies and to prevent sudden technology switching in the model. Since iC2050 is a linear model, the choice between two different technologies that produce the same output is made based on the net present cost attached to each technology.

The following parameters have been defined:

- **Substitution Rate:** The share of initial capacity (2019) that can be replaced each year by a new capacity.
- **Deployment Rate:** The pace at which new production capacity can be deployed from year to year.

Technologies

Types of technologies

Different types of technologies are modelled in iC2050. Each of them has a defined set of output materials, which are produced proportionally from the input material that feeds the process. These technologies are classified into four categories, as shown in Figure 12. The full list of technologies modelled in iC2050 is available in Annex 2.

Figure 12

Type of technologies modelled in iC2050

Chemical production

Chemical production technologies produce one or more of the 18 main products modelled in iC2050. Those technologies require a feedstock input, and in most cases energy in the form of heat or electricity.

Feedstock production

Feedstock production technologies are similar to chemical production technologies, but the output materials, which do not belong to the 18 main chemical products, are used as feedstock in chemical processes.

Heat generation

Heat generation technologies generate the heat that is required for chemical reactions and are classified based on the temperature of their generated heat. A threshold of 500°C has been set to separate between low and high temperature heat.

Carbon capture

Carbon capture technologies are separated between low and high concentration based on the CO_2 concentration within the flue gas stream, which is captured. The captured CO_2 can either be used in the model as feedstock, or transported and stored in an offshore storage location.

Each technology is characterized by a set of parameters that define its cost, material consumption and abatement potential. The list of parameters that characterize a technology in iC2050 are listed in Figure 13.

Figure 13

Technology characterisation parameters

Material Inputs

Material Outputs

Capital Cost

Maintenance Cost

Availability Date

GHG Intensity

Heat Consumption

Electricity Consumption

Heat Production

Utilisation Factor

Lifetime

The modelled technologies range from conventional technologies, that have been commercially available for a significant period of time, to alternative technologies that would be available for deployment in future years up to 2050.

The emission reduction due to technology switch can occur on different emission scopes. Scope 1 direct emissions could be reduced by switching to technologies with lower energy intensity, or by switching from traditional fossil fuel powered heaters to electrical heating. Scope 2 emissions depend on the CO_2 intensity of the electricity supply, and the amount of electricity needed to produce a certain amount of product. In scenarios where the CO_2 intensity of electricity is higher, scope 2 emissions can be reduced by switching to technologies with lower electricity consumption.

Scope 3 upstream emissions depend on the raw materials consumed by the chemical industry as feedstock or fuel. Those materials have GHG intensity factors allocated to them based on the carbon footprint during the extraction and production of those materials. The same product can be produced using multiple technologies in iC2050. This creates competition between technologies to meet the product demand at the lowest NPC. In many instances, various technologies can be used to produce the same product, each requiring different types of feedstock. Consequently, the model can switch technologies to reduce scope 3 upstream emissions by opting for those that utilize feedstock and fuels with lower CO_2 intensity.

Scope 3 downstream emissions are accounted for all polymers included in the iC2050 product scope. Chemical recycling technologies, which are modelled explicitly in iC2050, are one of the levers that would enable the decrease of end-of-life emissions by creating useful feedstock from polymers that have reached the end of their useful lifetime instead of incinerating them.

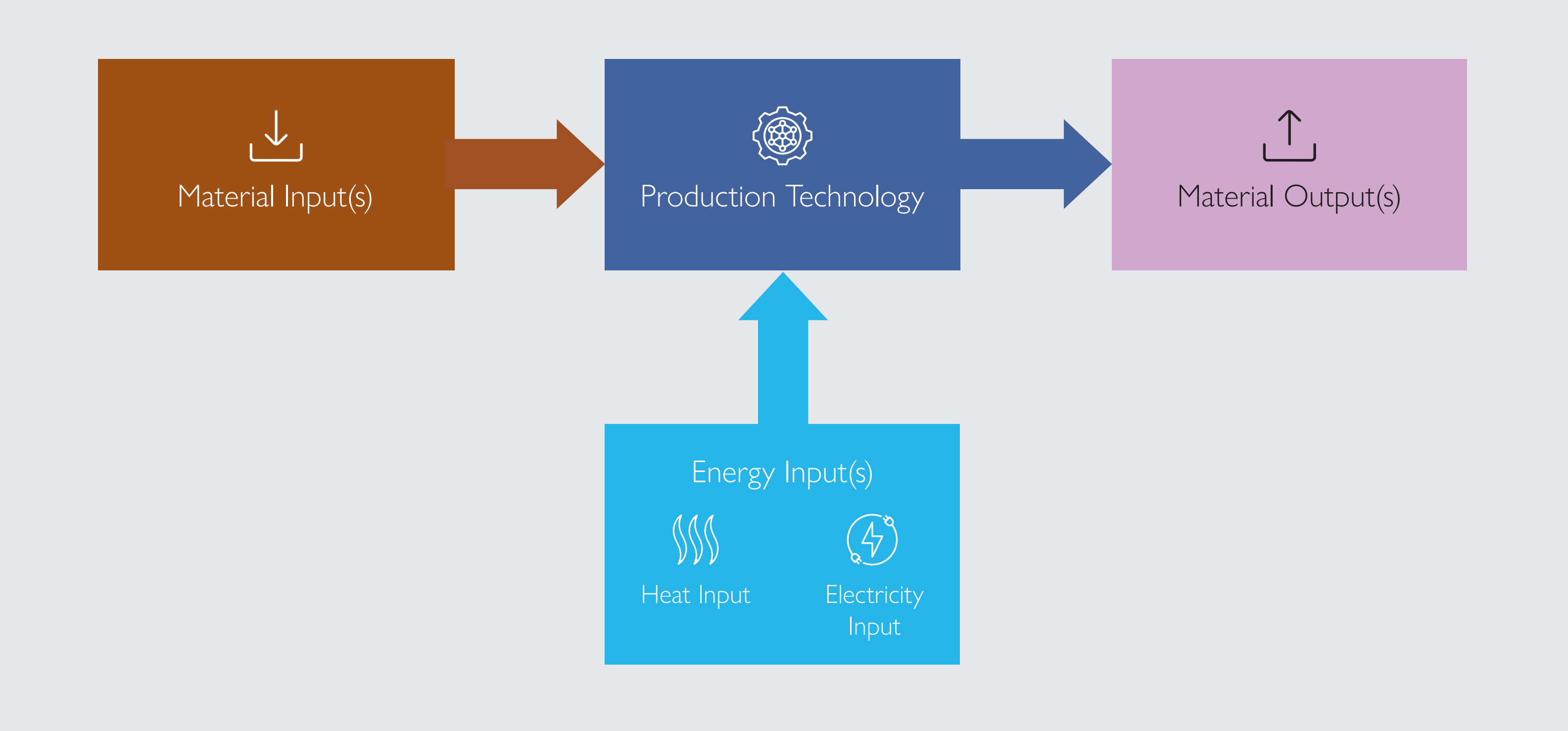
The model chooses to invest in the deployment of new technologies endogenously. These choices and trade-offs consider emission reductions in a combined way, which allows the model to satisfy the overall net zero emission constraint in 2050.

Production technologies

Production technologies use raw materials or intermediates as feedstock and produce useful chemicals as outputs. The output will then either be used further as feedstock in the next production steps, or it will satisfy the final demand for one of the 18 chemicals in the scope of the model.

Figure 14

Production technologies scheme



Material inputs (feedstock or fuels) can either be sourced from a market that is characterised by a limited availability and defined prices, or they can be produced internally within the chemical industry. The raw materials available in the EU27 vary depending on the assumptions of the considered scenario (See Annex 4 for more details). They are classified as fossil-based, bio-based, or circular materials, based on the origin of their carbon content.

Energy inputs can either be supplied in the form of heat energy or electricity. The heat energy is generated within the chemical industry through the modelled heating technologies. The electricity is purchased from an electricity market that is characterised by a price, a yearly available amount, and a GHG intensity. The characteristics of the electricity market are exogenously defined by the modeler as part of the scenario assumptions between 2019 and 2050.

Output materials are produced based on the defined yields of the technology. The carbon content of those outputs is determined based on the origin of the input materials. Product-specific targets for the type of carbon embedded in the product can be implemented in the form of constraints to the model.

The detailed representation of steam cracking technologies in iC2050 is shown in Figure 15. The output materials of the cracker are used as inputs to create polymers and other intermediates such as benzene. The fuel gas is used to generate heat via an integrated fuel gas furnace and supplied to the cracker. The remaining fuel gas is either used to produce hydrogen or sold.

Figure 15

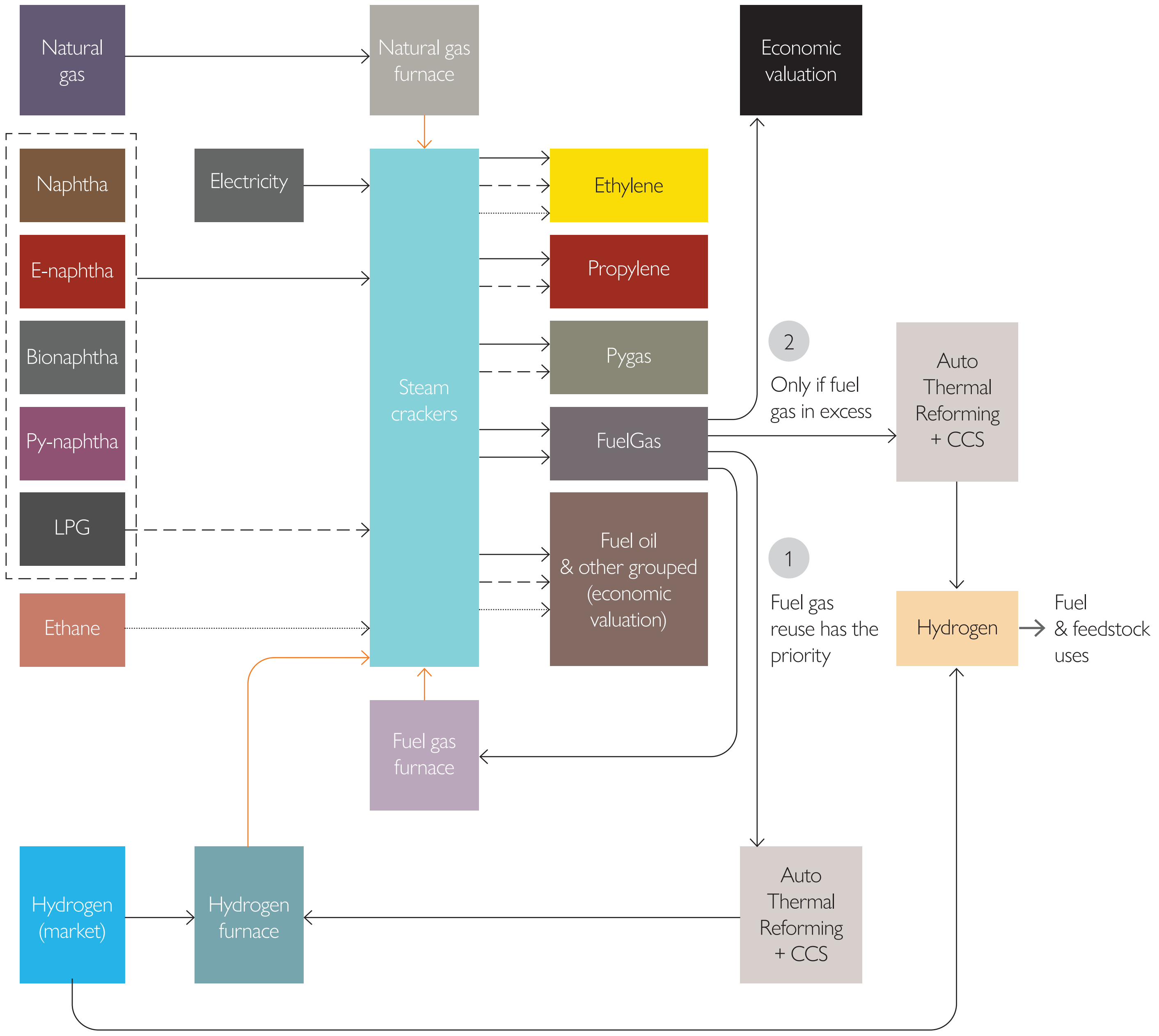
Representation of steam cracking in the iC2050 model

1

Fuel gas reuse (in steam crackers) can either be **burned directly** in a fuel gas furnace or **converted into hydrogen** to feed a hydrogen furnace.

2

Excess fuel gas (offsite) can either be **converted into hydrogen** and then used as a feedstock/heat source or **valorised.**



The full list of steam cracking technologies modelled in iC2050 is shown in Annex 2.

Heating technologies

Heat production technologies require material inputs in the form of fuel. Figure 16 shows the scheme for heat production technologies in iC2050.

Figure 16

Heat production scheme

Heat is classified in two categories, based on the heat temperature:

- The heat generated with a temperature below 500°C is classified as low-temperature heat;
- The heat generated with a temperature above 500°C is classified as high-temperature heat.

The production technologies that require heat energy are classified into two categories based on the temperature of their heat demand. A specific set of heating technologies are consequently able to supply the required heat based on the required temperature.

The full list of heat technologies modelled in iC2050 is listed in Annex 2.

Carbon capture technologies

The third type of technologies present in iC2050 is carbon capture. CC technologies require energy input in the form of electricity. The output is a quantity of CO_2 captured from production or heat generation processes. A schematic representation of carbon capture technologies that are deployed on heat generation process is shown in Figure 17.

Implementation of carbon capture technologies is based on the concentration of the captured CO_2[83]:

- **low-concentration streams:** Chemical absorption with amine scrubbing is the most mature post-combustion CO_2 capture technique. This process uses MEA solvents (amine) to capture CO_2 coming from low-purity gas streams. In the model, any emission stream that contains less than 95% of CO_2 in the flue gas by volume is assumed to be a low-concentration stream.
- **high-concentration streams:** High purity CO_2 **(> 95% in volume)** is captured from flue gas streams in the chemical sector, where further separation stages are not required. The only steps required in this process are compression/liquefaction, drying and limited purification. Power is used mainly to compress the CO_2 to 35 bars, the level needed for gaseous pipeline transport.

Each technology, which results in direct CO_2 emissions is classified based on the CO_2 concentration in the flue gas stream resulting from this technology.

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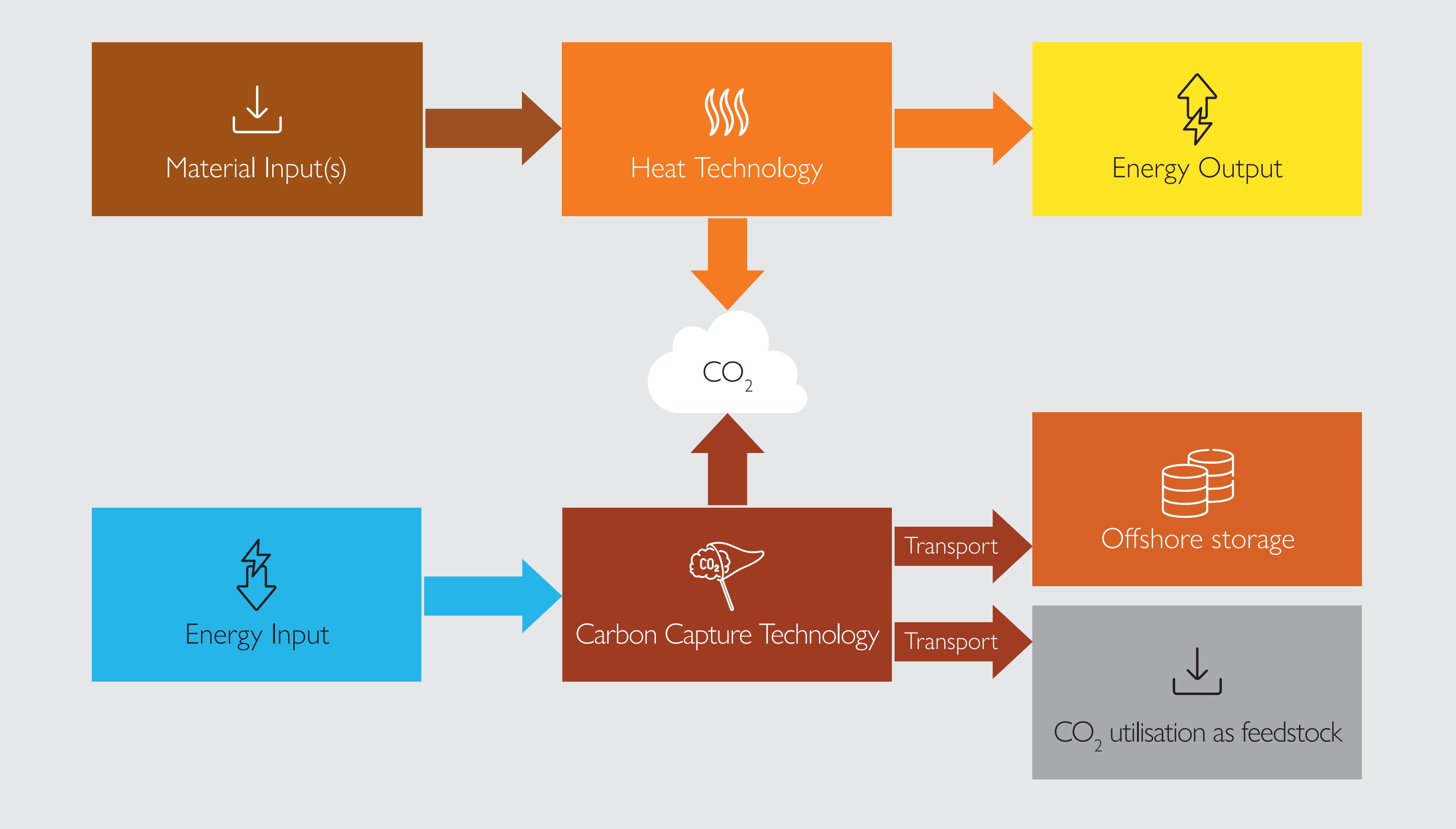
[83] More energy is required to capture CO_2 from low-concentration streams thus leading to a higher cost compared to capturing CO_2 from high-concentration streams.

Figure 17

Deployment of carbon capture technologies applied to heat generation



The captured CO_2 is tracked based on the origin of carbon, and the accounting rules are applied accordingly. One of the characteristics defining the carbon capture technology is the capture rate, which can change over the modelling timeframe. A rate less than 100% would lead to having residual emissions that are not captured. The capture rate is different for low and high concentration streams.

The process of capturing CO_2 at a process-level involves a series of additional steps that require transporting it to a storage or industrial site, depending on whether the CO_2 would be stored permanently or used as feedstock. The infrastructure that is required for carbon capture and then storage or use, is modelled in iC2050 in the form of capacities, costs and distances. Since the model operates on a sectoral level, aggregating the EU27 as a single region, no specific emitter-to-sink distance is used. An average distance is used to calculate an average transport cost between emitter sites and sinks in the EU27.

The captured CO_2 is assumed to be stored at offshore storage sites, which requires transporting the captured CO_2 over inland and subsea distances. The storage capacity is limited by a maximum injection capacity given for every year.

The costs associated with capturing and storing or using CO_2 allow the model to determine whether the deployment of carbon capture as an abatement solution is economically optimal under the assumed scenario conditions.

The costs of carbon capture abatement solutions is divided into:

- **Capture Cost:** this includes the technology CAPEX and operational costs.
- **Transport Cost:** the cost of inland and subsea transport of the captured CO_2.
- **Storage Cost:** the cost of storing the captured CO_2.

The capital cost of carbon capture is annualised based on the assumed WACC. A levelised cost of carbon capture and storage is derived for each year based on the defined cost assumptions. The cost of electricity and fuels for heat generation affect the operational costs of carbon capture, and the transport cost are affected by the unit cost of CO_2 transport and the total distance. The carbon capture at the process level is penalised by a capture rate which sets a limit on the maximum amount of CO_2 that can be captured at the source.

Cost of technologies

Capital expenditures (CAPEX)

The starting point for calculating the CAPEX in iC2050 is the Purchase Cost of Equipment (PCE). The data is provided in the form of a cost per unit of installed capacity (€/Mtons of capacity). The model calculates the total PCE costs based on the capacity installations that the model decides to deploy. The PCE for a given technology is defined for every year within the modelling period, which allows defining trajectories for technologies that have a lower Technology Readiness Level (TRL) but are expected to have a lower PCE in the future, due to technology improvement.

Additional costs that represent Physical Plant Costs (PPC) are added on-top of the PCE to account for additional costs such as piping, instrumentation, site development and other physical costs. The PPC are assumed to be a share of the PCE as described below. The PPC depends on the process type[84].

$$PPC = PCE \times (1 + \sum_{n-1}^{9} f_n)$$

Estimating the costs of installing new capacities accurately is difficult. Projects that are implemented over long periods of time, which often involves unplanned costs. These are known as contingency costs. To account for those costs, an additional factor is added to the physical plant costs to derive the CAPEX as shown below:

$$CAPEX = PPC \times (1 + f_{contingency})$$

The Purchase Cost of Equipment (PCE) and the physical technology cost factor assumptions are listed in Annex 3.

Total physical plant cost (PPC)	
f_1: Equipment erection	f_6: Utilities
f_2: Piping	f_7: Storages
f_3: Instrumentation	f_8: Site development
f_4: Electrical	f_9: Ancillary buildings
f_5: Building, process	

Operational costs

The operational costs of technologies are divided into two separate categories: “fixed” and “variable costs”. The fixed cost includes the maintenance cost per technology, which is assumed to be a share of the purchase cost of equipment. The variable cost are calculated based on the production levels of each technology, and include electricity, feedstock and fuel costs.

The fuel and feedstock prices are listed in Annex 3, and the electricity price that has been assumed is shared under each scenario.

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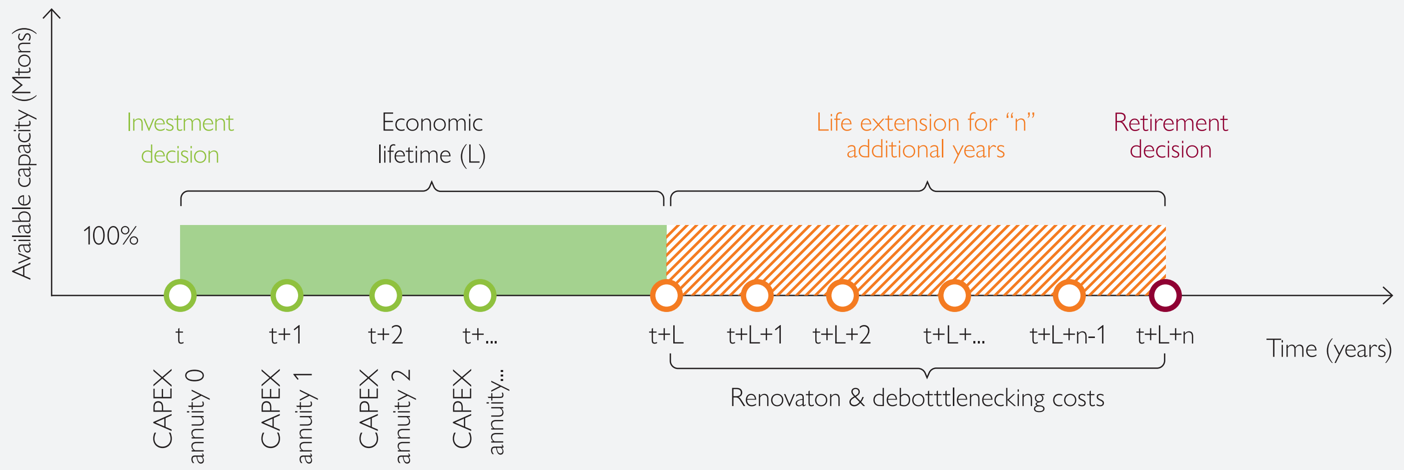
[84] Towler G., Sinnott R. (2013)/ Chapter 7 — Capital Cost Estimating, Chemical Engineering Design (Second Edition), Butterworth-Heinemann,2013, Pages 307-354, ISBN 9780080966595, https://doi.org/10.1016/B978-0-08-096659-5.00007-9

Economic lifetime

Every technology that is modelled in iC2050 has a limited economic lifetime. Capital investments are annualized over the economic lifetime of the technology. The WACC is used along with the economic lifetime to calculate the Capital Recovery Factor (CRF), which is used to annualise capital investments. It is not possible to close the newly installed capacities in the model before the end of their economic lifetime. After this period expires, the model has the choice to keep operating those capacities or shutting them down. To continue operating capacities beyond their economic lifetime, additional renovation and debottlenecking costs should be paid for every additional year of operation, as shown in the figure below.

Figure 18

Economic lifetime of capital investments



Direct process emissions

Direct emissions are differentiated into two categories: CO_2 and non-CO_2 emissions. The non-CO_2 emissions are measured in tons of $CO_{2\text{-eq}}$ and include: nitrous oxide (N_2O), methane (CH_4), HFCs, nitrogen trifluoride (NF_3), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6). Processes have a GHG intensity allocated to represent the amount of emissions (CO_2 or non-CO_2) that are released per unit of production.

Availability and technology readiness

The chemical industry continues to evolve and develop technologies that are more efficient and environmentally friendly. When selecting the technologies that were modelled in iC2050, the potential for commercial availability of those technologies before 2050 was taken into consideration. A minimum TRL of 5[85] was considered as the cut-off limit for selecting the technologies that are explicitly modelled in iC2050.

The modelled technologies have different technology availability dates, which restricts the model from deploying any new capacities before the technology becomes commercially available. The availability dates of technologies depend on several factors, which often involve some degree of uncertainty and hence, this parameter can be varied between different scenarios to reflect different patterns for technology development. The "Base Case" assumptions for technology availability are listed in Annex 2.

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[85] Source: European Commission. (2013). Horizon 2020. Work Programme 2014-2015. General annexes – G. Technology readiness level (TRL). h2020-wp1415-annex-g-trl_en.pdf

Resources

Each resource is available in a limited quantity, which reflects physical and policy constraints present in the represented scenario. The model includes more than 70 different technologies that transform raw materials into useful products or heat energy. In some cases such as steam crackers, the feedstock is converted into final products such as ethylene and propylene, and other co-products such as pygas and fuel gas, are utilised as feedstock and fuels.

The availability of fossil and bio-based resources is specified in the model as part of the scenario assumptions. The defined quantity sets the upper limit for resource consumption, ensuring that the amount of resources used cannot exceed what is available. Feedstock and fuels can either be sourced from the market or produced internally within the model.

Biomass availability

The limited availability of resources is a constraint that is implemented in the model to ensure that the scenario outcomes are realistically bound by physical limitations. Biomass resources are one of the possible materials that, if sourced sustainably, could be an alternative source of carbon-containing feedstock to the chemical industry. Biomass can be also utilised as a fuel source for heat generation in the model either through biomass boilers, or through biomethane boilers and furnaces.
The upper limit for biomass availability takes into account that a minimum sustainability criterion has to be achieved to source this biomass. An evaluation of the volumes of sustainable biomass available to the EU27 chemical industry has been performed based on a study by CE Delft that is presented in Annex 5.

Policies and ambition

The level of climate and circularity ambition is reflected in the form of constraints. Along with the climate-neutrality constraint that is implemented in 2050, intermediate targets can be set by constraining the maximum yearly emissions in the model for any year between 2019 and 2050. The emission cap can either be set over the total emissions that are included in the emission mode, or only on direct scope 1 emissions.

Direct emissions related to the chemical sector's activities have an associated carbon price, which penalises the objective function of the model. Introducing a carbon price into the scenario reflects the additional cost burden that is associated with CO_2 emitting technologies. This measure also prevents the model from delaying the deployment of abatement until the latest possible point in the modeling period.

Finally, a minimum share of non-fossil carbon can be implemented as a constraint into the model. The model also classifies every material under one of the three categories of carbon: fossil-based, bio-based, or circular. This allows tracking carbon flows within the industry up to the final product.

Annex 2

List of technologies

Table 13

Chemical production technologies

Product (and by-products)	Technology	Feedstock	Energy carrier	Conventional or new technology	Availability year
Ammonia	Haber-Bosch synthesis	Hydrogen Nitrogen	Electricity Natural Gas	Conventional	2019
Ammonia	Haber-Bosch synthesis with Air Separation Unit (external H_2)	Hydrogen Nitrogen	Electricity Natural Gas	New technology	2020
BTX (Benzene, Toluene and Xylene)	Benzene recovery through catalytic reforming	Reformate/ pyrolysis gas	Electricity Steam	Conventional	2019
BTX (Benzene)	Toluene hydrodealkylation	Toluene	Electricity Steam Fuel oil	Conventional	2019
BTX (Benzene)	Benzene recovery by adsorption	Pyrolysis gas / Coke oven gas	Electricity Steam	Conventional	2019
BTX (Benzene and Xylene)	Aromatic extraction from pyrolysis gasoline + disproportionation (TDP)	Reformate/ pyrolysis gas	Electricity Steam	Conventional	2019
Chlorine	Hydrogen chloride oxidation – Deacon process	Hydrogen chloride	Heat	Conventional	2019
Chlorine	Mercury Cell Electrolysis	Sodium chloride	Electricity Steam	Conventional	2019
Chlorine	Ion exchange membrane electrolysis	Sodium chloride	Electricity Steam	Conventional	2019
Ethylene	Bioethanol dehydration	Ethanol	Electricity Heat	New technology	2019
Ethylene (+ propylene and other C4s)	Methanol-to-olefins	Methanol	Electricity Heat	New technology	2019
Ethylene oxide	Catalytic ethylene oxidation	Ethylene	Electricity	Conventional	2019
High Value Chemicals (Ethylene, propylene, BTX)	Steam cracking	Naphtha/ ethane/ LPG	Heat Electricity	Conventional	2019

Product (and by-products)	Technology	Feedstock	Energy carrier	Conventional or new technology	Availability year
High Value Chemicals (Ethylene, propylene, BTX)	Partial electrified steam cracking	Naphtha/ ethane/ LPG	Heat Electricity	New technology	2030
High Value Chemicals (Ethylene, propylene, BTX)	Electrified steam cracking	Naphtha/ ethane/ LPG	Electricity	New technology	2035
Methanol	Dry methane reforming	Methane	Heat Electricity	New technology	2025
Hydrogen (+solid carbon)	Methane pyrolysis	Methane	Electricity	New technology	2030
Hydrogen	Steam Methane Reforming (SMR)	Methane	Electricity Fuel oil	Conventional	2019
Methanol	Carbon dioxide hydrogenation	Hydrogen CO_2	Electricity	New technology	2025
Methanol	Biomass gasification with methanol synthesis	Lignocellulosic Biomass	Electricity	New technology	2019
Methanol	Mixed plastic waste gasification to methanol	Residue-derived fuel (RDF)[86]	Electricity	New technology	2019
Mono-ethylene glycol (MEG)	Ethylene oxide hydration	Ethylene oxide	Electricity	Conventional	2019
Polyethylene Terephthalate	PET polymerization	Ethylene glycol Terephthalic Acid	Steam Electricity Fuel oil	Conventional	2019
Syngas/Hydrogen	Auto Thermal Reforming of Natural gas	Natural gas	Electricity	New technology	2025
Propylene	Propane Dehydrogenation (PDH)	LNG	Electricity Heat	Conventional	2019
Propylene	Fluid catalytic cracking	Crude oil	Electricity Steam	Conventional	2019
Propylene	Olefin metathesis or ethylene dimerization	Ethylene	Electricity Fuel oil	Conventional	2019
PET (Polyethylene Terephthalate)	Polyesterification (PTA-EG route)	Purified Terephthalic Acid (PTA) Monoethylene Glycol (MEG)	Heat Electricity	Conventional	2019
Polyethylene	Catalytic ethylene polymerization	Ethylene	Heat Electricity	Conventional	2019
Polypropylene	Polypropylene polymerisation	Propylene	Heat Electricity	Conventional	2019
Polystyrene	Styrene polymerization	Styrene	Heat Electricity	Conventional	2019
Polystyrene	Polystyrene recycling by dissolution	Brominated PS and e-waste PS	Electricity	New technology	2019
Purified Terephthalic Acid (PTA)	Paraxylene oxidation	Xylene	Steam Electricity Fuel oil	Conventional	2019
Polyvinyl chloride (PVC)	Paraxylene oxidation	Ethylene Chlorine	Steam Electricity Fuel oil	Conventional	2019
Styrene	Alkylation of benzene with ethylene (EB/SM)	Ethylene Benzene	Electricity Fuel oil Steam	Conventional	2019
Styrene	Propylene oxide/ Styrene monomer process (PO/SM)	Propylene	Electricity Fuel oil Steam	Conventional	2019
Styrene	Polystyrene recycling by pyrolysis	Polystyrene	Electricity Steam	New technology	2019

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[86] A type of solid fuel produced from unsorted mixed municipal solid waste streams

Table 14

Carbon capture technologies

Carbon capture technologies	Availability year
CO_2 capture in high-concentration streams	2025
CO_2 capture in low-concentration streams	2025

Table 15

Feedstock production technologies

Product	Feedstock production technologies	Feedstock	Availability year
Biomethane	Biomass gasification	Agricultural residues	2019
Bionaphtha	Biomass gasification with Fischer-Tropsch	Woody biomass	2019
Bioethanol	Enzymatic hydrolysis and fermentation	Lignocellulosic biomass	2019
Bioethanol	Fermentation-based ethanol production	Sugar crops	2019
Py-naphtha	Plastic waste pyrolysis for mixed plastic waste	Mixed plastic waste	2026
R-PET	Chemical recycling to Bis(2-hydroxyethyl) terephthalate(B-HET) (PET monomer)	End-of-life PET	2019

Table 16

Heat generation technologies

Heat generation technologies	Availability year
Natural gas boiler	2019
Oil boiler	2019
Natural gas furnace	2019
Electric boiler	2019
Hydrogen boiler	2019
Hydrogen burners	2019
Biomass boiler	2019
Integrated fuel gas furnace	2019

Table 17

Classification of technologies by low or high concentration of CO_2 in the flue gas

Technology	Low purity/concentration of CO_2	High purity/concentration of CO_2
Biomass gasification with methanol synthesis	Yes	
Biomass boiler	Yes	
Enzymatic hydrolysis and fermentation		Yes
Fermentation-based ethanol production		Yes
SMR with catalytic methanol syntesis	Yes	
Haber-Bosch ammonia synthesis		Yes
Steam methane reforming	Yes	
Natural gas boiler	Yes	
Oil boiler	Yes	
Catalytic ethylene oxidation		Yes
Fluid catalytic cracking	Yes	
Rest of the industry	Yes	
Polystyrene recycling by dissolution	Yes	
Plastic waste pyrolysis for mixed plastic waste	Yes	
Chemical recycling to B-HET (PET monomer)	Yes	
Polystyrene recycling by pyrolysis	Yes	
Natural gas furnace	Yes	
Integrated fuel gas furnace	Yes	
ATR from fuel gas		Yes
ATR from natural gas		Yes
Incineration	Yes	
Mixed plastic waste gasification to methanol	Yes	

Annex 3

Technology assumptions

Table 18

Technology Purchase Cost of Equipment (PCE) Assumptions (Mio €$_{2019}$/Mton or GW$_{th}$)

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Ammonia from Haber-Bosch with green H_2		350	350	350	350	350	350	350	Morgan (2017), ECN (2017)
Biomass gasification	4,228.687	4,228.687	3,467.524	2,706.36	2,664.073	2,621.786	2,579.499	2,537.212	Danish Energy Agency (2021)
Liquid fuels from biomass gasification and Fischer-Tropsch	6,613.757	6,613.757	6,283.069	5,952.381	5,740.262	5,528.143	5,409.574	5,291.005	Danish Energy Agency (2021)
Bioethanol from cellulosic biomass	5,543.956	5,543.956	4,019.368	2,494.78	2,342.321	2,189.862	2,134.423	2,078.983	Danish Energy Agency (2021)
Bioethanol from sugar fermentation	704.524	704.524	690.433	676.343	661.419	646.495	645.487	644.479	Danish Energy Agency (2021)
Bioethanol dehydration	433.333	433.333	433.333	433.333	433.333	433.333	433.333	433.333	Uslu et al. (2021)
Methanol -to-Olefins	1,248.809	1,248.809	1,248.809	1,248.809	1,248.809	1,248.809	1,248.809	1,248.809	Uslu et al. (2021)
Electric boiler	115	115	112.154	109.378	106.67	104.03	101.455	98.944	Danish Energy Agency (2021)
Hydrogen boiler	238.391	238.391	238.391	238.391	238.391	238.391	238.391	238.391	Rutten (2020)
Hydrogen burner	359.377	359.377	359.377	359.377	359.377	359.377	359.377	359.377	Romgems et Dams (2018)
Biomass boiler	121.105	121.105	118.108	115.184	112.333	109.553	106.841	104.197	Towler et Sinott (2013)
Steam cracker	192.9	192.9	192.9	192.9	192.9	192.9	192.9	192.9	Based on IEA (2020), Spallina et al. (2017)
Partially electrified steam cracker				265.228	265.228	265.228	265.228	265.228	Own assumptions based on DNV GL (2018), Navigant (2019)
Electrified Steam Cracker				522.5	522.5	522.5	522.5	522.5	Own assumptions based on DNV GL (2018), Navigant (2019)
Alkaline electrolysis		13,850.83	10,419.61	6,988.398	5,074.703	3,161.008	3,161.008	3,161.008	IRENA (2018)
Blue H_2 via ATR from natural gas			2,230.009	2,230.009	2,230.009	2,230.009	2,230.009	2,230.009	H-vision (2019)
Blue H_2 via ATR from fuel gas			2,230.009	2,230.009	2,230.009	2,230.009	2,230.009	2,230.009	H-vision (2019)

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Methane pyrolysis				3,500	3,150	2,800	2,520	2,520	Dechema (2019)
Methanol from CO_2 and H_2	292.156	291.69	289.362	287.034	284.706	282.377	280.049	277.721	Nyari (2020)
Methanol from biomass via syngas	1,456.326	1,456.326	1,456.326	1,456.326	1,456.326	1,456.326	1,456.326	1,456.326	Uslu et al. (2021)
Methanol from mixed plastic waste gasification		1,800	1,631.027	1,462.054	1,462.054	1,462.054	1,462.054	1,462.054	Iaquaniello et al (2017)
Polystyrene chemical recycling by dissolution	2,270.731	2,270.731	1,339.962	1,339.962	1,339.962	1,339.962	1,339.962	1,088.387	PBL (2021)
PET chemical recycling by solvolysis	1,179.679	1,179.679	1,179.679	727.902	727.902	727.902	727.902	591.24	PBL (2021)
Polystyrene pyrolysis	1,731.56	1,731.56	1,731.56	1,068.431	1,068.431	1,068.431	1,068.431	867.836	Bassil et al. (2018)

Table 19

Technology maintenance cost assumptions (Mio $€_{2019}$ /Mton or GW_{th})

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Ammonia from Haber-Bosch with green H_2		8.75	8.75	8.75	8.75	8.75	8.75	8.75	Morgan (2017)
Biomass gasification	67.997	67.997	56.157	44.317	43.429	42.541	41.653	40.765	Danish Energy Agency (2021)
Liquid fuels from biomass gasification and Fischer-Tropsch	158.73	158.73	158.73	158.73	157.764	156.798	157.764	158.73	Danish Energy Agency (2021)
CCS Low purity	18.017	18.017	15.388	14.229	13.158	12.168	11.252	10.405	Lensink (2021)
CCS High purity	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	Lensink (2021)
Bioethanol from cellulosic biomass	106.328	106.328	79.746	53.164	53.357	53.55	53.357	53.164	Danish Energy Agency (2021)
Bioethanol from sugar fermentation	56.751	56.751	56.751	56.751	56.751	56.751	56.751	56.751	Danish Energy Agency (2021)
Bioethanol dehydration	21.667	21.667	21.667	21.667	21.667	21.667	21.667	21.667	Uslu et al. (2021)

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Methanol -to-Olefins	62.44	62.44	62.44	62.44	62.44	62.44	62.44	62.44	Uslu et al. (2021)
Electric boiler	1.132	1.132	1.105	1.079	1.053	1.026	1	0.973	Danish Energy Agency (2021)
Hydrogen boiler	4.189	4.189	4.189	4.58	4.58	4.58	4.58	4.58	Romgems et Dams (2018)
Hydrogen burner	3.594	3.594	3.594	3.594	3.594	3.594	3.594	3.594	Rutten (2020)
Biomass boiler	1.132	1.132	1.105	1.079	1.053	1.026	1	0.973	Towler et Sinott (2013)
Steam cracker	19.293	19.293	19.293	19.293	19.293	19.293	19.293	19.293	Based on IEA (2020), Spallina et al. (2017)
Partially electrified steam cracker				1.326	1.326	1.326	1.326	1.326	Own assumptions based on DNV GL (2018), Navigant (2019)
Electrified Steam Cracker				2.6125	2.6125	2.6125	2.6125	2.6125	Own assumptions based on DNV GL (2018), Navigant (2019)

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Methane pyrolysis				175	175	175	175	175	Dechema (2019)
Methanol from CO_2 and H_2	5.843	5.879	6.056	6.233	6.411	6.588	6.766	6.943	Szima & Cormos (2018), Nyari (2020)
Methanol from biomass via syngas	72.816	72.816	72.908	73	73	73	73	73	Uslu et al. (2021)
Methanol from mixed plastic waste gasification		66.667	60.408	54.15	54.15	54.15	54.15	54.15	Iaquaniello et al (2017)
Polystyrene chemical recycling by dissolution	274.191	274.191	274.191	274.191	274.191	274.191	274.191	274.191	PBL (2021)
PET chemical recycling by solvolysis	154.403	154.403	154.403	154.403	154.403	154.403	154.403	154.403	PBL (2021)
Polystyrene pyrolysis	456.3	456.3	456.3	456.3	456.3	456.3	456.3	456.3	Bassil et al. (2018)

Table 20

Variable costs (excluding energy and feedstock) (Mio €$_{2019}$/Mton of product or Mio €$_{2019}$/PJ of heat production)

Process	2019	2020	2025	2030	2035	2040	2045	2050	Source
Biomass gasification	33.999	33.999	28.078	22.158	21.714	21.27	20.826	20.382	Danish Energy Agency (2021)
Liquid fuels from biomass gasification and Fischer-Tropsch	12.987	12.987	12.987	12.987	12.994	13	12.994	12.987	Danish Energy Agency (2021)
Bioethanol from cellulosic biomass	0.025	0.025	0.019	0.013	0.013	0.013	0.013	0.013	Danish Energy Agency (2021)
Bioethanol from sugar fermentation	56.751	57.933	57.933	57.933	57.933	57.933	57.933	57.933	Danish Energy Agency (2021)
Electric boiler	0.147	0.147	0.147	0.147	0.132	0.118	0.118	0.118	Danish Energy Agency (2021)
Biomass boiler	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	Towler et Sinott (2013)
Methanol from CO_2 and H_2	8.793	8.793	8.793	8.793	8.793	8.793	8.793	8.793	Perez-Fortes et Tzimas (2016)
Polystyrene chemical recycling by dissolution	266.585	266.585	266.585	266.585	266.585	266.585	266.585	266.585	PBL (2021)
PET chemical recycling by solvolysis	264.345	264.345	264.345	264.345	264.345	264.345	264.345	264.345	PBL (2021)
Polystyrene pyrolysis	242.619	242.619	242.619	242.619	242.619	242.619	242.619	242.619	Bassil et al. (2018)

Table 21

Cost assumptions for mixed plastic waste pyrolysis

Technology	Scenario	Parameter	Year								Source
			2019	2020	2025	2030	2035	2040	2045	2050	
Plastic waste pyrolysis for mixed plastic waste	Other Scenarios	Purchase cost of equipment (PCE) [Mio€/Mtons Cap.]	1452,74	1452,74	1316,37	1179,99	1069,22	958,45	958,45	958,45	Based on: — Oliveira Machado Dos Santos (2020) — Fiviga, A., Dimitriou (2018) — Netherlands institute for sustainable packaging. KIVD (2018)
		Maintenance cost [Mio€/Mtons Cap.]	533,33	533,33	533,33	533,33	533,33	533,33	533,33	533,33	
		Variable cost [Mio€/Mtons Prod.]	67,73	67,73	67,73	67,73	67,73	67,73	67,73	67,73	
	Waste recycling and Feedstock Targets scenarios	Purchase cost of equipment (PCE) [Mio€/Mtons Cap.]	1147,885	1147,885	1040,128	932,372	888,6093	844,8467	801,084	757,3214	
		Maintenance cost [Mio€/Mtons Cap.]	380,9524	380,9524	380,9524	380,9524	380,9524	380,9524	380,9524	380,9524	
		Variable cost [Mio€/Mtons Prod.]	48,38095	48,38095	48,38095	48,38095	48,38095	48,38095	48,38095	48,38095	

Annex 4

Resource characteristics

Table 22

Assumed GHG intensity per type of feedstock (tCO$_{2\text{-eq}}$/Mton of feedstock)

Raw material	2019	2020	2025	2030	2035	2040	2045	2050	Source
Agr. residues	41,975	41,975	37,778	33,580	29,383	25,185	20,988	16,790	CE Delft assumptions based on CE Delft and RH DHV (2020)
Biomethane	50,000	50,000	45,000	40,000	35,000	30,000	25,000	20,000	Own assumptions based on CE Delft and RH DHV (2020)
Crude oil	470,781	470,781	362,224	212,682	151,536	90,390	66,463	42,536	2019-2020: Own assumptions based on IHS Markit data Post-2020: Own assumptions based on IEA — The Oil and Gas Industry in Net Zero Transitions (NZE) (2023)
Fuel oil	470,781	470,781	362,224	212,682	151,536	90,390	66,463	42,536	
Hydrogen	8,024,554	8,024,554	8,131,219	782,834	698,018	613,202	552,407	491,613	IEA (2019), IFPen, SINTEF, Deloitte (2021)
Ligno. biomass	274,375	274,375	246,938	219,500	192,063	164,625	137,188	109,750	CE Delft assumptions based on CE Delft and RH DHV (2020)
Naphtha	589,146	589,146	453,295	266,155	189,636	113,116	83,173	53,231	2019-2020: Own assumptions based on IHS Markit data Post-2020: Own assumptions based on IEA — The Oil and Gas Industry in Net Zero Transitions (NZE) (2023)
NG	244,476	244,476	188,102	110,445	78,692	46,939	34,514	22,089	
NGL	804,010	804,010	618,615	363,224	258,797	154,370	121,680	72,645	
RDF	50,000	50,000	45,000	40,000	35,000	30,000	25,000	20,000	CE Delft assumptions based on CE Delft and RH DHV (2020)
Sugar crops	27,079	27,079	24,372	21,664	18,956	16,248	13,540	10,832	CE Delft assumptions based on CE Delft and RH DHV (2020)
Woody biomass	230,159	230,159	207,143	184,127	161,111	138,095	115,079	92,064	CE Delft assumptions based on CE Delft and RH DHV (2020)
CCU other ind.	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	CE Delft assumptions based on CE Delft and RH DHV (2020)

Table 23

Assumed import emissions ($tCO_{2-eq}/Mton$)

Product	2019	2020	2025	2030	2035	2040	2045	2050	Source
Ammonia	1,987,421	1,987,421	1,663,799	1,340,177	944,215	548,254	308,393	68,532	For 2019-2020: Own assumptions based on IHS Markit data Post-2020: Own assumptions based on IEA Net Zero by 2050 (NZE) report (IEA, 2021)
Benzene	716,110	716,110	638,419	560,728	435,746	310,765	168,894	27,023	
Chlorine	1,408,518	1,408,518	1,255,707	1,102,896	857,070	611,244	332,198	53,152	
Ethylene	2,617,128	2,617,128	2,333,194	2,049,260	1,592,497	1,135,735	617,247	98,760	
Ethylene oxide	2,833,974	2,833,974	2,526,514	2,219,055	1,724,446	1,229,838	668,390	106,942	
Hydrogen	9,651,690	9,651,690	8,080,055	6,508,419	4,585,477	2,662,535	1,497,676	332,817	
MEG	2,090,439	2,090,439	1,863,646	1,636,853	1,272,013	907,172	493,028	78,884	
Methanol	495,231	495,231	430,220	365,209	281,077	196,945	107,077	17,209	
Propylene	2,087,773	2,087,773	1,861,270	1,634,766	1,270,390	90,6015	49,2399	78,784	
PTA	2,452,946	2,452,946	2,186,825	1,920,703	1,492,595	1,064,486	57,8525	92,564	
Styrene	2,189,317	2,189,317	1,951,797	1,714,276	1,332,179	950,081	516,348	82,616	
Toluene	1,141,132	1,141,132	1,017,330	893,528	694,368	495,208	269,135	43,062	
Xylene	1,440,176	1,440,176	1,283,930	1,127,685	876,333	624,982	339,664	54,346	

Table 24

Price of biomass resources

Raw material	Price unit	2019	2020	2025	2030	2035	2040	2045	2050	Source
Agr. residues	$€_{2019}$/GJ	Confidential			5.353	5.471	5.588	5.706	4.941	Ruiz et al. (2019)
Biodiesel	$€_{2019}$/kg				0.858	0.858	0.858	0.858	0.858	OECD/ FAO (2020)
Biomethane	$€_{2019}$/MWh				30.643	25.643	25.643	25.643	46.714	IEA (2020)
Bio-naphtha	$€_{2019}$/kg				0.663	0.663	0.663	0.663	0.893	Trading Economics (2021)
Ligno. biomass	$€_{2019}$/GJ				11.647	11.824	11.647	11.471	12.412	Ruiz et al. (2019)
Sugar crops	$€_{2019}$/GJ				5.294	5.353	5.471	5.588	5.706	Ruiz et al. (2019)
Woody biomass	$€_{2019}$/GJ				3.882	3.647	3.412	3.294	3.176	Ruiz et al. (2019)

Table 25

Assumptions for fossil feedstock availability in Mtons per year

Resource	2020	2025	2030	2035	2040	2045	2050	Source
CO_2	0	99,01	198,02	156,83	115,64	96,10	76,55	The CO_2 availability is based on Deloitte's analysis based on: Chan et al. (2019) FuelsEurope (2019) EUROFER (2019) CEMBUREAU (2020) Fossil feedstock availabilies are based on own assumptions.
Crude oil	79,27	79,27	79,27	79,27	79,27	79,27	79,27	
Fuel oil	1000	1000	1000	1000	1000	1000	1000	
Naphtha	185,56	185,56	185,56	185,56	185,56	185,56	185,56	
Natural gas	35	30,33	24,50	22,75	21,00	19,25	17,50	
LPG	30	26	21	19,50	18,00	16,50	15,00	
Reformate gasoline	79	79	79	79	79	79	79	
Coke oven gas	35	30	25	23	21	19	18	
Ethane	30	26	21	20	18	17	15	

Annex 5

Detailed explanation on estimation biomass potential in the EU27

This annex summarises the methodology to estimate the availability of sustainable biomass for the European chemical industry for the period between 2020 to 2050, is based on a literature study.

Approach

Time period

The estimation of biomass availability covers the period from 2020 to 2050, with a granularity of five-year intervals. Most data sources do not provide such a detailed timeline. They rather look at the biomass potential in one or several decades in the future (mostly 2030 and/or 2050). Based on these data, we provide an estimate of the development over time.

Geographical scope

The estimation of total sustainable biomass availability is split up geographically in two parts: biomass produced in the EU, and biomass imported from the rest of the world. Biomass demand from other sectors, is estimated for the EU only.

Sustainable potential

Various types of biomass potential can be identified. The two primary types assessed in the literature are 'technical potential' and 'sustainable potential'. The technical potential refers to the quantity of biomass that could be technically supplied, considering the technical and physical limitations of production, collection, and transport, while excluding biomass used for food, animal feed, and clothing production. Regarding forestry, trees used for the wood processing industry are often excluded from the technical potential estimation as well, when considering the availability of forestry streams for energy production or as feedstock.

The sustainable potential represents the amount of biomass that could be supplied in a sustainable way. Because different sustainability criteria can be considered here, many different definitions of 'sustainable biomass potential' exist. The overall sustainable biomass potential is considerably lower than the overall technical potential because the harvesting of trees and plants that lead to environmental damage (according to the applied definition of sustainability) are not included in the sustainable potential.

In this report and project, we only consider the sustainable biomass potential.

Biomass categories

Different generic biomass categories can be distinguished. One common way of differentiation is to look at the origin of the biomass:

- Production streams for agriculture
- Residual streams from agriculture
- Production streams for forestry
- Residual streams from forestry
- Production streams for aquaculture
- Residual streams from aquaculture

In the residual streams, a further distinction can be made between primary, secondary and tertiary residue streams. Primary residues are typically parts of plants that are left behind on the field or in a forest after harvest, secondary residues are biomass residues that remain behind in a production process (e.g. in a sawmill), tertiary residues are biomass products usually interpreted as waste, such as organic waste from households[87].

Each biomass category consists of various subcategories and types of feedstocks. For instance, agricultural production streams encompass subcategories such as sugar crops, starch crops, oil crops, and lignocellulosic crops. Unfortunately, different organisations and studies use different categorisations.

When considering the suitability of each of these biomass categories for use in the chemical industry, it seems that all could be used as a feedstock and/or as an energy source. Therefore, we did not exclude any biomass category from our analysis[88]. However, not all types of biomass considered here are suitable for each and every processes considered in the iC2050.

Methodology

The main research steps are listed below and visualised in Figure 19. These lead to an estimation of the sustainable biomass potential for the European chemical industry, in the form of quantitative scenarios for 2020 to 2050 with a five-year interval.

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[87] Source: CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

[88] Note that aquatic biomass is not considered here. Research into large-scale production is ongoing but still at an early stage, so that reliable estimates for future growth of this potential do not yet exist.

1) Estimation of the sustainable biomass potential produced in the EU: For this first step, we used the ENSPRESO dataset on biomass from the JRC (JRC, 2020), which has been compiled for the purpose of energy modelling (Ruiz et al, 2019). This dataset includes a large list of biomass categories with three different sustainability scenarios, and estimations for various years. It was also confirmed that the data are in line with a number of other contemporaneous studies, such as (CE Delft and RH DHV, 2020) and (EC, 2020). The database was developed for energy modelling purposes, not feedstock for the (chemical) industry, but both applications use the same types of biomass. The data therefore represent the sustainable biomass potential for both energy and feedstocks. We have adopted these scenarios, and added estimations for the missing years, by means of interpolation.

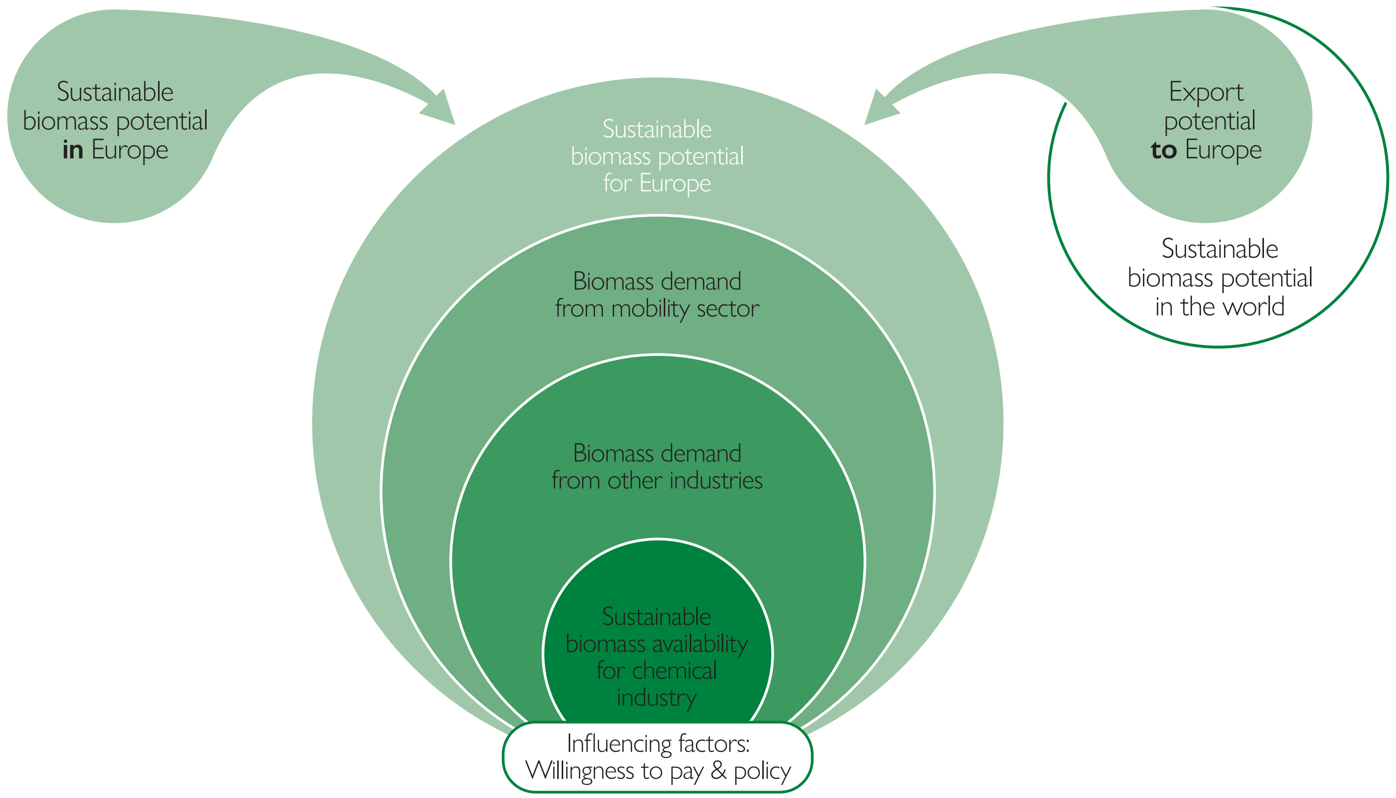
2) Estimation of the import potential to the EU: to estimate the amount of sustainable biomass that could be imported to the EU from the rest of the world, we first looked at the results of a literature study of the global sustainable biomass potential that was carried out within the Dutch 'Bio-Scope' project[89]. To allow for comparison with the EU potential found in the previous step, these results are adapted to the biomass categorisation used in ENSPRESO. Next, we looked at the results of a literature study of sustainable biomass import potential in the EU that was performed within the European ADVANCEFUEL project[90]. We then combined the Bioscope and ADVANCEFUEL estimations and used them to estimate the sustainable biomass EU import potential for future decades.

3) Estimation of the total biomass potential available for the EU: We added up the biomass potential produced in the EU and the import potential in the EU to get a total sustainable biomass potential available for EU in future years.

4) Assessment of competing demand for sustainable biomass, resulting in three scenarios for sustainable biomass availability for the European chemical industry: In this step, we first assessed how the demand for sustainable biomass will develop in other sectors and industries in the EU between now and 2050. This then led to an estimate of how much of the total sustainable biomass potential available for the EU could be directed to the European chemical industry. These final amounts have been used in the various scenarios.

Figure 19

Research steps



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[89] Source: CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

[90] Source: Hoefnagels R., Germer S. (2018). Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels — D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels.

Sustainable biomass potential production in the EU

The ENSPRESO biomass dataset[91] includes a large list of biomass categories, three different sustainability scenarios, and estimations for various years.

We adopted both the biomass categorisation and the set of scenarios used by the JRC. The three JRC scenarios, called 'High', 'Medium' and 'Low', use a different set of assumptions that relate to the strictness of the applied sustainability criteria and the productivity of agriculture and forestry. Key parameters that vary between the different scenarios are[92]:

- Productivity of energy crops: available crops land, yields increase for biomass.
- The share of agricultural residues available for energy and feedstock, which depends on the competition for alternative use, the collection ratio of residues, harvest ratios for pruning, straw, etc.
- Timber demand and harvesting techniques.
- Competing use for stem wood and residues from forestry, wood and pulp & paper industries.
- Collection ratio and competing uses of various biomass waste streams.

To illustrate the rationale behind the scenarios:

- The **'Low scenario'** applies the strictest sustainability criteria and is also the most conservative in productivity rate increases. Moreover, it is assumed that fewer policy stimulation measures are in place, leading to lower levels of mobilisation of domestic biomass supply.
- In the **'Medium scenario',** the total sustainable biomass potential remains relatively stable over time. Biomass streams from agriculture and forestry have a similar contribution. The potential in the Medium scenario is estimated to be 1.4 to 1.6 times higher than the potential in the Low scenario.
- The potential in the **'High scenario'** is 2.2 to 2.8 times higher than in the Low scenario.

The range in biomass availability is mainly due to different estimates of the potential for primary forestry residues, followed by lignocellulosic crops, agricultural residues and manure.

Table 26

Sustainable biomass potential in the EU in all scenarios, based on JRC[91] (Mtons dry matter)

	2020	2030	2040	2050
Low scenario				
Agriculture	219	235	246	248
Forestry	228	193	193	164
Total	**447**	**428**	**440**	**412**
Medium scenario				
Agriculture	304	337	345	350
Forestry	304	276	279	294
Total	**608**	**613**	**623**	**644**
High scenario				
Agriculture	447	501	519	535
Forestry	556	575	580	610
Total	**1.003**	**1.077**	**1.099**	**1.145**

Chart 107

Sustainable biomass potential in the EU, in the Low scenario (Mtons dry matter)

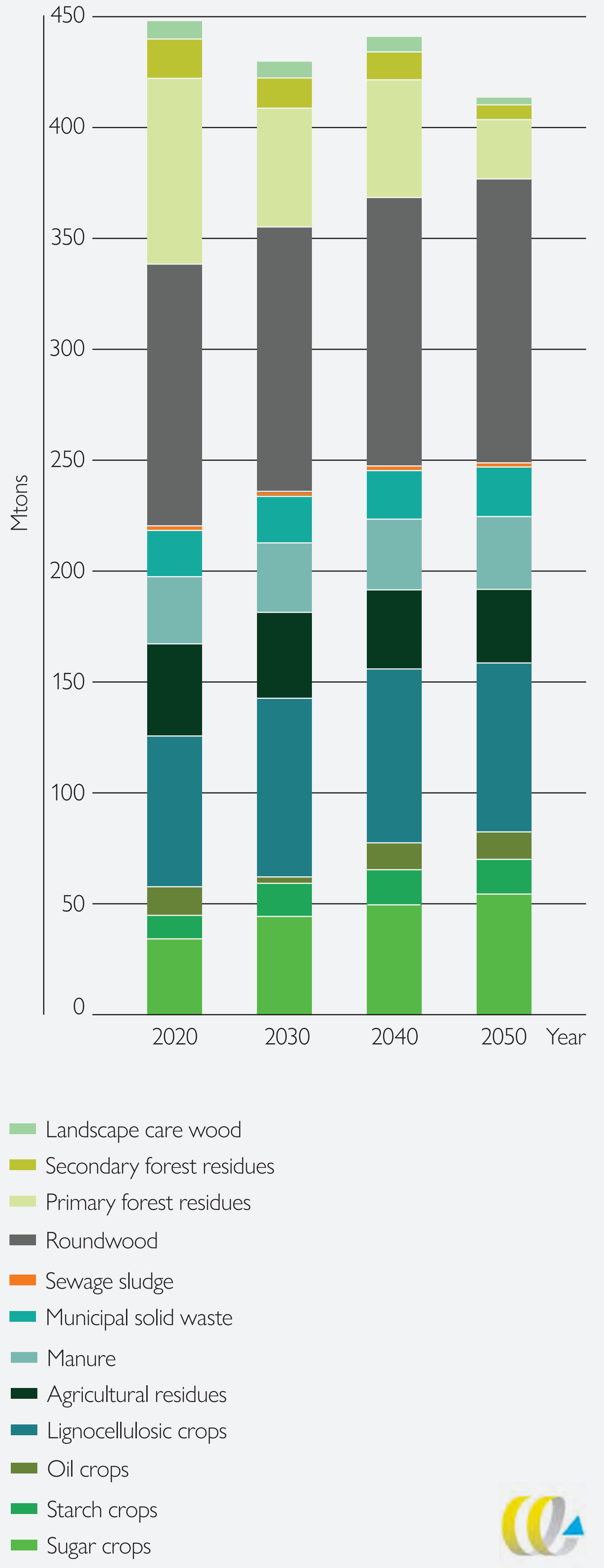
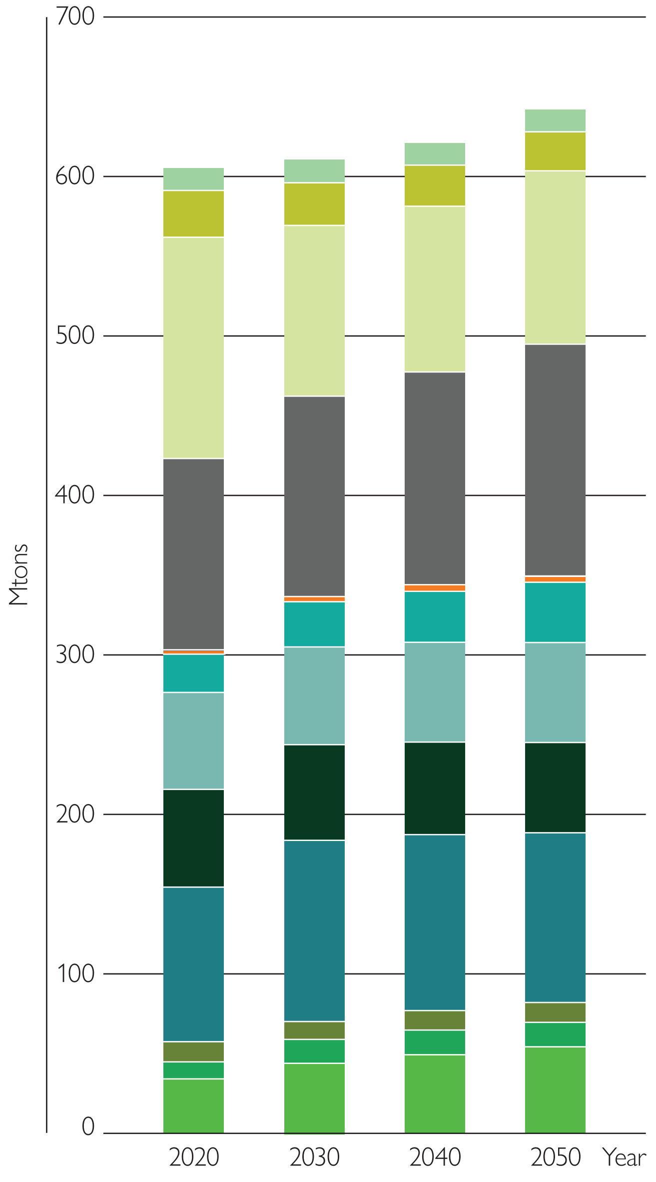


Chart 108

Sustainable biomass potential in the EU, in the Medium scenario (Mtons dry matter)



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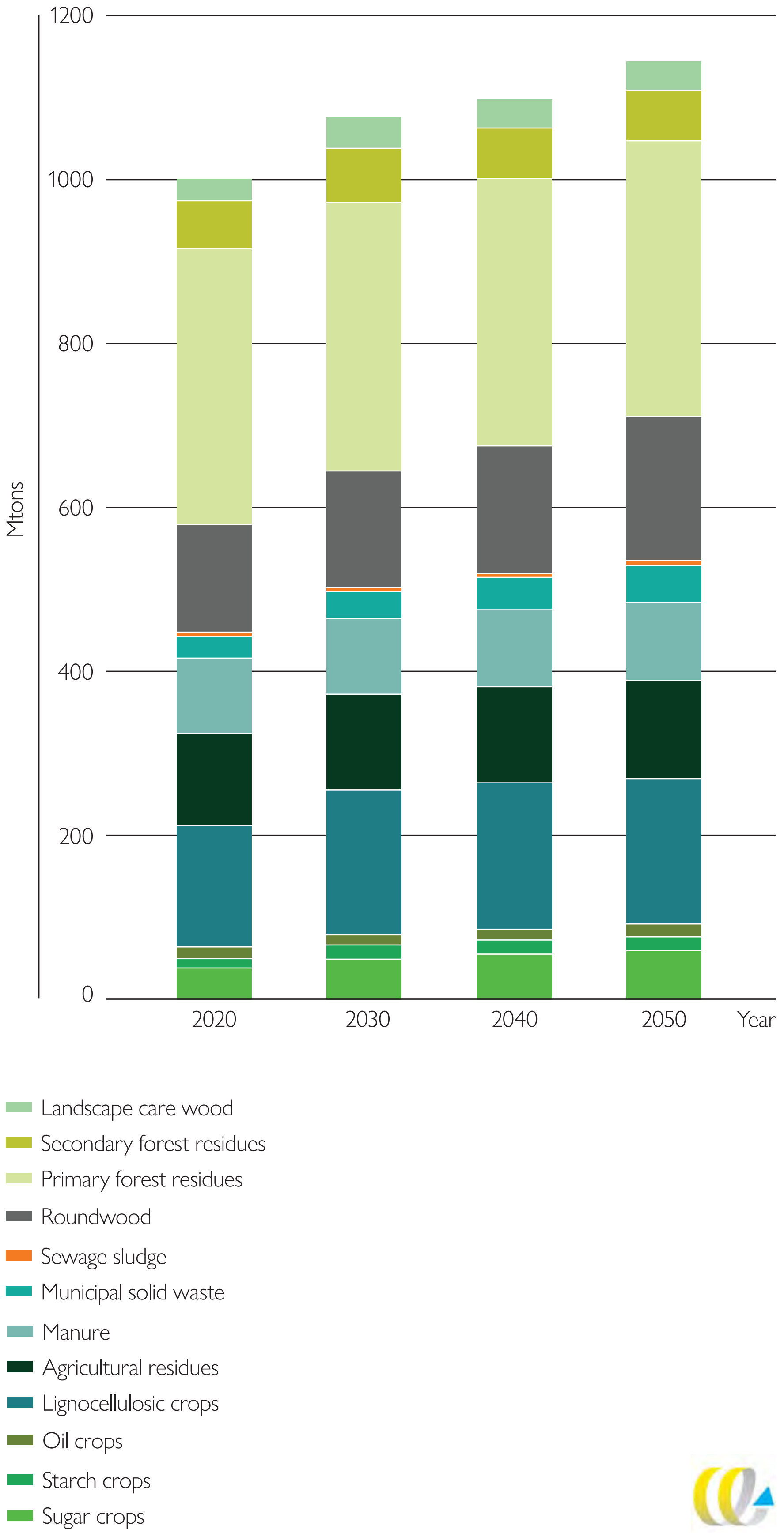
[91] Source: Ruiz P. (2019). ENSPRESO — BIOMASS. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f

[92] Source: Ruiz P. (2019). ENSPRESO — BIOMASS. European Commission, Joint Research Centre (JRC) [Dataset] PID: http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f

To confirm that these data are realistic, we compared them to the findings in the Bio-Scope study[92].

Chart 109

Sustainable biomass potential in the EU, in the High scenario (Mtons dry matter)



[92] CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

Import potential of sustainable biomass to the EU

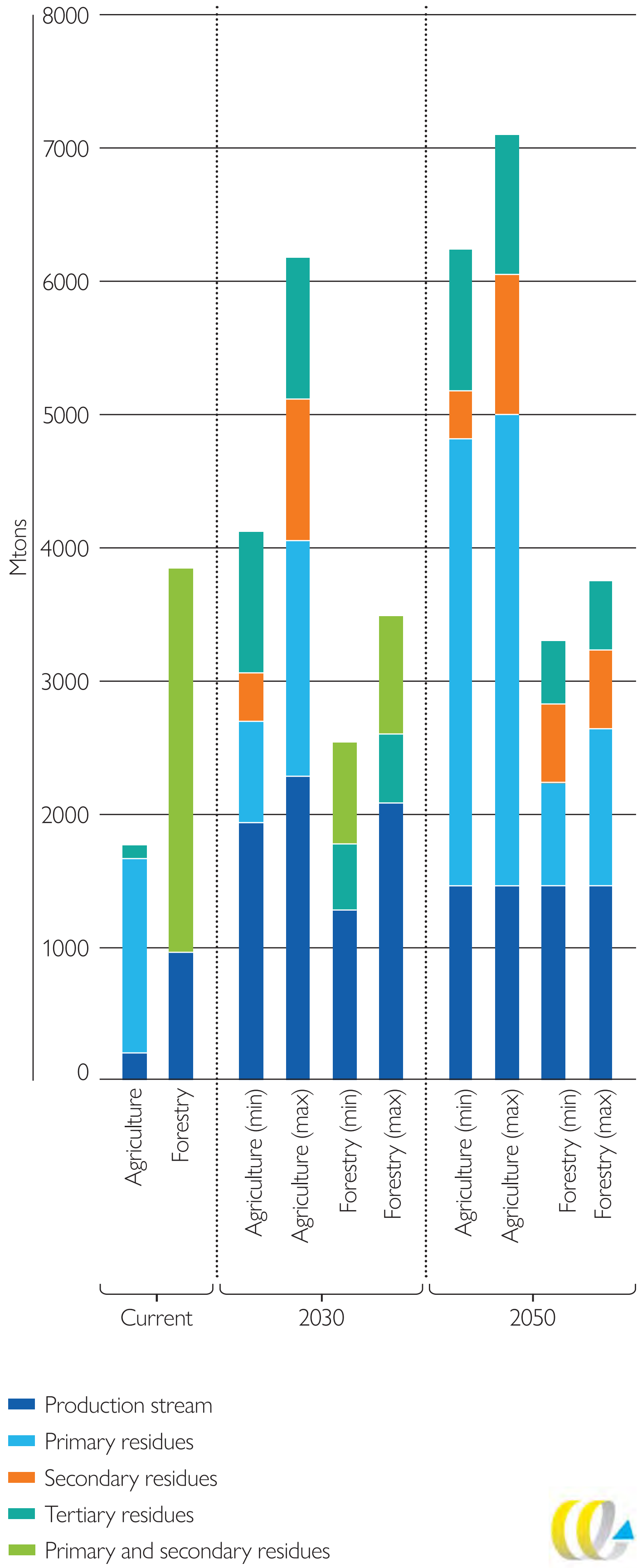
To estimate the import potential of sustainable biomass to the EU, we first estimated the global sustainable biomass production potential, excluding the European potential. Secondly, we estimated which part of the biomass potential in the rest of the world could become available for imports in by the EU.

Global production potential including the EU

The Bio-Scope study[93] included an extensive literature analysis regarding the global biomass potential that could become available as a source for energy and industry feedstock. The main results from the Bio-Scope literature study on the global sustainable biomass potential are shown in Chart 110.[94]

Chart 110

Sustainable biomass potential worldwide (Mtons dry matter)



[93] CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

[94] For an overview of the literature that was assessed to arrive at these data, we refer to CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

These results show that the global sustainable potential in agriculture in 2030 could be a factor 2.5 to 3.5 larger than current biomass production, and the sustainable potential in forestry. More efficient farming and the use of degraded lands for agriculture may improve biomass production, but a growing world population and a possible reduction of arable land due to soil depletion, desertification and flooding may cancel out such developments.

Similarly, we see that the maximum potential from forestry in 2050 is similar to 2030, indicating that the availability of sustainable biomass from forests may not increase significantly. In many climate modelling scenarios from the Intergovernmental Panel on Climate Change (IPCC) and other institutes, afforestation and forest conservation are important measures to mitigate global warming, limiting the availability of forest resources for our economies. These measures are also important to protect ecosystems. Therefore, it is well conceivable that the sustainable potential of biomass from forestry will stabilise between 2030 and 2050, despite possible improvements in forestry management.

Potential in the rest of the world (outside the EU)

Based on these data, we estimated the sustainable biomass production in the rest of the world outside the EU. Results are shown in Table 26. These were estimated taking the following steps:

- The main input data is formed by the global biomass potential reported above, from the Bio-Scope study.
- We subtracted the Bio-Scope estimations of the EU potential from the global biomass potential estimations from the same study. The resulting values represent an estimation of the potential in the rest of the world.
- Next, we reclassified the biomass categories that were used in Bio-Scope to match the categories list used in JRC ENSPRESO[95], and adapted the data accordingly. This involved the following:
  - The agricultural production stream from Bio-Scope was divided into sugar crops, starch crops and oil crops using the shares of these biomass types that were given in the ENSPRESO data for the EU.
  - The potential for lignocellulosic crops was not included in the Bio-Scope data and needed to be added. For 2050, a potential of 3.6-57 EJ was estimated, which is based on estimation of 'global tradable resources' in Committee on Climate Change report "Biomass in a low-Carbon economy"[96]. We assume that 25% of this potential is reached in 2030, and that the current potential is equal to zero.
  - Specific estimates of municipal solid waste, sewage sludge, manure and landscape care wood were not included in the Bio-Scope data. We assume that these biomass resources are not available for global trade.
  - The estimation of tertiary residues from forestry from Bioscope have been added to the secondary forestry residues category.

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[95] Source: JRC, 2020

[96] Committee on Climate Change (CCC). (2018). Biomass in a low-Carbon economy.

Table 27

Sustainable biomass potential in the rest of the world[93] (Mtons dry matter)

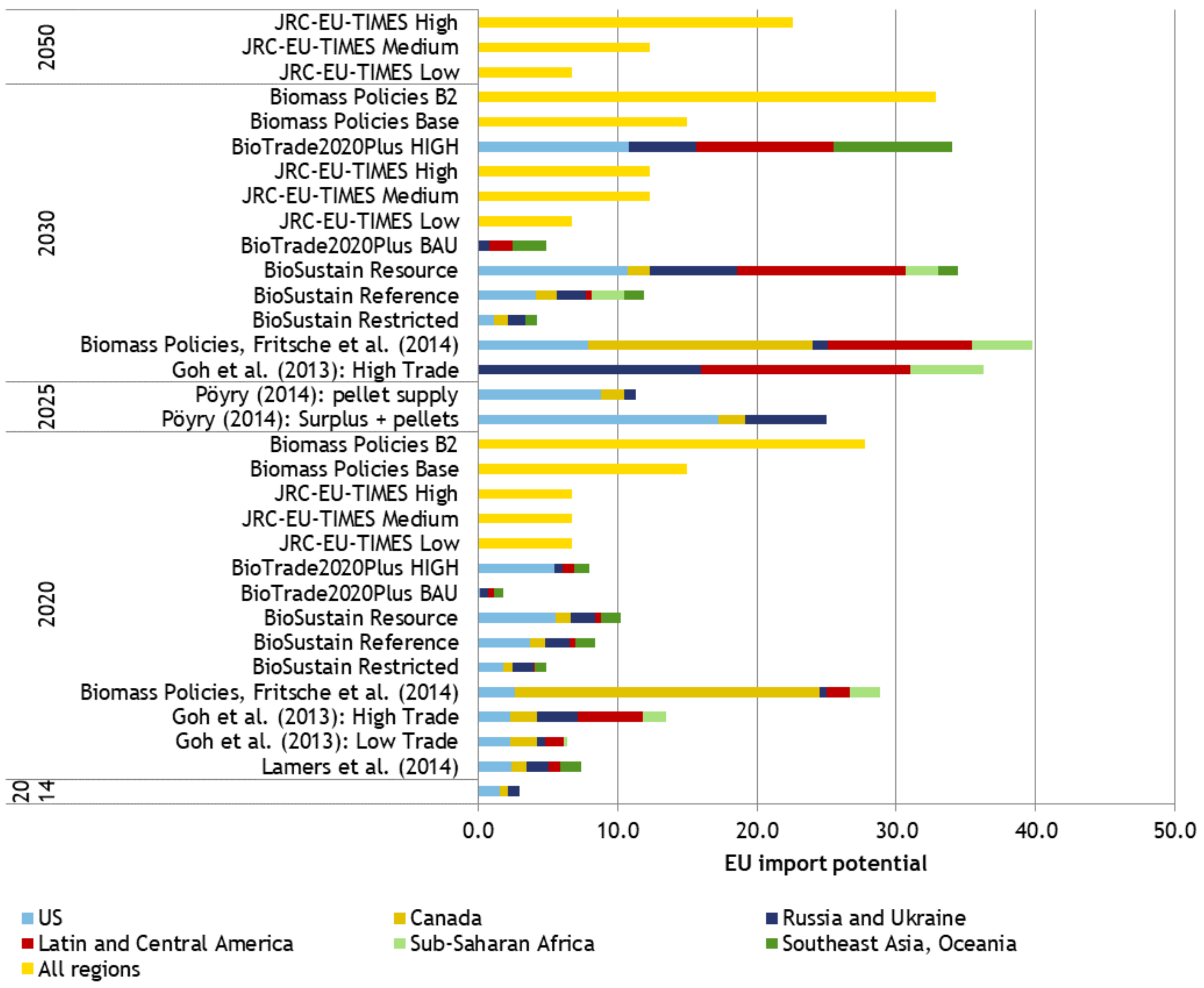
	2020	2030		2050	
		Min	Max	Min	Max
Sugar crops	81	1,280	1,187	880	880
Starch crops	37	424	393	249	249
Oil crops	40	85	297	200	200
Lignocellulosic crops	0	53	838	212	3,353
Agricultural residues	1,412	988	2,541	3,529	4,412
Manure	0	0	0	0	0
Municipal solid waste	0	0	0	0	0
Sewage sludge	0	0	0	0	0
Roundwood	718	1,065	1,735	971	971
Primary forestry residues	1,338	294	271	694	1,106
Secondary forestry residues	1,362	682	647	959	982
Landscape care wood	0	0	0	0	0
Sum	**4,988**	**4,871**	**7,909**	**7,694**	**12,153**

Resulting import potential

Only a limited amount of the sustainable biomass produced in the rest of the world will be available for imports in the EU, because the countries of origin and other world regions will demand their share as well. The European ADVANCEFUEL study[97] includes a literature study of the export potential to the EU of solid biomass and biofuels. The resulting comparison of findings from the literature for solid biomass is shown in Chart 111.

Chart 111

Comparison of import potential scenarios of solid biomass vs. 2014 (Mtons)[97]



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[97] Source: Hoefnagels, Germer. (2018). Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels — D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels.

Summing up the minimum and maximum estimations of the EU import potential for solid biomass and biofuels from Hoefnagels & Germer[98], we obtain a range for the total import potential in 2020, 2030 and 2050, as reported in Table 27. When we compare the potential sustainable biomass production in the rest of the world (as estimated in the previous section) with the EU import potential, we find an EU import share of maximum 2.0%.

Table 28

Estimation of EU import share based on ADVANCEFUEL[97]

	2020		2030		2050	
	Min	Max	Min	Max	Min	Max
Biomass potential in rest of the world (see previous section) (Mt dry matter)	4,988	4,988	4,871	7,909	7,694	12,153
EU import potential, based on ADVANCEFUEL study (Mt dry matter)	20	97	32	161	42	228
EU import share based on ADVANCEFUEL	0.4%	1.9%	0.7%	2.0%	0.6%	1.9%

According to the lead author of the ADVANCEFUEL fuel project deliverable, an EU import share of 1 to 2% is not unexpectedly low. After all, sourcing countries will first fulfil their own biomass demand, and other world regions compete with the EU for biomass. Moreover, the capacity to mobilise and process biomass resources in the different sourcing countries is an important limiting factor for export.[99]

Nevertheless, there are two reasons why we consider that the calculated import shares may be somewhat too conservative: the studies/scenarios collected by Hoefnagels & Germer look at a limited amount of countries, and do not consider all biomass streams that were included in the Bio-Scope study. To take these caveats into account, we estimated that the EU import share could increase to 3.0% of the global potential outside the EU and applied this value to the estimation of the biomass potential in the rest of the world from the previous sub-section.

Then to also take into account the uncertainty in global potential, we developed three different scenarios that can align with scenarios for EU biomass availability. We used the minimum and maximum estimations from Bio-Scope for the Low and High import scenario, respectively. The values for the Medium scenario were then determined by using the same ratios to the ones in the Low and High scenario of the EU ENSPRESO data. The results are shown in Table 28.

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[98] Source: Hoefnagels, Germer. (2018). Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels — D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels.

[99] Ric Hoefnagels, University of Utrecht, personal communication, April 2021.

Table 29

Estimation of EU import potential (Mtons dry matter)

Scenario	2020			2030			2050		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Sugar crops	2	2	2	38	38	36	26	26	26
Starch crops	1	1	1	13	12	12	7	7	7
Oil crops	1	1	1	3	4	9	6	6	6
Lignocellulosic crops	0	0	0	2	8	25	6	36	101
Agricultural residues	42	42	42	30	43	76	106	114	132
Manure	0	0	0	0	0	0	0	0	0
Municipal solid waste	0	0	0	0	0	0	0	0	0
Sewage sludge	0	0	0	0	0	0	0	0	0
Roundwood	22	22	22	32	38	52	29	29	29
Primary forestry residues	40	40	40	9	9	8	21	25	33
Secondary forestry residues	41	41	41	20	20	19	29	29	29
Landscape care wood	0	0	0	0	0	0	0	0	0
Total	150	150	150	146	172	237	231	273	365

Availability of sustainable biomass for the EU

To estimate the availability of sustainable biomass for the EU, we simply added up the estimations of the sustainable biomass potential in the EU and the estimations of the EU import potential. This leads to the outcomes shown in Chart 112, Chart 113, Chart 114, Chart 115.

We can make the following main observations:

- Most of the available sustainable biomass will come from the European Union itself. The share of sustainable biomass that could be imported is limited to 25-36% of the total availability in the Low scenario, and 13-24% in the High scenario.
- The sustainable biomass potential increases over time in the Medium and High scenario. The estimated availability increases by 8% between 2020 and 2050 in the Low scenario, 21% in the Medium scenario, and 31% in the High scenario.
- Biomass streams from agriculture and forestry have a similar contribution, especially in the High scenario. In the Low and Medium scenarios, the share of agricultural biomass rises from ca. 45% in 2020 to ca. 60% in 2050.
- The potential in the Medium scenario is estimated to be 1.3 to 1.4 times higher than in the Low scenario. The potential in the High scenario is 1.9 to 2.3 times higher than in the Low scenario.

Chart 112

Availability of sustainable biomass for the EU in 2030 and 2050, including imports (Mtons dry matter)

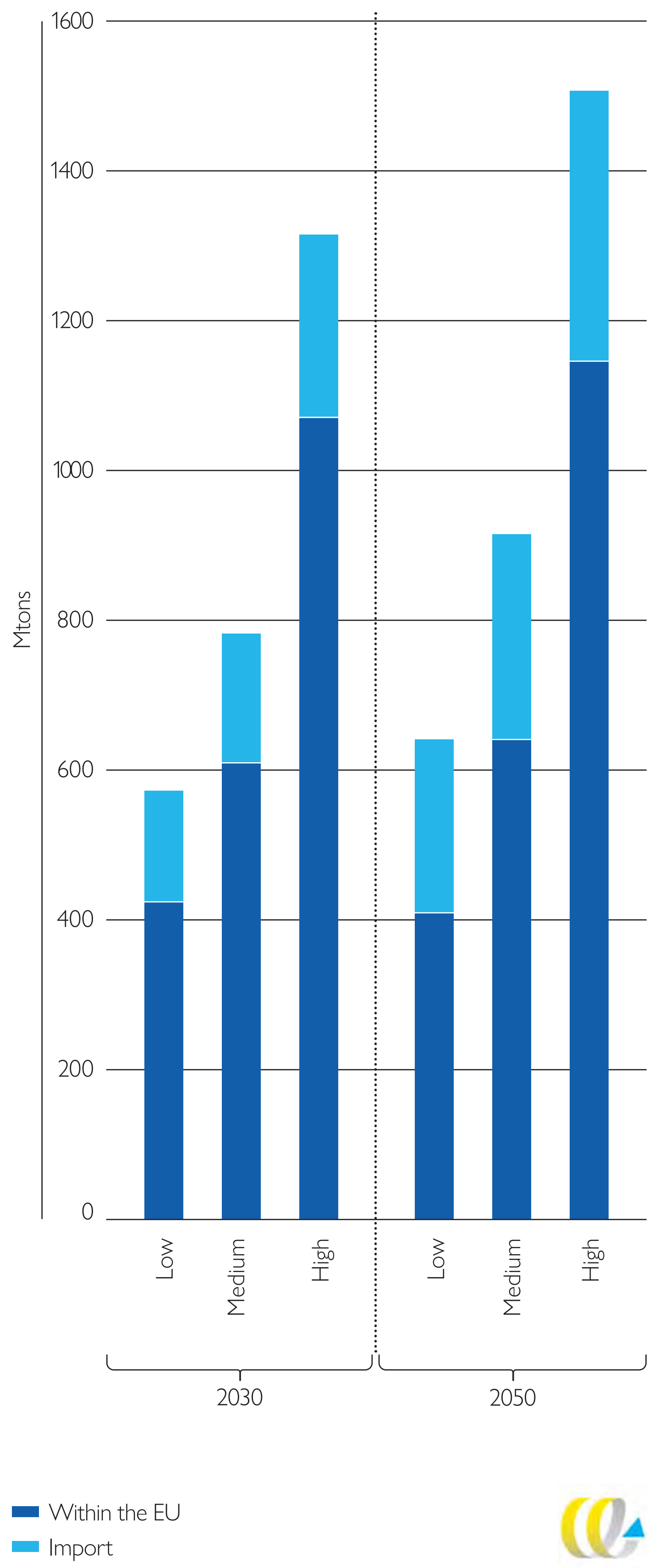

Chart 113

Availability of sustainable biomass for the EU, in the Low scenario, including imports (Mtons dry matter)

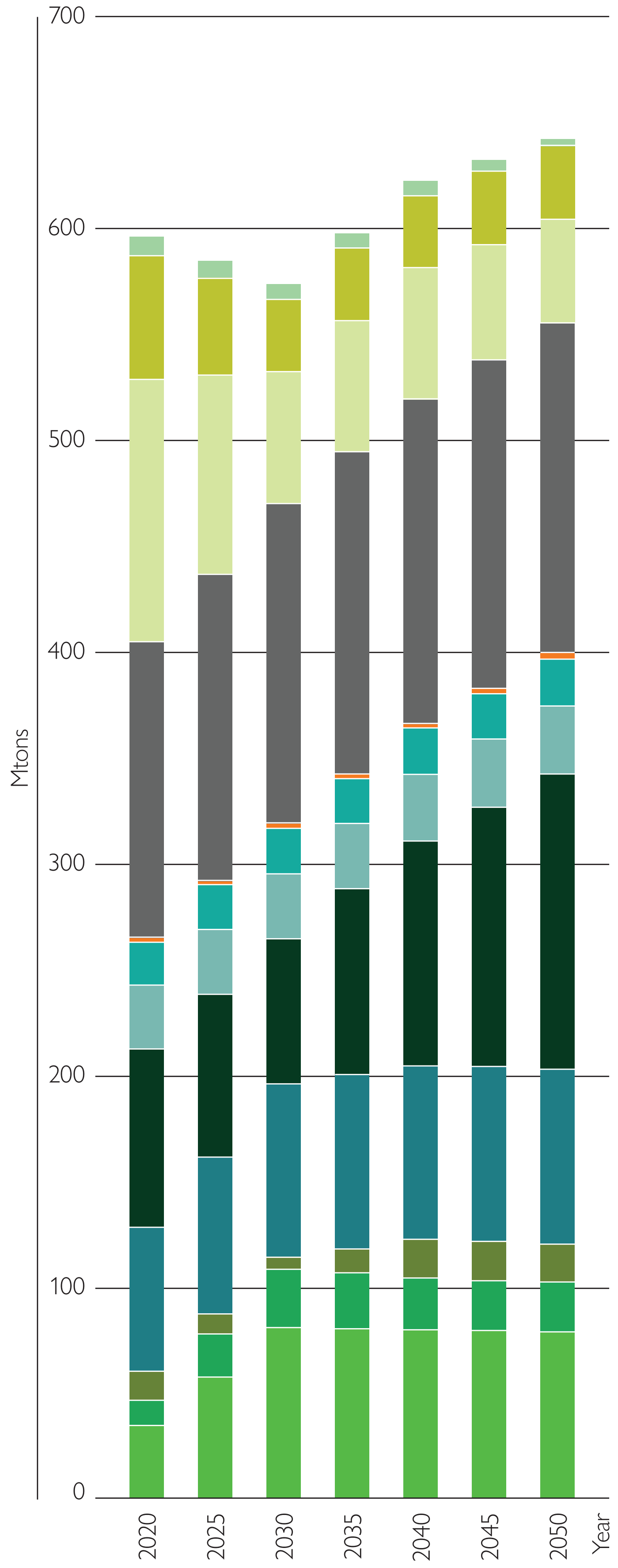

Chart 114

Availability of sustainable biomass for the EU, in the Medium scenario, including imports (Mtons dry matter)

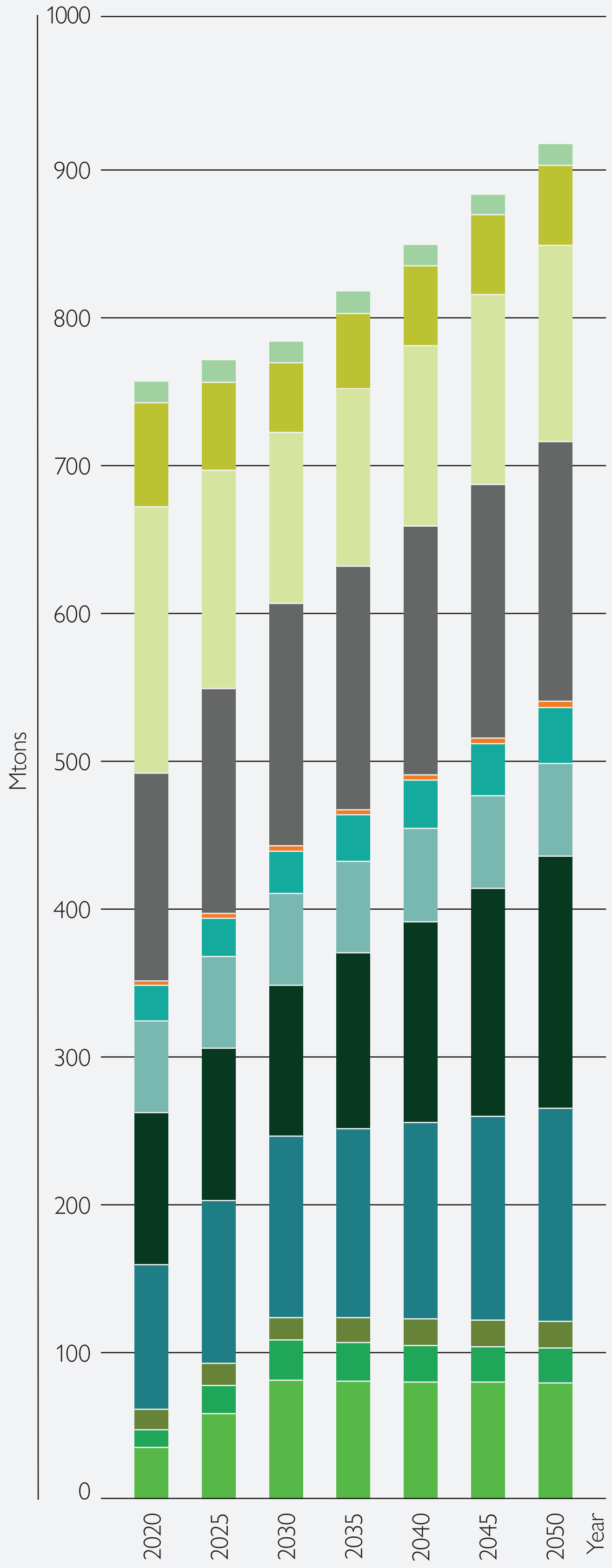

Chart 115

Availability of sustainable biomass for the EU, in the High scenario, including imports (Mtons dry matter)

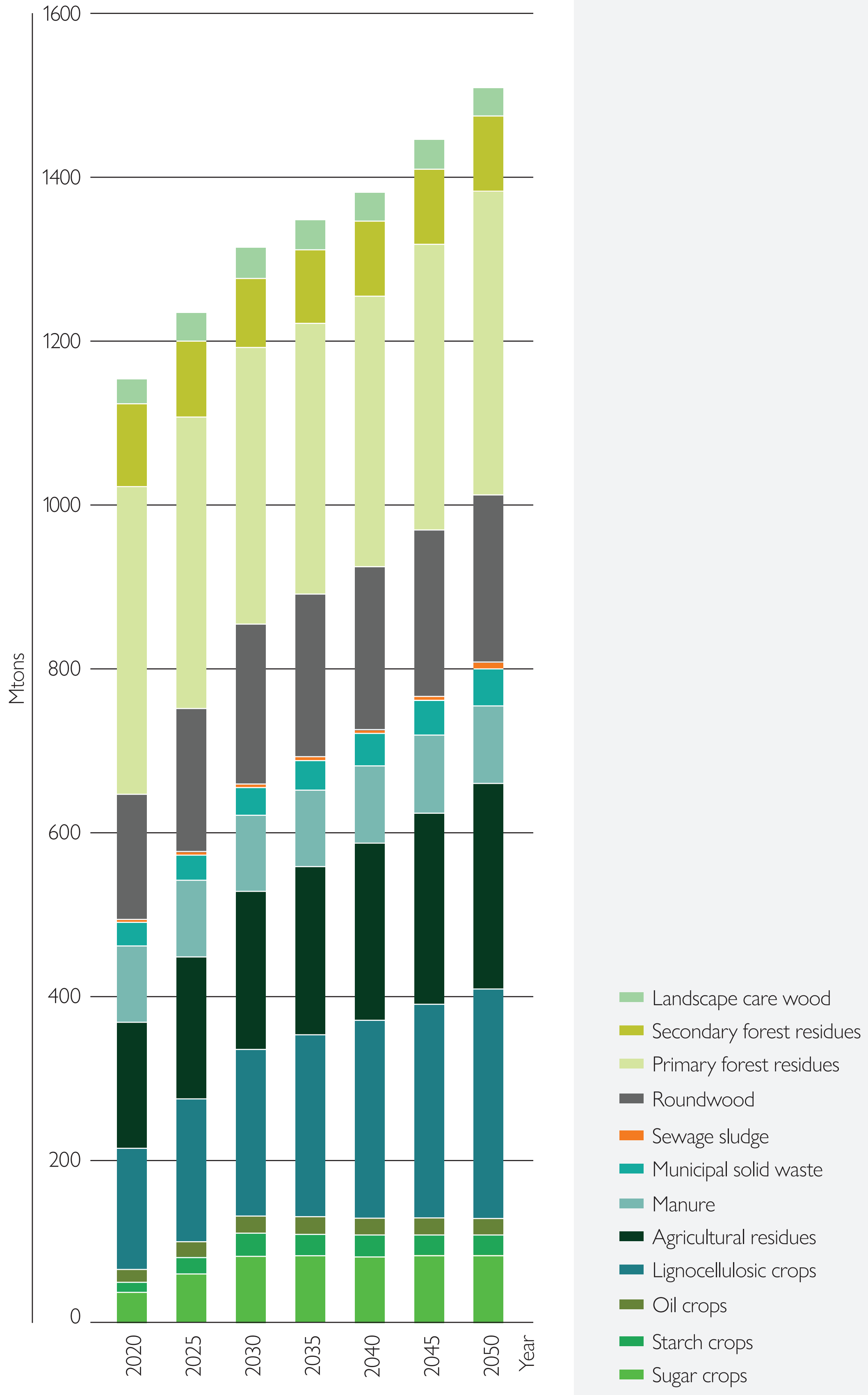

Table 30

Detailed results: availability of sustainable biomass for the EU, including imports (Mtons dry matter)

	2020	2025	2030	2035	2040	2045	2050
High availability scenario							
Sugar crops	40	85	86	86	40	85	86
Starch crops	13	28	26	24	13	28	26
Oil crops	15	21	20	20	15	21	20
Lignocellulosic crops	148	203	242	279	148	203	242
Agricultural residues	154	192	215	252	154	192	215
Manure	93	93	94	95	93	93	94
Municipal solid waste	29	34	41	48	29	34	41
Sewage sludge	2	2	3	4	2	2	3
Roundwood	154	196	199	205	154	196	199
Primary forestry residues	376	336	330	370	376	336	330
Secondary forestry residues	100	86	91	91	100	86	91
Landscape care wood	29	38	36	36	29	38	36
Total	1,153	1,314	1,382	1,510	1,153	1,314	1,382
Medium availability scenario							
Sugar crops	37	82	81	81	37	82	81
Starch crops	12	27	24	23	12	27	24
Oil crops	14	15	18	18	14	15	18
Lignocellulosic crops	97	122	132	144	97	122	132
Agricultural residues	104	103	136	170	104	103	136
Manure	62	62	63	64	62	62	63
Municipal solid waste	24	29	33	38	24	29	33
Sewage sludge	2	2	2	2	2	2	2
Roundwood	142	164	168	176	142	164	168
Primary forestry residues	179	116	122	134	179	116	122
Secondary forestry residues	70	47	54	54	70	47	54
Landscape care wood	15	15	14	14	15	15	14
Total	757	785	849	917	757	785	849
Low availability scenario							
Sugar crops	37	83	82	81	37	83	82
Starch crops	12	27	24	23	12	27	24
Oil crops	14	5	18	18	14	5	18
Lignocellulosic crops	68	82	82	82	68	82	82
Agricultural residues	84	68	105	139	84	68	105
Manure	30	31	32	32	30	31	32
Municipal solid waste	21	22	22	23	21	22	22
Sewage sludge	1	1	2	2	1	1	2
Roundwood	140	151	153	157	140	151	153
Primary forestry residues	124	63	62	48	124	63	62
Secondary forestry residues	58	34	34	35	58	34	34
Landscape care wood	9	8	7	4	9	8	7
Total	597	575	623	643	597	575	623

Competing demand for sustainable biomass in the EU

There will be many sectors competing for the available sustainable biomass, so only a part of the total sustainable biomass potential will become available for the European chemical industry. To understand how much of the total available sustainable biomass will be available for the European chemical industry, we must make an estimation of the demand for biomass in other European sectors.

Since these data are not readily available, this analysis consisted of the following steps:

- Determining the current and future biomass demand for energy
- Translating this overall data to demand per biomass type
- Estimating which share of this overall demand is for the chemical industry
- Calculating EU biomass demand from other sectors

In the next section, we then combine the resulting demand scenarios with the availability scenarios, to develop the final scenarios for the availability of sustainable biomass for the chemical industry.

Determining current and future EU biomass demand for energy

This assessment is based on the scenarios developed by the European Commission for the Impact Assessment of the Climate Target Plan[100]. The Impact Assessment reports EU-wide results for various scenarios, on total biomass demand per biomass-category and per sector. The sectors that will be the main competitors for sustainable biomass are the transport and energy sector, as can be seen in the following graph, from EC, 2020, which shows the bioenergy use in the various scenarios developed by the European Commission. This includes biomass demand for fuels for intra EU aviation and navigation. Different scenarios reflect the different ambition levels of the ReFuel EU aviation and FuelEU maritime initiatives.[101]

Translating these overall data to demand per biomass type

The demand data per biomass category in the Impact Assessment of the Climate Target Plan is on a higher aggregation level than our own estimations. To translate these high-level data to demand per biomass type, the biofuels demand data from the Impact Assessment is divided between sugar crops, starch crops and oil crops by using the 2020 distribution of availability of those crops. The same methodology is applied to distribute the high-level data on demand of biosolids between lignocellulosic crops, roundwood, primary forestry residues, secondary forestry residues and landscape care wood. It is therefore assumed that the current availability of biomass reflects the distribution of demand for specific crops in various scenarios.

For the 2030 low and high biomass demand scenarios we use respectively the mix-50 and the ALLBNK scenario from the Impact Assessment. For the 2050 low and high scenarios we use the REG and ALLBNK scenario.

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[100] Source: European Commission. (2020). Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. EUR-Lex - 52020SC0176 - EN - EUR-Lex (europa.eu)
[101] Please note that (European Commission, 2020) does not provide data on biomass use for feedstock.

Chart 116

Bioenergy use in the EU27 in 2015, 2030 and 2050, results of different scenarios (EC, 2020)

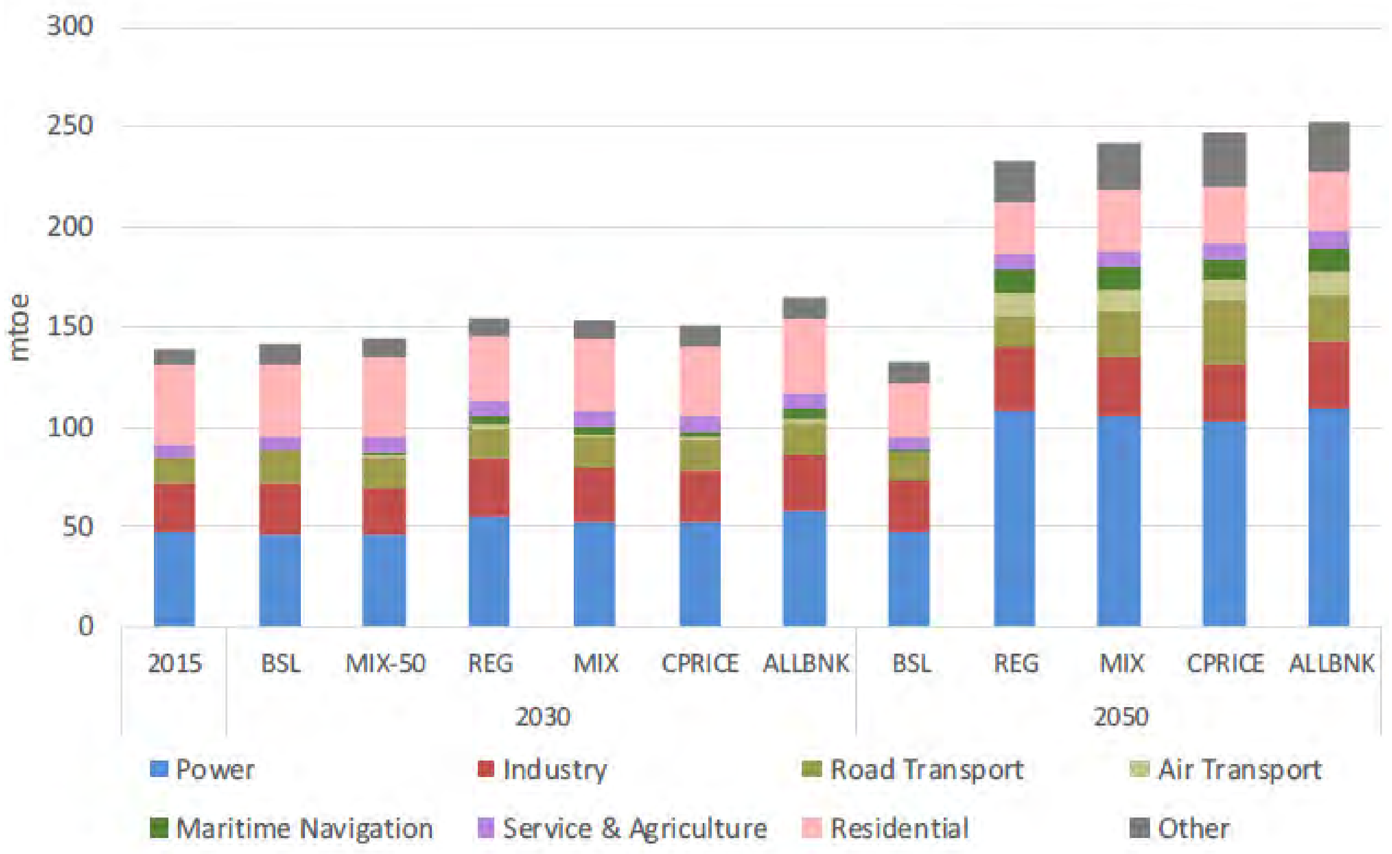
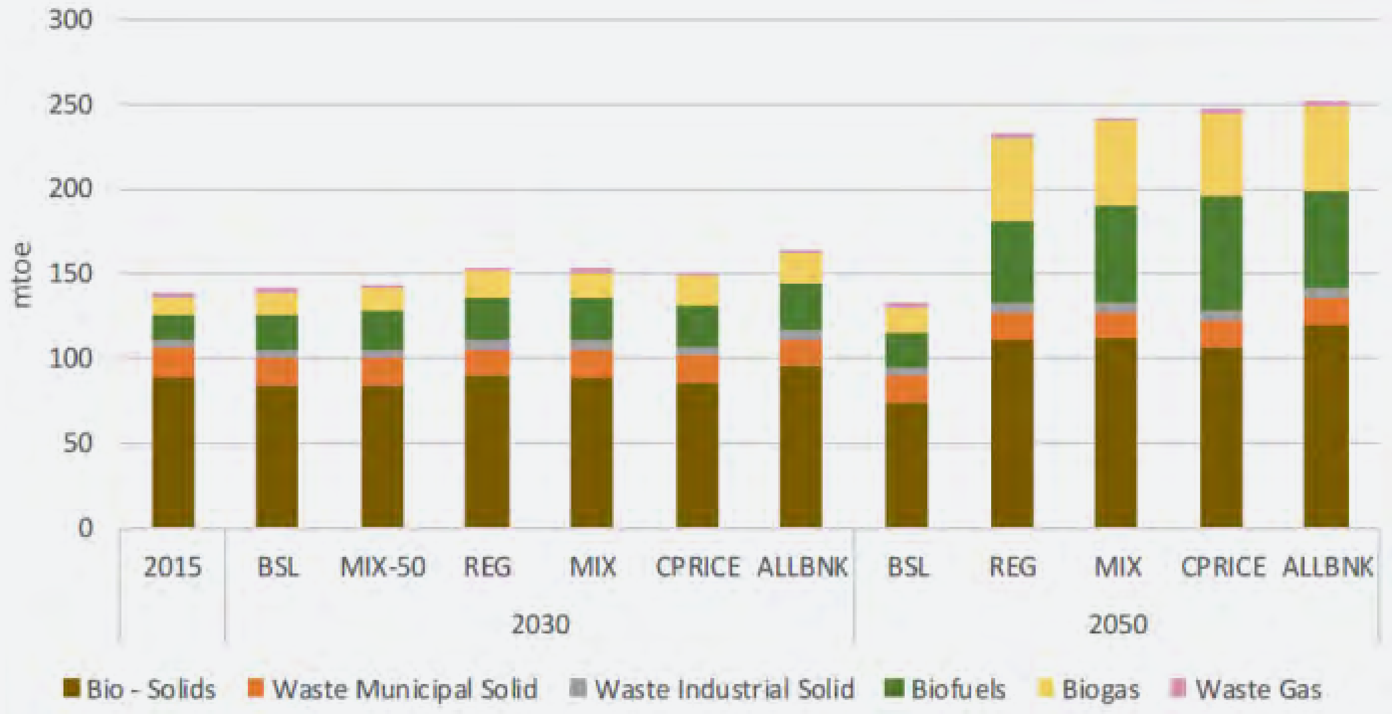


Chart 117

Gross inland consumption of biomass and waste for energy (EC, PRIMES 2020)



Estimating which share of this overall demand is for the chemical industry

The demand data include the chemical industry, but for the purposes of this report, the forecast of demand from the chemical industry has to be extracted from the scenario results. This level of detail is not included in (EC, 2020), and had to be estimated based on the consumption of biomass per sector, as reported in the Impact Assessment . However, the bioenergy demand is reported for EU industry as a whole. The chemical industry is currently the largest industrial consumer of biomass, and that share is likely to expand because of the increased use of biomass for feedstock purposes.

To estimate this share, we used the analysis in the Bio-Scope study[102], which included an assessment of biomass demand in industry in the Netherlands. Some key results are shown in Table 30. This study finds that the majority of biomass used in industry is currently used for heat, in the chemical industry (43% of the total, in 2015) and in other industrial sectors (47%). Current industrial demand for biomass as feedstock in the chemical industry is limited. In projections for 2030 and 2050, the demand for industrial heat is reduced (possibly to zero) or increases only slightly. The share of biomass demand for feedstock purposes increases to 53% (2030 low scenario) up to 100% (2050 high scenario).

Table 31

Distribution of biomass demand in industry in the Netherlands (based on findings in (CE Delft and RH DHV, 2020)

	2015	2030		2050	
		High	Low	High	Low
Feedstock chemical industry	9%	90%	10%	81%	100%
Heat demand chemical industry	43%	5%	43%	9%	0%
Heat demand other industry	47%	5%	47%	10%	0%
Total demand industry	100%	100%	100%	100%	100%

The Bio-scope study also contains a literature analysis with regard to the crops used in the chemical industry, covering the same biomass sources that are distinguished in this report. However, one of the conclusion from the analysis in CE Delft and RH DHV, 2020 is that it is not easy to determine which types of biomass will be used and to what extent, due to lack of data as well as uncertainties in the future developments.

Calculating the demand from other sectors

We can now subtract the estimated biomass demand for chemicals from the overall biomass demand to determine the non-chemical demand for biomass. These results are based on the assumption that demand for the various biomass types is reduced uniformly, i.e. demand for the various biomass types is reduced by the same percentage. Table 31 shows the resulting demand from outside the chemical sector.

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[102] Source: CE Delft, RH DHV. (2020). Bio-Scope: Toepassingen en beschikbaarheid van duurzame biomassa. CE_Delft_190186_Bio-Scope_Def.pdf

Table 32

Detailed results: demand for sustainable biomass in the EU27, excluding the chemical sector (Mtons dry matter)

Scenario	2020			2030			2050		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Sugar crops	24	23	22	33	32	30	71	66	61
Starch crops	7	7	7	11	10	9	23	21	19
Oil crops	9	9	8	12	12	11	27	25	23
Lignocellulosic crops	36	35	33	35	33	32	48	43	39
Agricultural residues	8	8	8	7	7	8	8	9	11
Manure	27	27	26	35	33	31	113	112	110
Municipal solid waste	38	39	39	35	37	39	38	37	37
Sewage sludge	8	7	7	7	5	4	8	6	4
Roundwood	38	53	69	36	51	65	50	65	80
Primary forestry residues	92	76	61	89	73	58	121	96	71
Secondary forestry residues	24	27	29	24	25	27	32	33	33
Landscape care wood	7	6	4	7	6	4	9	7	5
Total	318	315	313	333	325	317	547	520	492

Conclusion: availability of sustainable biomass for the European chemical industry

As a final step in this analysis, the results from the previous sections can be linked to the total biomass availability scenarios developed earlier. We have 3 total availability scenarios and 3 scenarios for demand from other sectors. These have to be integrated into 3 scenarios for the biomass availability for the chemical industry. They can then be used as constraints in the IC2050 model.

Different combinations of these availability and demand scenarios are possible. As it is reasonable to assume that higher availability is likely to go together with lower cost and therefore higher demand, we have combined high availability with high demand from other sectors, and likewise medium demand with medium availability and low demand with low availability. Table 32 shows the results for those scenarios.

Table 33

Detailed results: sustainable biomass available for the chemical sector (Mtons dry matter)

	2020	2025	2030	2035	2040	2045	2050
High availability scenario							
Sugar crops	17	34	51	42	33	21	8
Starch crops	5	11	17	13	9	5	2
Oil crops	6	7	9	4	0	0	-
Lignocellulosic crops	112	140	168	185	201	216	231
Agricultural residues	132	155	179	191	203	212	222
Manure	65	62	58	39	20	10	-
Municipal solid waste	-	-	-	2	4	7	10
Sewage sludge	-	-	-	-	-	-	-
Roundwood	116	138	159	158	156	156	156
Primary forestry residues	284	266	247	236	224	237	249
Secondary forestry residues	75	69	62	63	63	61	59
Landscape care wood	22	26	31	29	27	27	26
Total	835	908	982	962	942	952	962
Medium availability scenario							
Sugar crops	14	32	50	41	32	20	9
Starch crops	4	11	17	13	9	5	2
Oil crops	5	4	4	2	-	-	-
Lignocellulosic crops	63	76	89	91	94	97	100
Agricultural residues	76	80	83	97	111	111	110
Manure	35	32	29	14	-	-	-
Municipal solid waste	-	-	-	-	-	0	1
Sewage sludge	-	-	-	-	-	-	-
Roundwood	89	101	113	112	111	111	111
Primary forestry residues	103	73	43	40	38	38	38
Secondary forestry residues	44	33	21	23	25	23	21
Landscape care wood	9	9	10	9	8	7	7
Total	442	451	460	443	427	412	398
Low availability scenario							
Sugar crops	15	31	48	43	38	27	16
Starch crops	5	11	18	14	10	7	4
Oil crops	5	3	-	1	1	1	-
Lignocellulosic crops	35	42	50	49	47	45	43

	2020	2025	2030	2035	2040	2045	2050
High availability scenario							
Agricultural residues	52	47	41	40	39	37	34
Manure	4	2	0	0	-	-	-
Municipal solid waste	-	-	-	-	-	-	-
Sewage sludge	-	-	-	-	-	-	-
Roundwood	71	78	86	82	78	66	54
Primary forestry residues	63	34	5	2	-	-	-
Secondary forestry residues	30	18	6	5	4	3	1
Landscape care wood	4	4	3	3	3	1	-
Total	284	271	257	238	220	186	152

When subtracting the demand from other sectors (Table 32) from the total available sustainable biomass (Table 33), we found that for some biomass types the demand exceeded the availability due to the sometimes quite rough assumptions that had to be made in this analysis. We correct this by assuming that if demand exceeds availability for a specific crop, the surplus demand shifts towards alternative crops, as shown in Table 32. This correction ensures that all demand is accounted for in the calculation.

Table 34

Assumptions on shifts in demand, when demand exceeds availability for specific crops

Crop	Alternative crop when demand > availability
Oil crops	Sugar crops
Manure, Municipal solid waste, Sewage sludge	Agricultural residues
Primary forestry residues, Landscape care wood	Roundwood

Comparison with the current situation

To put our findings into perspective, we compared our estimations for the year 2050 with the current use and import of biomass by the EU. The results are shown in Table 34.

Table 35

Comparison of estimated available biomass for the EU with current situation

	Our estimation for 2050	Current situation	Source current situation	Remarks on the data for the current situation
Biomass supply for the EU, excl. biofuels import (Mtoe)		140	(EC Knowledge Centre for Bioeconomy, 2019)	Supply from within EU plus import of solid biomass. Excluding import of biofuels. Figure from 2016.
Biofuels import (Mtoe)		3	(Bioenergy International, 2019)	3.3 Mt of biodiesel in 2018, converted using an energy content of 37.8 MJ/kg.
Biomass supply for the EU (Mtoe)	**261-613**	**143**		Biomass supply for EU plus biofuels import.
Within the EU	167-465	134.4	(EC Knowledge Centre for Bioeconomy, 2019)	96% of 140 Mtoe.
Import	94-148	8.6		4% of 140 Mtoe, plus 3 Mtoe biofuels import.
Import share	24-36%	6%		

Most of the biomass currently used for bioenergy in the EU originates from the EU itself. In 2016, 96% came from within the EU[103]. For wood that is used in the EU as a material, a biomass flow diagram from the JRC shows that most of the wood used as a material comes from the EU as well Georgieva & Zaimova, 2019[104]. In addition, most of the biodiesel used in the EU is produced within the EU itself.[105] A volume of 3 Mtoe of biodiesel was imported by the EU in 2018[106].

Comparing our estimation for 2050 with the current situation, we can see that there is a substantial potential for growth of both sustainable biomass production within the EU (by a factor of 1.3 to 3.5) and biomass import in the coming decades (by a factor 11 to 17). Also, the comparison indicates that the relative importance of biomass import may increase if the import potential is used to a fuller extent in the future (from 6% in the current situation to 24-36% in 2050).

[103] Source: European Commission's knowledge centre for bioeconomy. (2019). Brief on biomass for energy in the European Union. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109354/biomass_4_energy_brief_online_1.pdf

[104] Source: Georgieva, N., Zaimova, D. (2019). Policies for Increasing the Share of Biomass in Energy Production. International Conference on Technics, Technologies and Education (ICTTE). DOI:10.15547/ictte.2019.05.007

[105] The EU production of biodiesel in 2019 was more than four times larger than the biodiesel import (Kotrba R. (2020). 2020 EU biodiesel production remains stable, consumption down 6%. Source: Kotrba R. (2020). 2020 EU biodiesel production remains stable, consumption down 6%. Biodiesel magazine. 2020 EU biodiesel production remains stable, consumption down 6% | Biodiesel Magazine

[106] Source: Bioenergy International. (2019). European biodiesel imports from Argentina and Indonesia increase sharply. https://bioenergyinternational.com/markets-finance/european-biodiesel-imports-from-argentina-and-indonesia-increase-sharply

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