Chemicals in transition

The three pillars for transforming chemical value chains

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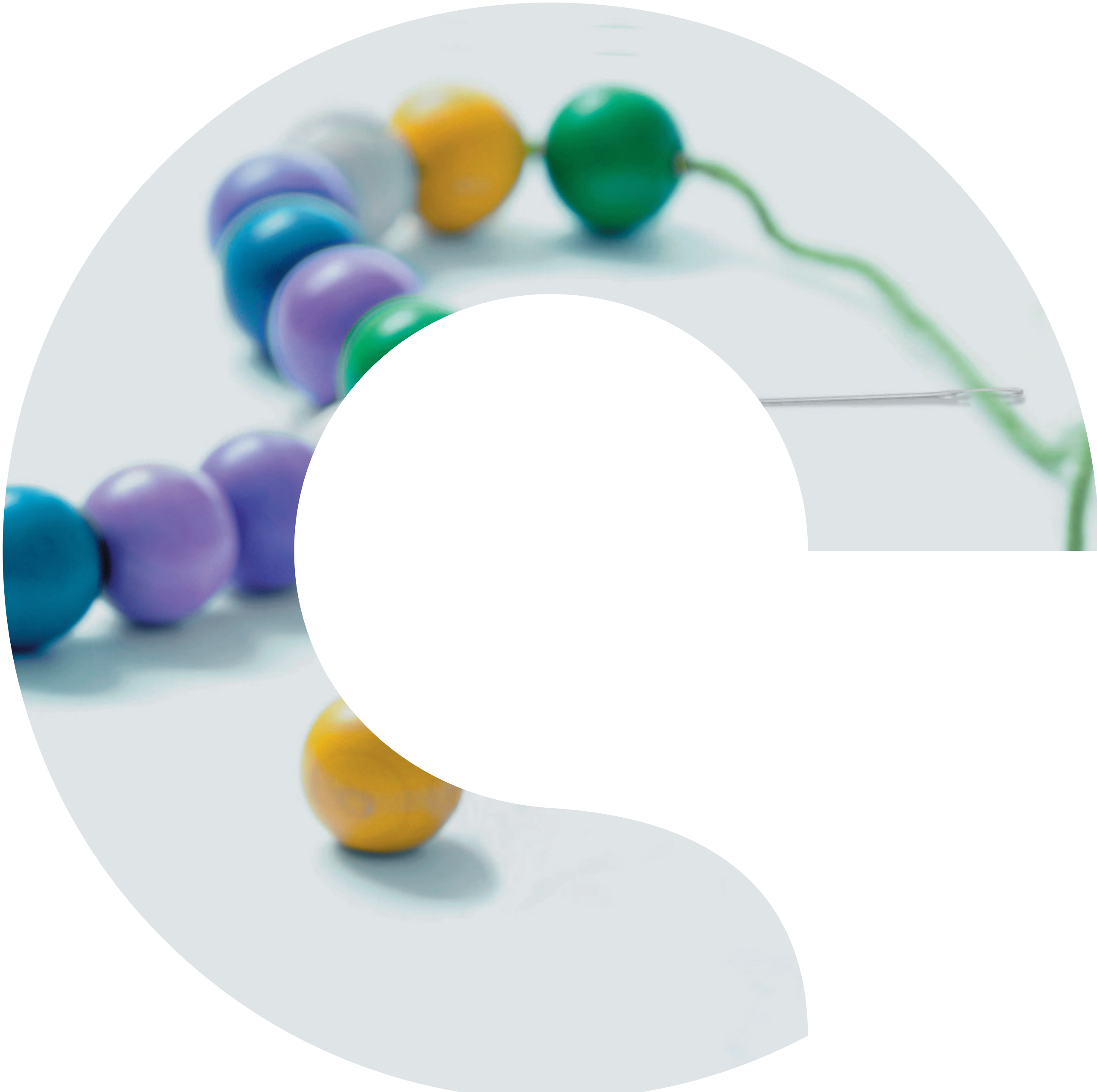
Agora Industry



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Preface

Dear reader,

As the largest industrial consumer of fossil gas in Germany, the chemical sector has been hit severely by the scarcity of fossil gas and the high prices caused by the fossil energy crisis following Russia's invasion of Ukraine. At the same time, this has opened a window in which to speed up the transformation necessary for achieving the climate targets for industry in 2030 and 2045 and to stay competitive in the global race for climate-neutral products and technologies.

So the chemical industry stands at a crossroads: It needs to develop a common pathway that takes into account the climate targets, limited domestic resources and the resilience of value chains while maintaining the industry's economic strength. At the same time, Germany and the EU must create an environment that fosters investment in the technologies of the future in order to maintain the innovative energy that is crucial for the economic strength of the sector and for delivering the key materials for a climate-neutral society.

This study contributes to developing such a transition pathway for a chemical industry that uses materials and resources efficiently, a pathway based on three key complementary strategies: direct electrification and flexibility, a circular economy and renewable feedstocks. Our study shows that an integrated approach can create cross-sectoral synergies for this transition and can eventually result in CO_2 sinks – a climate-positive chemical value chain.

I hope you enjoy reading this study.

Frank Peter
Director, Agora Industry

Key findings at a glance:

1. **High fossil energy prices and the reform of the European Union Emissions Trading System (EU ETS) have increased the urgency for the transformation of the chemical industry: The sector needs to phase out its use of fossil fuels and be climate-neutral before 2040.** To maintain innovation, value creation and jobs in Europe, decisive action by companies and policymakers to enable the transition is needed.

2. **The transition of the chemical sector must address all emissions along the entire value chain. More than half of the life-cycle emissions from chemicals occur after their use when they are disposed of and usually incinerated, releasing the carbon they contain into the atmosphere.** To unlock the sector's potential to utilise and store carbon more sustainably, three parallel strategies are key: 1) the direct electrification of process heat; 2) a circular economy; and 3) replacing fossil with renewable feedstocks.

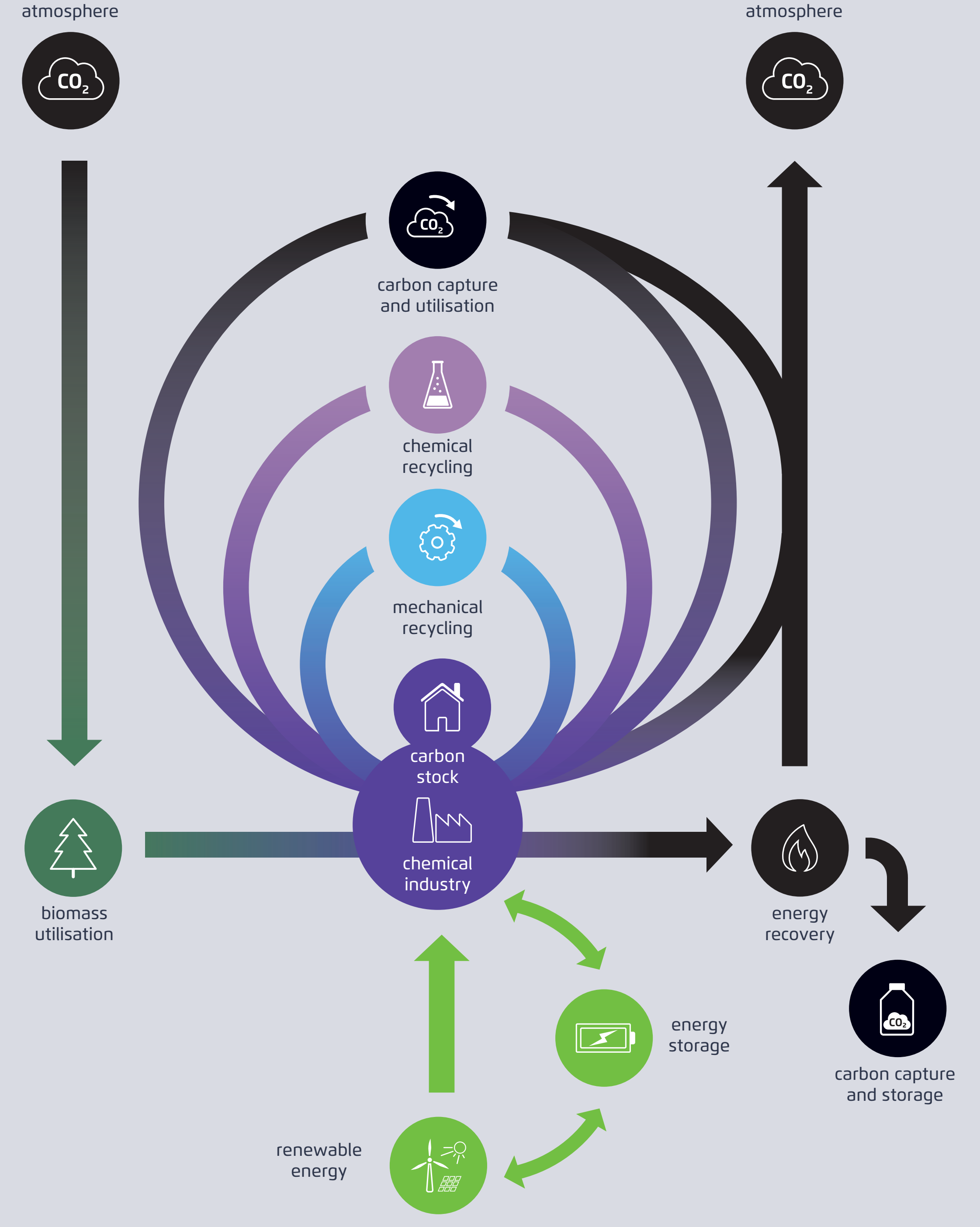
3. **A policy mix of supply-side and demand-side measures for the chemical industry is needed to complement the ETS reform.** Investment support and technology standards create incentives for electrification. Mandatory quotas for recycled content will help to foster a more circular economy. In combination with prioritising uses that extend the lifetime of limited biomass resources, the additional demand for electricity and hydrogen can be reduced to a minimum.

4. **To ensure the competitiveness of the chemical industry in a climate-neutral economy, the federal government should develop a detailed roadmap by the end of 2024, with the involvement of industry, trade unions, civil society and the scientific community.** A special focus must be placed on the transition of the particularly energy-intensive production of basic chemicals, which are the starting point of many subsequent value chains.

Contents

Concept for a climate-positive chemical value chain based on direct electrification and flexibility, acircular economy and renewable feedstocks

Figure 1



Agora Industry and Carbon Minds (2023)

1 Executive summary

The transformation of the chemical industry is crucial to achieving climate neutrality. As an industry that evolved from the availability of fossil resources, it is still based on a linear value chain today in which fossil resources are processed to chemicals, and at the end of their useful life, final products based on these chemicals are incinerated or landfilled. Historically, Germany has played an important role in the global chemical industry. A large number of important innovations originated in Germany, and Germany remains the location of numerous global chemical companies and the world's largest exporter of chemicals. The chemical industry in Germany therefore needs to be a role model for the global transformation of chemicals towards climate neutrality.

The production of chemicals alone is one of the largest sources of CO_2 for Germany, accounting for five percent of total emissions. The extraction of fossil fuels and the end-of-life treatment of chemical-based products are responsible for additional emissions that are up to three times greater than the production-related emissions. In the past, the chemical industry has proven that it can be innovative and can set new standards: since 1990, production has increased by 63 percent while energy demand has decreased by 19 percent and greenhouse gas emissions by 55 percent (VCI 2021b). The accelerated emissions cap reduction path in the recent EU ETS reform implies that EU industry will need to be climate-neutral before 2040. For the transition to net zero in the remaining 15 years, further efficiency gains will not suffice. The linear value chain must be replaced by an energy- and resource-efficient circular economy based on renewables.

Germany is currently confronted with multiple challenges, which include:

1. **The climate crisis**. The window for remaining within the 1.5 degrees Celsius limit is closing, necessitating radical CO_2 mitigation in this decade. Furthermore, all credible climate neutrality scenarios assume that we will need massive CO_2 sinks to protect our climate.

2. **The energy crisis**. The chemical industry is the largest industrial consumer of natural gas in Germany. The loss of vast imports of cheap oil and gas from Russia and the related increase in energy prices fundamentally call into question the economic viability of the production of bulk chemicals in this country. The forced relocation of production would have disastrous consequences for the economy and for climate protection.

3. **Unstable value chains**. Both the COVID-19 pandemic and the energy crisis have shown the fragility of crucial value chains. In order to ensure greater resilience in the future and to make the transformation a success, a secure supply of raw materials is essential.

4. As a result of these challenges, **industrial policy is becoming increasingly important globally**. International competition, in particular the U.S. Inflation Reduction Act (IRA), which provides support for green technologies, is putting pressure on the EU not to fall behind in scaling up clean technologies.

The chemical industry, together with all other sectors along the chemical value chain, is severely affected by these multiple challenges, but it can also play a key role in tackling them. A common vision for the chemical industry of the future is needed, one that is shared with the energy sector, with suppliers of renewable feedstocks, with producers of consumer products and with the waste industry, in order to empower industry to make future-proof investment decisions and to use the crises as a spur for fossil energy savings and emissions reductions.

To date, studies addressing the transformation of the chemicals industry in Germany have mainly focused on direct emissions from the production of plastics while ignoring the "shadow" emissions from the feedstock supply and from end-of-life treatment. Other studies have focused on circularity and end-of-life treatment while ignoring primary production. However, a cross-sectoral view that includes all parts of the value chain reveals that a comprehensive transformation to renewable energies and feedstocks and circularity can have a positive climate impact across the whole economy.

A new approach to the transition of the chemical value chain needs to take into account all life-cycle emissions and aim at an efficient allocation of available resources and energy sources, bearing in mind other sectors and branches of the economy. Here, a three-pronged transition strategy is crucial to reducing emissions fast and to achieving climate-positive benefits.

1. **Direct electrification and flexibilisation** of process energy reduces both the emissions from chemicals production and the amount of fossil fuel needed and makes the most efficient use of limited available renewable energies.

2. Establishing a **circular economy** reduces both end-of-life emissions from chemical products and fossil feedstock demand. Designing products for long-term use, re-use and repair and recycling reduces the quantity of material needed while maintaining the same utility. Mobilising the potential of mechanical recycling and additionally introducing chemical recycling technologies turns waste into a local resource and reduces dependence on fossil imports.

3. Replacing fossil with **renewable feedstocks**. Since carbon is the main building block of most chemicals, the remaining fossil carbon feedstocks will need to be replaced by renewable sources. In addition to electricity-based hydrogen and its derivatives, biomass – consisting largely of the chemical building blocks carbon and hydrogen – is a promising feedstock that can replace fossil feedstock imports. To maximise the efficient and effective use of this limited resource, existing biomass should be diverted from pure energy applications to a sequential use, first in materials, then in feedstocks, and lastly in energy (the so-called "cascading use" of biomass). In principle, a wide variety of different types of biomass can be used to produce chemicals, but care must be taken to ensure that additional demand for biomass for chemicals does not lead to land use intensification or direct or indirect land use change with detrimental effects on ecosystems and carbon cycles. This approach also enables local value creation and reduces dependence on fossil imports.

Combining the production of bio-based chemicals with a circular economy approach offers an opportunity to create net CO_2 sinks. Biogenic carbon is stored in long-lifetime products and kept in use by recycling products multiple times. Non-recyclable bio-based chemicals can – in line with the principle of cascading use – be incinerated and used energetically. Capturing and sequestering the residual unavoidable emissions by combining incineration of biogenic waste with Carbon Capture and Storage (BECCS) further preserves the CO_2 sink. In this way, the chemical value chain can be a driver of carbon management across the economy and contribute to achieving Germany's climate targets.

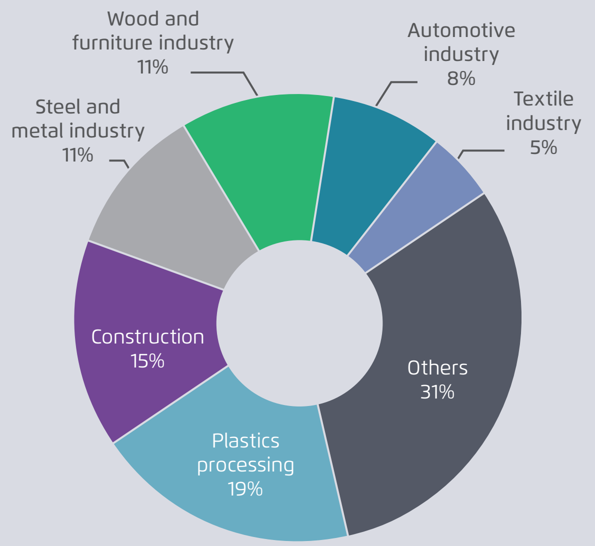
A comprehensive policy framework that is aligned with the climate goals is needed to enable and to push forward the transition of the chemical sector. With the reform of the EU ETS, the rapid reduction of the emmissions cap and the upcoming inclusion of waste incineration, the chemicals sector will soon be exposed to a clear price signal for CO_2 emissions. This fiscal framework at EU level needs to be complemented by additional measures to ensure that investments in clean technologies are made today. In particular, the following measures are necessary to support the three strategies listed above.

Investment in the direct electrification of process energy needs to be incentivised by means of a special support program for the rapid production and market ramp-up of industrial heat pumps. In addition, introducing a legally binding *zero-carbon standard* for new investments – e.g. for process heat up to 500 degrees Celsius, where there is commercially available CO_2-free technology – would prevent new additional investment going into carbon-intensive technologies. The establishment of green lead markets to incentivise investment in circular technologies needs to be supported by the introduction of quotas for recycled content to support high-quality recycling. Likewise, product standards are needed to enforce the long-term and efficient use of high-quality plastics and the adoption of design for recycling; unnecessary applications of plastics should be banned by law. Replacing fossil with renewable feedstocks requires a regulatory framework aligned with a hierarchy for efficient and sustainable use. For bio-based chemicals, the most important requirement is that the regulatory framework, principally the EU Renewable Energy Directive, is revised to abolish perverse incentives for pure bioenergy use and to introduce instead incentives for sustainable material and feedstock use of biomass.

2 The chemical industry in Germany today[1]

The chemical industry is a complex industry characterised by a large number of different processes and products used for many different applications. **Polymers** make up the largest group of chemical industry products. They come in different forms – as plastics, for example for packaging (e.g. PET), as building materials such as pipes (e.g. PVC), as coatings for metals or wood, as base material for components in vehicle manufacturing, and in textiles – to name just a few. Figure 2 gives an overview of the main uses of the more than 30 000 different chemicals used in other industrial sectors.

Use of chemical products in other sectors in Germany in 2019 — Figure 2



VCI (2021b)

As shown in Figure 3, polymers make up approximately 50 percent of all chemical products. **Fine chemicals** such as detergents, cleaners and cosmetics make up roughly a third of all products. The production of ammonia-based **fertilisers**[2] accounts for the smallest share, with 11 percent.

Despite the complexity of the processes and the variety of the products of the chemical industry, most value chains are based on only 10 basic chemicals.[3] In 2019, 24 million metric tonnes (Mt) of these basic chemicals were produced in Germany, of which 14 Mt were **organic**, i.e., carbon-based, chemicals (Carbon Minds 2020, VCI 2021a). The remaining 10 Mt were the **inorganic** chemicals ammonia, chlorine, and caustic soda, which do not contain carbon. Figure 3 shows in simplified form the variety of products based on these basic chemicals (inner circle) together with the most important downstream products (outer circles). Due to the central role of basic chemicals in the chemical industry, they also play a key role in the transformation of the entire value chains.

The various value chains that branch out from basic chemicals also shape the production sites. A small number of large chemical sites – so called Verbund sites – produce basic chemicals and supply precursors and byproducts to many value chains both on site and at other chemical sites. Today, there are 25 of these integrated Verbund sites, which are interconnected within and among themselves (VCI 2023). The production processes for many different chemical products within and between the sites are interlinked through the exchange of energy and material flows and the joint use of infrastructures and industrial services.

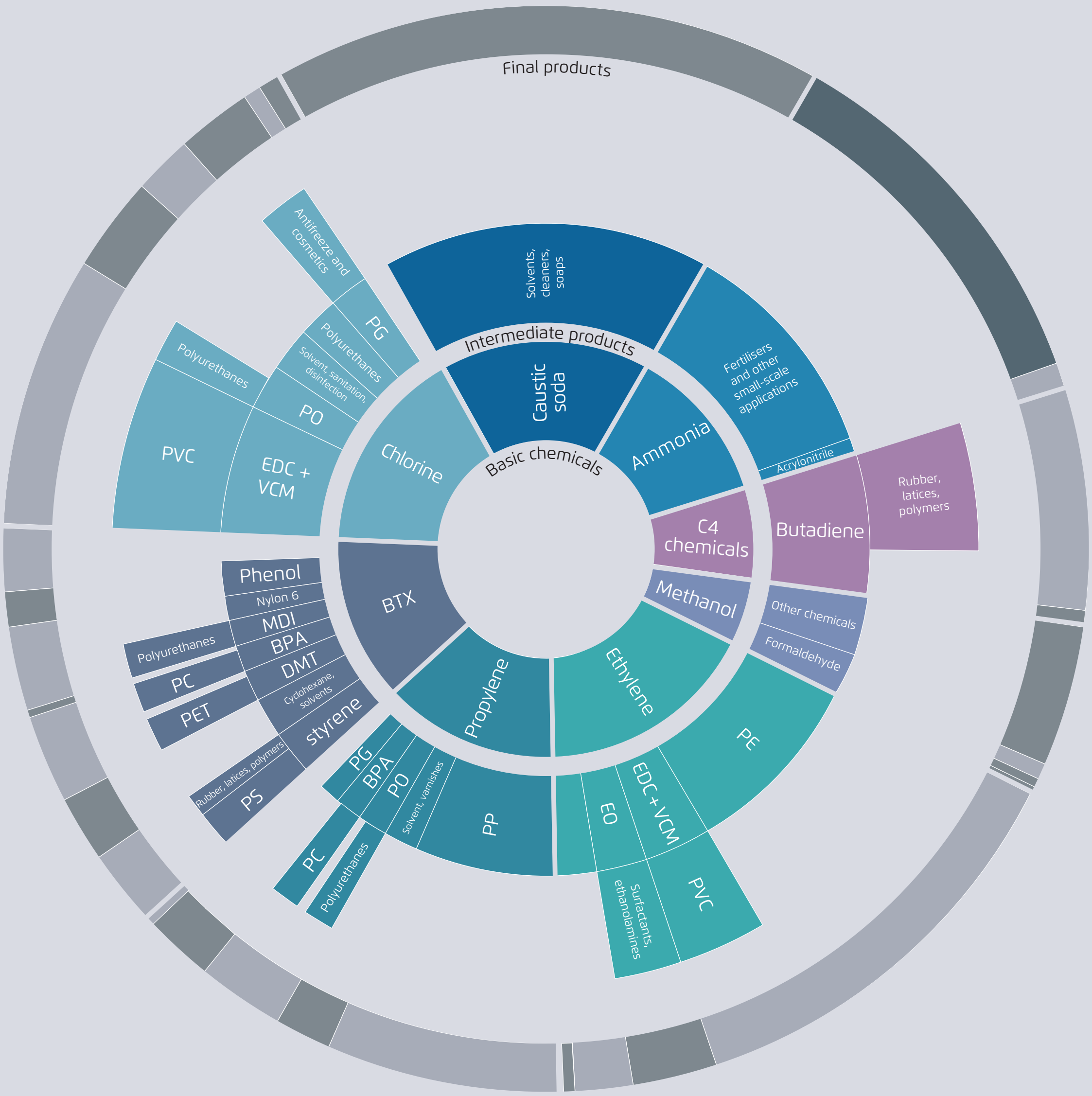
1 The reference year for the data in this Chapter is 2019 – the last year before the start of far-reaching distortions in international value chains with major consequences for the chemical industry.

2 Phosphate- and potassium-based fertilisers are not considered in this analysis.

3 The ten basic chemicals are ethylene and propylene (olefines), benzene, toluene, and xylene (aromatics, jointly referred to as BTX), C4 chemicals, methanol, chlorine, caustic soda and ammonia.

Dependence of selected intermediate and final products on basic chemicals

Figure 3



Final products:

- Polymers (52%)
- Fine chemicals (37%)
- Fertilisers (11%)

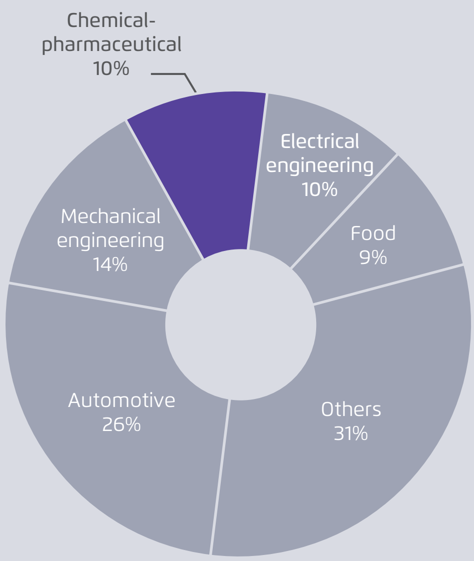
BTX	Benzene, toluene, xylene
PE	Polyethylene
EDC	Ethylene dichloride
VCM	Vinyl chloride monomer
PVC	Polyvinyl chloride
EO	Ethylene oxide
PP	Polypropylene
PO	Propylene oxide
BPA	Bisphenol A
PC	Polycarbonate
PG	Propylene glycol
PS	Polystyrene
DMT	Dimethyl terephthalate
PET	Polyethylene terephthalate
MDI	Methylene diphenyl diisocyanate

Agora Industry and Carbon Minds (2023) based on Carbon Minds (2020) and VCI (2021a, 2021b). Chemicals are shown twice if their production process requires different precursors (e.g. PVC is based on both ethylene and chlorine). The radian corresponds to mass flows.

The chemical-pharmaceutical industry is the third largest manufacturing sector in the German economy, responsible for 10 percent of the total revenue from all manufacturing industries (cf. Figure 4). In 2019, this revenue amounted to 211 billion euros (Destatis 2022).

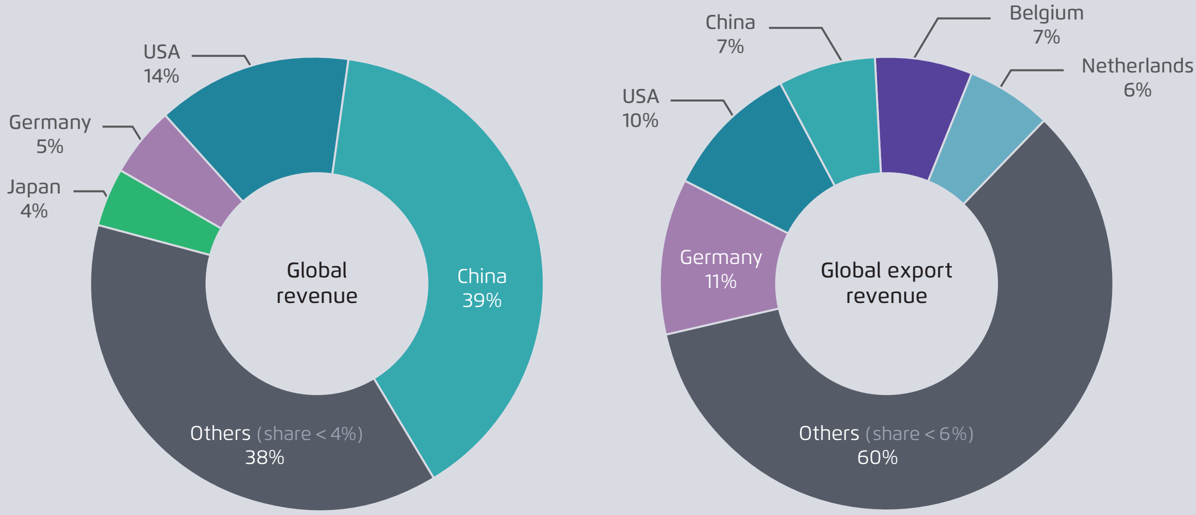
A large share of 63 percent of this revenue comes from exports, making the German chemical-pharmaceutical industry the largest exporter of chemicals and pharmaceuticals in the world in 2019, with a market share of 11 percent, ahead of China and the US (cf. Figure 5, VCI 2021a). The market for chemicals is an international one. Trade with basic chemicals and derived products is well-established, making them global commodities. Strong engineering expertise and innovation leadership made Germany an important player on the global markets for chemicals. However, the energy-intensive nature of the production of basic chemicals and their derivatives makes the chemical industry highly dependent on cheap energy. After the start of the Russian war of aggression against Ukraine,

Revenue by manufacturing industry in Germany in 2019 — Figure 4



Destatis (2022)

The comparative economic performance of the German chemical-pharmaceutical industry on the global stage in 2019 — Figure 5



VCI (2021a)

the production index for chemical products decreased by 21 percent between February and October 2022 (Destatis 2022).

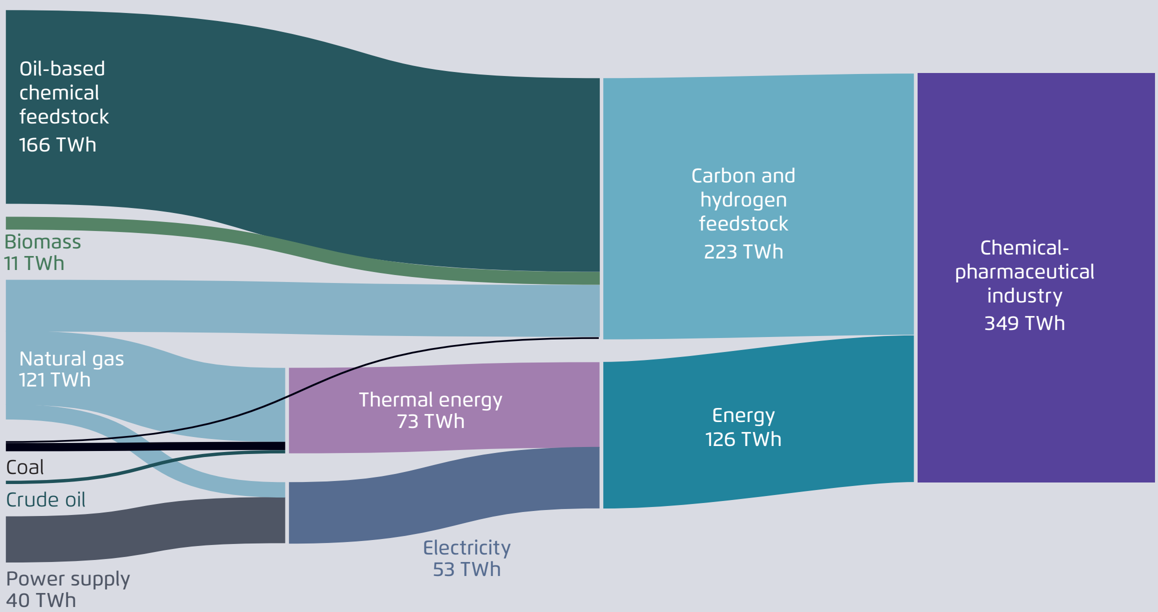
2.1 Resource use: switching from fossil feedstocks and energies to renewables

In 2019, the chemical sector used 349 Terawatt-hours (based on the lower heating value, TWh_{LHV}) of (mainly fossil) energies and resources to produce chemicals. The chemical sector is also a large consumer of electricity from the grid: although approximately 25 percent of its 53 TWh of electricity demand is produced on site, 75 percent is supplied by the power system. Figure 6 shows the feedstock and energy basis of the chemical industry. The supply of process energy in terms of power and heat accounts for 36 percent of the total energy demand. The remaining 64 percent is feedstocks – the materials that chemicals are made from.

Feedstocks

Today, most of the 223 TWh_{LHV} of feedstock is used for organic (carbon-containing) chemicals and comes from oil-based derivatives, such as naphtha, liquefied petroleum gas (LPG) and gas oils, which make up 74 percent of all feedstocks (cf. Figure 6). These oil-based derivatives are produced in refineries, where crude oil is refined into diesel, gasoline, fuel oil, naphtha, and LPG. The feedstocks for the chemical industry represent only a fraction of the production from refineries – refinery products that are not used in the chemical industry are not included in this study. Natural gas makes up 20 percent of feedstocks and is used mainly to produce fossil (grey) hydrogen, which is

Feedstock and energy inputs into the German chemical industry in 2019 — Figure 6



Agora Industry and Carbon Minds (2023) based on VCI (2021a, 2022a). The German chemical-pharmaceutical industry's most important sources of material feedstock and process energy according to the energy content. Refineries and oil-based feedstock used in other sectors are not included.

needed in the production of ammonia and in refineries as well as in the production of methanol.[4] Biomass currently makes up only a small proportion of total feedstocks for the chemical industry, roughly 5 percent, and is mainly used to produce chemicals used in products such as detergents, cleaning agents, cosmetics, plastics and lubricants (cf. Chapter 3.3.1).[5]

Process energy
The process energy demand of 126 TWh_{LHV} breaks down into 58 percent thermal energy and 42 percent electricity. The most frequently used technology to provide heat and on-site produced electricity for the chemical industry is natural gas-based combined heat and power (CHP) plants. This makes the chemical industry the largest industrial consumer of natural gas (Agora Energiewende 2022). In addition, coal, fuel oil and other fossil fuels are used in a few cases, for which however no data is available.[6] In addition to providing heat, CHP plants generate approximately 25 percent of the electricity demand from the chemical industry. The remaining 75 percent (around 40 TWh) is electricity drawn from the grid.

In total, natural gas – as both a fuel and a feedstock – and oil-based chemical feedstocks make up 83 percent of the German chemical industry's energy and feedstock supply.[7] The fossil energy crisis has therefore put the chemical industry under pressure, revealing its severe dependence on unreliable fossil fuel imports and its vulnerability to volatile energy prices. While state aid is important for cushioning high energy costs in the short term, it is crucial to respond to the crisis in a more structural way by reducing the need for fossil resources. Only by transforming its energy and resource base to renewable sources can the chemical industry structurally reduce its dependence on fossil fuel imports and its vulnerability to high energy prices.[8]

2.2 Greenhouse gas emissions: towards a life-cycle approach

Greenhouse gas (GHG) emissions associated with chemical industry products span the entire life cycle – they include emissions from the supply of feedstock, across the production and use phases of a product, right up to the end-of-life treatment.

In 2019, **direct emissions from the production of chemicals** accounted for 39 Mt $CO_{2\text{-}eq}$, which represents 21 percent of all industrial emissions in Germany (VCI 2022a). At just under 6 Mt, ammonia production accounted for a particularly large single-product share of the industry's total direct emissions. Since 1990, the chemical industry has managed to reduce GHG emissions by 55 percent – mainly due to strict regulation and process optimisation to mitigate nitrous oxide emissions.[9] The extensive elimination of nitrous oxide emissions accounts for about half of the GHG emission reductions since 1990 (VCI 2022a).

4 Around 30 percent of methanol production in Germany is based on natural gas. The other 70 percent uses oil-based products from refineries (Carbon Minds 2020).

5 The percentages refer to the energy content. The mass-related share of biomass is 13 percent.

6 In 2022, in response to high natural gas prices, the chemical industry increasingly switched its energy supply to other fossil fuels such as heating oil or coal. This is assumed to be a short-term measure to cushion energy costs rather than a long-term strategy.

7 Due to the share of fossil energies in the German electricity mix, the actual share of fossil energies is even greater than 83 percent.

8 Agora Energiewende presented a proposal for a structural response to high energy costs and inflation in November 2022 in the paper *Volle Leistung aus der Energiekrise* (Agora Energiewende 2022).

9 This study focuses on the chemical industry's GHG emissions (CO_2, nitrous oxides, methane, and other greenhouse gases). In addition, the chemical industry emits several other pollutants that can have severe environmental impacts, which are, however, not covered by this study.

Addressing these direct production-related emissions is crucial. However, they represent only a fraction of the overall life-cycle emissions from chemical products. Due to the lack of uniform standards for emissions accounting, reliable data on life-cycle emissions from chemicals are scarce. Based on the following calculations, it can be assumed that **indirect upstream and downstream emissions** are up to three times greater than direct emissions from the production of basic chemicals.

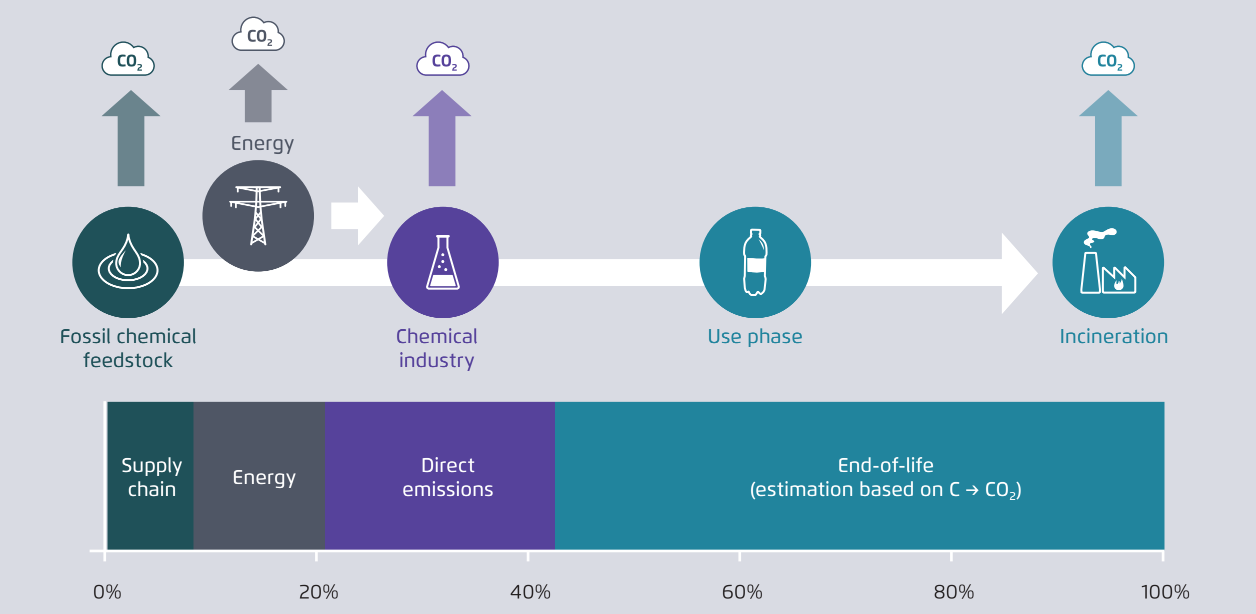
Upstream emissions: Based on statistical emissions factors for fossil resources[10] and the quantities of fossil resources needed to produce the ten basic chemicals, the supply of fossil resources accounts for approximately 6 Mt $CO_{2\text{-eq}}$. To a large extent, these are fugitive emissions of methane – a particularly climate-impacting greenhouse gas.

Downstream emissions: The end-of-life emissions are also difficult to estimate – more than 60 percent of products are exported and thereby withdrawn from the German recycling system. But products that remain in Germany are often not disposed of properly either – whether due to their application (e.g. cosmetics, detergents, tyre abrasion, etc.) or because of deficient waste collection (cf. Chapter 3.2). As recycling rates are low relative to the production volumes of all basic chemicals, the main method of waste treatment in Germany today is incineration.[11] Assuming that all basic chemicals and their derivatives are incinerated at the end of their life cycles, and that the embedded carbon enters the atmosphere as CO_2, the end-of-life emissions would amount to 42 Mt CO_2. The real figure, however, deviates from this estimate – partly

10 Statistical emissions factors for fossil resources based on the cm.chemicals database (Carbon Minds 2020).

11 Decreasing landfilling to protect human health and the environment is necessary in the EU and globally and therefore not considered as a viable option for waste treatment.

Estimated distribution of life-cycle emissions for basic chemicals produced in Germany in 2019 — Figure 7



Agora Industry and Carbon Minds (2023). Greenhouse gas emissions of ten basic chemicals according to the technology-specific impact in 2019 (VCI 2021b, Carbon Minds 2020). Emissions from manufacturing intermediate and final products are not considered.

due to methane emissions from existing landfills, but also due to products that accumulate in nature and that by default do not end up as CO_2. Moreover, product lifetimes vary widely, so that in some cases end-of-life emissions occur after a very long time lag. Figure 7 shows the life-cycle emissions of basic chemicals differentiated by upstream emissions (extraction of fossil resources), indirect emissions from the supply of energy[12] (fossil energies), direct process-related emissions from the production of basic chemicals and the corresponding end-of-life emissions under the described assumptions. Process emissions from basic chemicals to final product are not included here.

For comprehensive climate action, addressing the production-related emissions is not enough. Instead, the transformation of the chemical industry must address all life-cycle emissions. For this to happen, targeted policies are necessary, and strategic alliances must be forged along the entire value chain – between chemical companies and producers of end-consumer products and waste management companies, as well as with companies that provide feedstocks.

12 Including emissions from the power sector based on the average emissions in 2019.

3 The three pillars for tomorrow's chemical value chains

With the Paris agreement, the global community has committed to limiting global warming to 1.5 degrees Celsius, and most countries have put in place national climate neutrality goals targeting the middle of this century. Consequently, the global chemical industry, too, has to undertake a substantial transformation within the next three decades. While the goal of climate neutrality is an agreed target, the pathway to achieve it is still subject to many uncertainties, and as of now firm investment decisions of the required scale have not been taken. The chemical industry needs to transform its fossil-based linear value chain into an energy- and resource-efficient circular economy model based on renewable energies and renewable feedstocks – the chemical industry needs to "complete the circle".

The recent reform of the EU ETS requires the chemical industry in Europe to undertake a rapid shift towards net zero GHG emissions. It delineates an emissions reduction path for European industry to become climate-neutral before 2040. In Germany, the sectoral targets of the Climate Protection Act mean that ambitious emissions reductions are needed already in this decade. In addition to the climate crisis, the Russian invasion in Ukraine has underlined the need to urgently accelerate the defossilisation of our industry in order to reduce dependence on imports and regain energy sovereignty. In order to contribute its fair share of natural gas use reduction to the REPowerEU plan presented by the European Commission, German industry needs to roughly halve its natural gas consumption by 2030.

A bold and courageous transformation is key not only to the achievement of climate protection goals and energy sovereignty targets but also to the retention of jobs and value creation in Germany. As an important global player with a large share of exports, Germany could serve as a global role model. Bold and radical changes can be an opportunity for the German chemical industry to develop climate-neutral technologies and products and to accelerate the transition in other regions of the world.

Although energy efficiency has increased significantly over the last thirty years (chemicals production volume increased by 63 percent while energy consumption reduced by 19 percent (VCI 2022a)), a deep transformation is required to defossilise the chemical industry. When switching from a fossil to a renewable basis, both for energy and feedstocks, maximising efficiency is key. In order to reduce emissions as fast as possible, the available resources must be distributed as efficiently as possible.

Technologies and strategies should be selected for their efficiency, from a cross-sector perspective, with respect not only to the emissions from the production of chemicals but from the entire life-cycle (cf. Chapter 2). This requires a coherent set of objectives and strategies which must be shared by all relevant stakeholders along the value chain. For the decarbonisation of inorganic chemicals (chemicals such as ammonia and chlorine, which do not contain carbon), electrification – using renewable electricity – of both process energy and feedstock (via electrolysis) will play a key role.

When it comes to organic (carbon-containing) chemicals, a cross-sector approach is needed to achieve climate neutrality, but one that additionally enables the creation of CO_2 sinks. The chemical industry needs to become a carbon manager, treating waste as a resource, using renewable feedstocks and storing CO_2 from the atmosphere – captured in biomass via photosynthesis or via direct air capture. It is crucial that the industry becomes an integral part of a bioeconomy that aims to strengthen biodiversity, climate resilience, and CO_2 uptake while enabling the cascading use of

Priorities for a circular economy based on renewable carbon — Figure 8

Agora Industry (2023)

biogenic raw materials. Biogenic carbon must be kept in the cycle for as long as possible by means of both mechanical and, complementary to that, chemical recycling. For waste material that cannot be recycled and is incinerated, capturing the biogenic carbon to use as a feedstock for new processes can help close the carbon cycle (carbon capture and utilisation, CCU). In order to make the temporary CO_2 sink created by using renewable carbon sources permanent, the incineration of non-recyclable waste can be combined with carbon capture and storage (CCS) for the geological storage of residual biogenic CO_2 emissions. The actions required for this cross-sectoral CO_2 mitigation and carbon management is based on the three pillars of **direct electrification and flexiblity**, **circular economy** and **renewable feedstocks**. These pillars complement each other and are explained in the following chapters.

3.1 Direct electrification and flexibility

Electrification plays a crucial role in the transition of the chemical industry and can be separated into two parts: 1) the **direct electrification** of industrial process heat via heat pumps, electric boilers, furnaces and other technologies in a wide range of chemical processes at all temperature levels; and 2) **indirect electrification** through the replacement of fossil-based hydrogen, which is used e.g. in the production of ammonia, by renewable hydrogen. In addition, the processes already powered by electricity today (e.g. chlor-alkali electrolysis) must also be based on renewable energy in the future. Furthermore, by instituting flexible, system-serving electricity demand, industry can contribute to the deployment and integration of additional renewables – the basis for the energy transition (cf. Chapter 3.1.3).

The energy crisis has highlighted the dependence of the German chemical industry on cheap fossil gas from Russia. While it has been possible to switch some processes from natural gas to other fossil fuels such as light heating oil, in others, the demand for natural gas could only be reduced by cutting domestic production, e.g. of fertilisers, where no substitute for fossil gas as a feedstock is yet available: between February and October 2022, the production of chemicals decreased by 21 percent (Destatis 2022).

Today, almost 40 percent of all fossil fuels consumed by the chemical industry is used energetically to provide power and heat in industry, for example in CHP plants (cf. Fig. 6). The process energy used in the chemical industry in 2019 amounted to 73 TWh of heat[13] and 53 TWh of electricity. Natural gas is the most important energy carrier for the chemical industry, with a primary energy consumption of 77 TWh_{LHV} in 2019 – approximately eight percent of Germany's natural gas consumption.[14] As shown in Figure 6, coal and oil play a less important role as energy sources (VCI 2022a, VCI 2022b). It can be assumed that three quarters of the electricity consumed come from the grid while one quarter is co-produced on site via CHP plants.

In the interest of energy sovereignty, the German chemical industry needs to initiate a rapid industrial heat transition. The European REPowerEU plan sets out the ground plan for the energy crisis intervention until 2030: European industry is required to reduce its natural gas demand by 43 billion cubic metres (423 TWh_{LHV}) by 2030. If it is to make an appropriate contribution to achieving the target, German industry must roughly halve its natural gas consumption in the next 7 years.

Decarbonising process energy is also crucial from a climate perspective. The energy requirement for producing the ten basic chemicals alone is responsible for almost 10 Mt CO_{2-eq}. The German Climate Protection Law requires industry to reduce its annual emissions by 59 Mt CO_{2-eq} by 2030 in order to remain within the limit of 118 Mt CO_{2-eq} set for 2030. Compared with approximately 177 Mt CO_{2-eq} in 2022, this means industry's emissions must decrease by one third (Agora Energiewende 2023).

Emissions related to the generation and use of process energy must be addressed in a resource-efficient way that also contributes to the integration of energy generation and use in the chemical industry and to the transformation of our energy system at large. Climate-neutral heat offers opportunities to improve the integration of renewable energy through flexible consumption, e.g. in combination with heat storage.

Direct electrification of industrial heat will play a crucial role in reaching the 2030 gas savings and climate protection targets. A detailed analysis of the role of direct electrification and its implications for the power sector and for competitiveness was published by Agora Industry in the study *Power-2-Heat: Gas savings and emissions reduction in industry* (Agora Industry, FutureCamp 2022).

3.1.1 Strategies for climate-neutral heat

Energy efficiency

Today, 86 TWh_{LHV} of fossil fuels and approximately 40 TWh of electricity from the grid are used to cover the process energy demand from the chemical industry (cf. Figure 6). The principle of energy efficiency needs to be the top priority on the path to climate-neutral heat. While integrated Verbund sites typically have very good energy integration, the recycling of waste heat can be further improved – for example by using heat pumps. The development of catalysts and new processes are further ways to reduce energy demand in industry, beyond obvious approaches such as improving insulation (which is becoming more and more economic with rising energy prices).

The remaining energy demand must in future be met with renewable energies. A successful heat transition that is both economic and sustainable in the long term needs to take into account limited resources and their future competing uses. The focus must be on energy- and resource-efficient solutions.

Use of alternative fuels

A much-discussed topic in times of high energy prices is replacing fossil fuels in combustion processes by alternative fuels such as biomass, biomethane or even

13 Several processes involved in the conversion of fossil carbon feedstocks to chemicals and plastics produce by-products that are used as fuels on-site. These "by-product" fuels are not included here.

14 The percentage relates to natural gas used purely for energy. If natural gas used as a feedstock is included, the figure is 13 percent.

plastic waste.[15] The use of plastic waste as a fuel is already common practice in the cement industry. However, in view of the limited resources available in Germany, the use of alternative fuels is not a sustainable strategy: The resource use of plastic waste needs to focus on recycling in order to close the carbon cycle (cf. chapter 3.2). Biomass can be used more efficiently as a source of renewable carbon (cf. chapter 3.3). The energetic use of biomass and biomethane limits its potential to create long-term CO_2 sinks.

Use of renewable heat sources

The use of renewable heat sources is an important element of the heat transition. One option is deep geothermal energy, which harnesses heat at up to 180 degrees Celsius from rock strata at depths of 1 000 to 4 000 metres. Geothermal energy is regarded as having great potential in Germany but requires large, high-risk investments (Fraunhofer and Helmholtz 2022). Another technology option for the provision of low-temperature renewable heat is concentrated solar thermal energy in combination with heat storage systems. The main disadvantage here is the high spatial requirement (IN4climate.NRW 2021). In general, due to technical, geological, and spatial conditions, the use of renewable heat sources in the chemical industry is only possible in a small number of specific cases.

15 As renewable hydrogen is an electricity-based alternative fuel, it is dealt with in the section below and in the info box.

Direct electrification

Electricity-based processes such as heat pumps, electric boilers and resistance furnaces are an important element of the industrial heat transition and can be used in many sectors and industries.

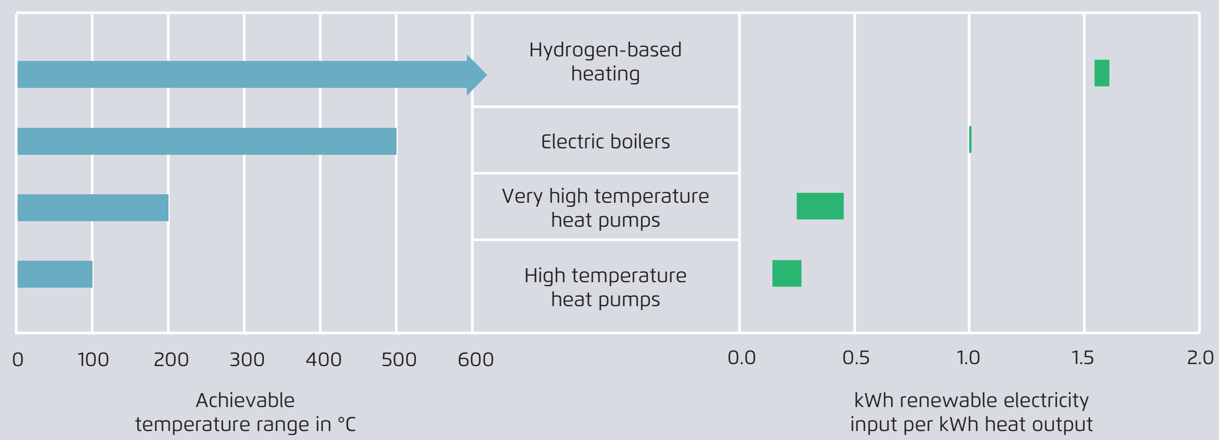
Industrial heat transition: direct electrification vs. renewable hydrogen

The direct use of electricity to provide process energy is the most resource-efficient and fastest way to contribute to climate protection and energy autonomy goals. Despite this, in the political debate, the indirect use of electricity through hydrogen receives much more prominence. Direct electrification, for example with heat pumps, electric boilers and electric furnaces, has two decisive advantages over energetically used hydrogen:

1. **Energy efficiency.** While direct electrification supplies heat at very high efficiencies, the production, transport, and combustion of hydrogen is subject to high efficiency losses. As shown in Figure 9, renewable hydrogen requires more than 1.5 kWh to provide 1 kWh of heat, while electric boilers require only 1 kWh, and particularly efficient heat pumps manage with just 0.25 kWh. As shown in Figure 10, direct electrification can in fact reduce the primary energy demand of the sector by 15 percent, while the use of renewable hydrogen would effectively lead to an increase of 31 percent.
2. **Availability and infrastructure.** The production, transport, and use of renewable hydrogen require new capital equipment (electrolysers) and infrastructure that must be specifically developed. Investment should instead be focused on decarbonising industrial processes where no other solution is available, such as the use of hydrogen as feedstock in chemical and metallurgical processes. For applications that can be electrified, the existing electricity network can be gradually expanded and reinforced, and the use of diverse and smart electrification technologies and demand-side flexibility can support the development of a cost-effective and resilient renewable electricity system. In addition, hydrogen also has an (indirect) greenhouse gas effect. Hydrogen infrastructure comes hand-in-hand with unavoiable leakage and should therefore be limited to a necessary level.

Achievable temperature ranges and electricity requirements of electricity-based technology options for climate-neutral heat

Figure 9



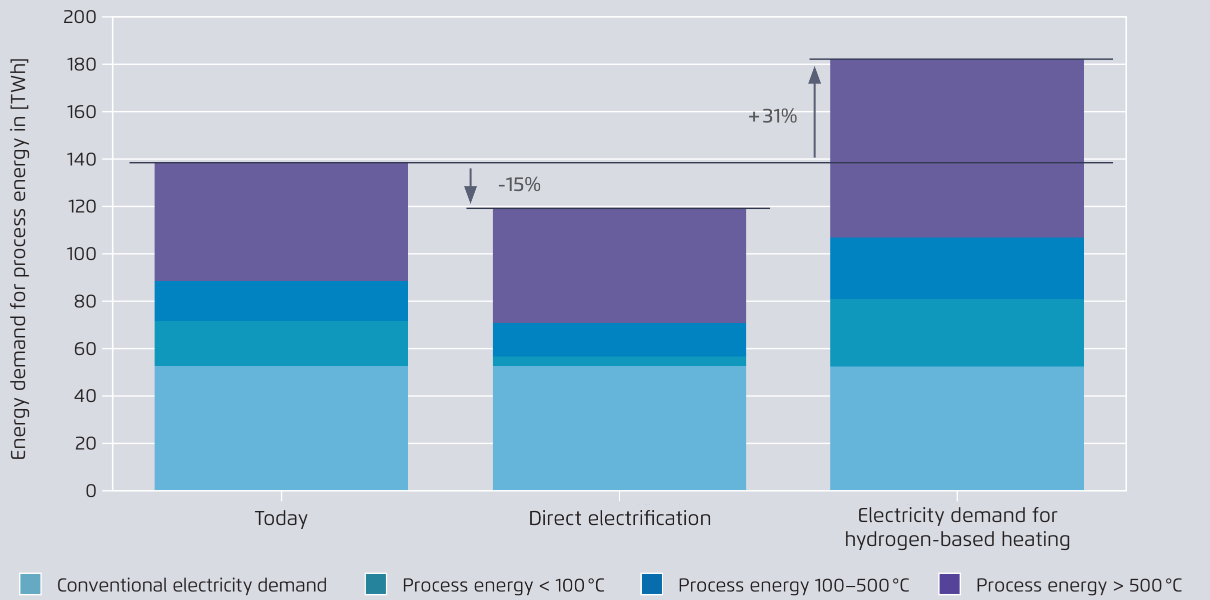
Agora Industry and FutureCamp (2022)

Heat pumps use waste or environmental heat as a heat source and electric compressors to upgrade the temperature of that heat to a level at which it can be used in industrial processes – which then become heat sinks. The smaller the temperature difference between the heat source and the heat sink, the higher the efficiency of the heat pump. On average, two to four kilowatt-hours of renewable heat can be provided from one kilowatt-hour of renewable electricity (Agora Industry, Future Camp 2022). In specific applications with particularly small temperature differences, even higher efficiencies are possible (Madeddu et al. 2020). Heat pumps available on the market today reach temperatures of up to 180 degrees Celsius, and with ongoing research and development, temperatures of up to 200 degrees Celsius are within reach (Joormann and Laister 2019). Even above this temperature level of 200 degrees Celsius, the use of heat pumps can be viable if the supply of waste heat at sufficient temperature levels can be ensured (cf. Figure 9).

Electric boilers are an established technology which produces heat by directly exposing electrodes under voltage to a heat transfer medium. In combination with electrical superheaters, electric boilers can produce steam at up to 500 degrees Celsius (Agora Energiewende and Wuppertal Institut 2019). Electric boilers can be operated independently from waste heat, reach higher temperatures than heat pumps, and have lower capital investments, but require larger amounts of renewable electricity (cf. Figure 9). The efficiency of electric boilers is close to 100 percent – i.e. one kWh of electricity provides one kWh of heat (Schüwer and Schneider 2018).

Electrifying processes in the chemical sector that demand heat below 500 degrees Celsius is particularly suitable given high efficiencies and technologies already available which can be used in various processes. Their applicability in different industries enables the transfer of know-how and experience and a rapid scale-up of manufacturing

Energy consumption for the provision of process energy for basic chemicals in Germany | Figure 10



Agora Industry and Carbon Minds (2023)

capacities (Agora Industry and Future Camp 2022; Madeddu et al. 2020).

Above 500 degrees Celsius, the heat transition is more sector- and process-specific. However, for high and very high temperatures, e.g. for steam cracking, technologies like electric furnaces or electric steam crackers are either already available or are currently in development. Resistance heaters, for instance, can reach temperatures close to 1500 degrees Celsius and achieve efficiencies of 98 percent (Lupi 2017). Already established technologies can directly electrify 78 percent of the heat demand, and as much as 99 percent of industrial heat is electrifiable with technologies currently under development (Madeddu et al. 2020).

The use of alternative fuels such as renewable hydrogen should primarily be reserved for those cases where direct electrification is not a technically feasible option. The use of energy-intensive, expensive, and, for the foreseeable future, scarce renewable hydrogen needs to be prioritised for non-energy applications such as the production of steel, ammonia, and methanol.

3.1.2 Electrifying feedstocks: green ammonia

Ammonia is one of the most emissions- and natural gas-intensive basic chemicals: in 2019 its production was responsible for approximately 6 Mt of direct CO_2 emissions and roughly 3 percent of Germany's total natural gas consumption.[16] It is predominantly used in fertiliser production, but also in some polymer production chains such as for nylon. Ammonia (NH_3) is an inorganic chemical composed of hydrogen (H_2) and air nitrogen (N) and is synthesised in the Haber Bosch process. Since ammonia is an inorganic chemical, i.e. does not

16 Estimate based on production volume according to Umweltbundesamt (2021b) and characteristic emissions and natural gas consumption of ammonia production according to Agora Energiewende and Wuppertal Institute (2019).

contain carbon, and its components hydrogen and nitrogen can be supplied comparatively efficiently with renewable electricity, it is treated in this chapter and not in Chapter 3.3, which focuses on organic chemicals.

The large quantities of hydrogen used for ammonia production today are mainly produced from fossil gas and water by steam methane reforming. For renewable ammonia, the hydrogen source must be renewable. The main option for the supply of renewable hydrogen is indirect electrification via water electrolysis, whereby renewable electricity is used to split water into its components, hydrogen and oxygen. Since in the production of ammonia renewable hydrogen used as a feedstock and not to produce heat, ammonia production is considered a no-regret option for the use of renewable hydrogen (Agora Energiewende 2021). In addition to its use in ammonia production, the fossil hydrogen is used as a feedstock in the production of methanol and in refineries should also be replaced by renewable hydrogen. Moreover, chemical recycling will create an additional demand for renewable hydrogen (cf. Chapter 3.2; Agora Energiewende 2021).

3.1.3 Flexible use of renewable electricity

The German government has set a target of generating 80 percent of its electricity consumption via renewables by 2030. Electricity production from solar PV and wind is volatile. In order to match production and consumption, electricity production from other sources must be increased at certain times (e.g. from baseload power plants). At other times, when renewable energy production exceeds demand in some regions, this excess availability of renewable electricity often results in the curtailment of renewable production. To enable large shares of renewables, the share of baseload energy demand needs to decrease – in part through making demand more flexible and in part through the use of storage technologies.

Both the electrification of process heat and the use of electrolysers provide important options for increasing flexibility in electricity consumption. Despite the high efficiencies of direct electrification technologies, which can reduce overall energy demand compared to the status quo (cf. Figure 10), a shift from natural gas to electricity significantly increases the overall electricity demand from industry. The more the industrial heat transition and the decarbonisation of the power sector are aligned, the greater the synergies for an efficient transition. A system-serving consumption can thereby stimulate the additional expansion of renewable energies.

With the further deployment of renewables, the periods when excess renewable power is generated will increase. This excess availability of renewable electricity causes a decline in wholesale electricity prices. Low prices and the curtailment of generation lead to low revenues that undermine the value of renewable energy and thus lower the profitability of investment in additional renewables – the so-called *cannibalisation effect*. To counteract this *cannibalisation effect*, additional demand must be created during periods of particularly high renewable electricity production. Conversely, when renewable production is low, demand needs to be decreased to limit the utilisation of costly hydrogen-fuelled power plants or costly electricity storage. Figure 11 shows the modelling results for power prices for a climate-neutral power system.[17] The volatility of production leads to a wide range of power prices – very low prices at some hours and high prices at others. Industrial consumers who increase the flexibility of their electricity consumption benefit the power system by balancing supply and

17 With 80 percent renewable power production in 2030, a climate-neutral power sector by 2035 would be within reach. Agora Energiewende, together with Prognos and Consentec, has investigated how this goal can be achieved in the study *Climate-neutral power system 2035* (Agora Energiewende, Prognos and Consentec 2022).

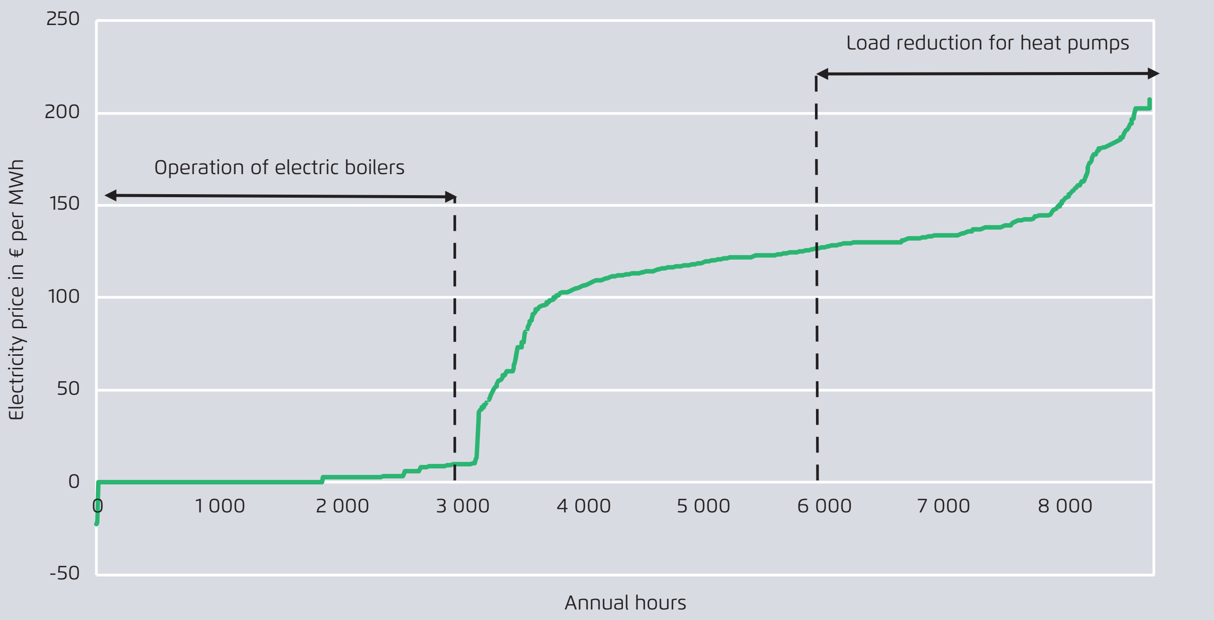
demand and, from an economic standpoint, benefit directly from cheap renewable electricity.

Today's conventional electricity demand in the chemical industry is mostly not flexible. The high efficiency of the chemical industry can be attributed in part to continuous, i.e. constantly operated, processes. This is a result of decades of engineering, and it is in many cases critical to profitability. In the industrial heat transition, electricity demand based entirely on renewables can and must be more flexible (Agora Energiewende, Prognos and Consentec 2022).

In the short term, combining electrified processes with existing fossil processes can reduce emissions and increase experience with using the technology. Chemical production sites usually have back-up capacity for energy supply in order to guarantee the operation of downstream processes during shutdowns. Electrifying back-up capacities for steam production, for example, enables hybrid fossil and electricity-based production. Another option is to supplement existing facilities with electrified systems and to reduce the utilisation of fossil processes when renewable electricity availability is high and power prices are low.

Another opportunity for flexible operation is in the production of renewable hydrogen, used for example for ammonia production, or as a back-up for the power system, where hydrogen can be produced in times of high renewables production and can then be reconverted to electricity when production from wind and solar is low. The chemical industry today is the largest consumer of fossil hydrogen (Agora Energiewende 2021). Supplementing existing fossil-based hydrogen production with hydrogen electrolysis can partially decarbonise both refineries and the

Electricity prices for the scenario *Climate-neutral power system 2035* — Figure 11



Agora Energiewende, Prognos and Consentec (2022) production of ammonia and methanol and provide flexibility to the power system.

In both the medium and long term, storage technologies for power, heat, hydrogen, and intermediate products can provide a flexible demand of electricity and enable constantly operated downstream processes.

Renewable energies offer a lower levelised cost of electricity (LCOE), i.e. lifetime costs, than fossil-based electricity production. The LCOE of renewables is on average much lower than the electricity prices on the wholesale market. Electricity market pricing is primarily determined by the costs of the (to date usually fossil) marginal power plant supply. While the LCOE of renewables is mainly determined by investment costs and thus constant at a low level, the LCOE of fossil power plants is determined by fossil fuel prices and the CO_2 price. As the energy transition progresses and the share of renewables in the electricity mix increases, renewables are increasingly providing the marginal power supply, resulting in systemically low electricity prices. A rapid energy transition in the energy-intensive chemical industry is

Power Purchase Agreements (PPAs)

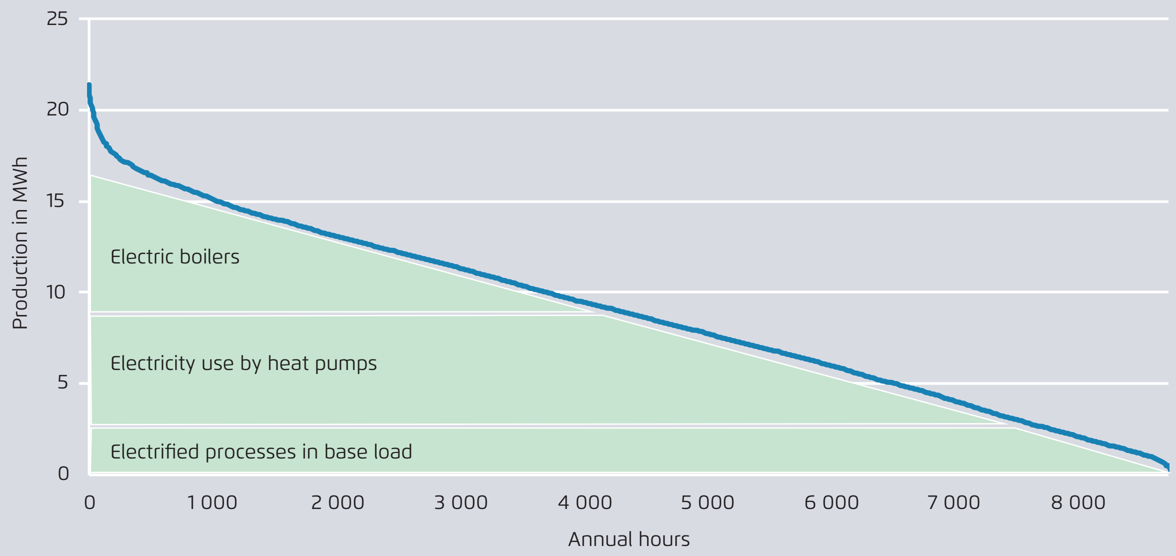
One way for companies to benefit from the low LCOE of renewables in the short term is to deploy their own renewables or via the purchase of renewably generated electricity through long-term corporate green Power Purchase Agreements (PPAs). Combining investment in renewables and flexible electrification is a way to mutually hedge both risks: electrified industrial facilities gain access to predictable cheap power prices, and for renewable energy producers, the demand for the electricity produced is ensured at economic rates.

To illustrate how companies can mutually optimise both the generation and use of renewable electricity, Figure 12 depicts the load duration curve for the power production of a hypothetical portfolio of 10 Megawatts (MW) each of photovoltaics, onshore and offshore wind power. As shown in the graph, such a portfolio can, for example, be combined with 7.5 MW of electric boilers that operate at up to 4 000 full-load hours annually. In addition, another 7 MW of heat pumps can be operated between 4 000 and 8 000 hours. Heat pumps are capital-intensive investments but need relatively little electricity per unit of heat provided. As a result, many full-load hours are required to make the investment profitable. Electric boilers are less capital-intensive but require much more electricity per unit of heat output, which makes them more attractive for operation at low full-load hours with low electricity costs. The flexible use of electric boilers and heat pumps enables a base-load electricity consumption of 2.5 MW for processes that are not suitable for flexible operation. The described flexibilities of electric boilers and heat pumps result from hybrid operation with existing plants. For a complete supply of renewable heat, direct electrification can be combined with storage technology. Since process steam cannot be stored easily, electricity-based heat is generated flexibly and stored in a suitable medium, such as special cement or ceramics. Steam is generated in a continuous subsequent process.

In the case as described of mutually hedged investments in renewables and electrification, companies can still purchase and sell electricity on the power market. A portfolio of flexible loads and power generation together with active and effective participation in the power market also allows businesses access to low-cost renewable electricity for their base-load processes.

Electricity production of a renewable portfolio consisting of 10 MW each of photovoltaics, onshore and offshore wind power

Figure 12



Agora Industry and FutureCamp (2022). Data basis for the yield by generation technology is national production in 2020 divided by nationally installed capacity based on the Agorameter.

therefore an important element in securing Germany's industrial base against international competition.

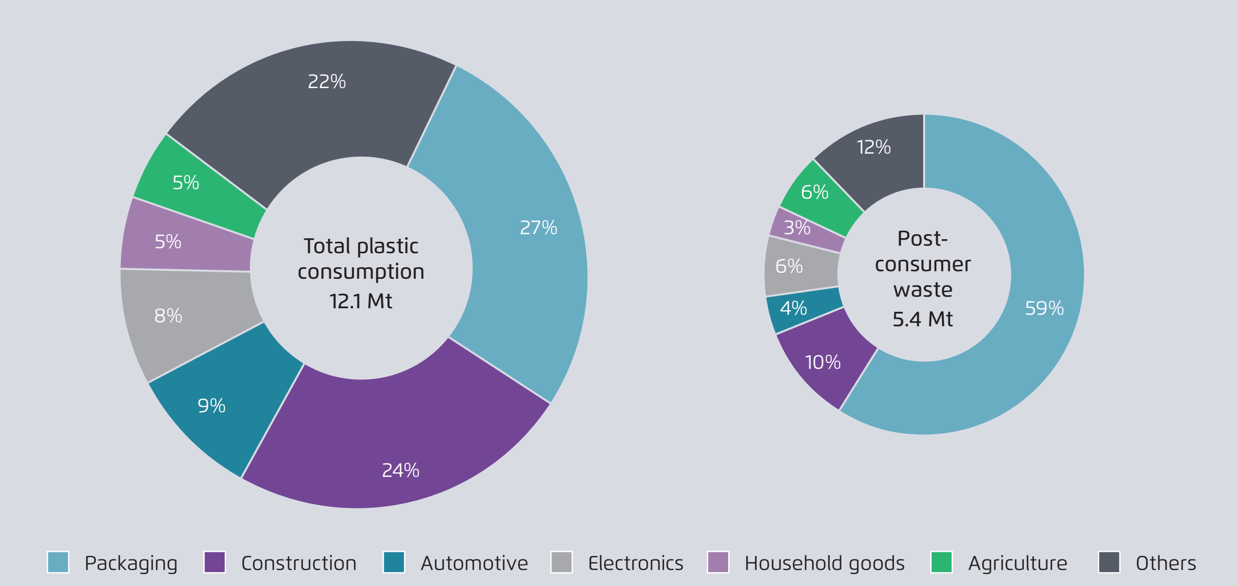
3.2 Closing the carbon cycle

Most of the fossil carbon used to produce organic chemical products (particularly plastics) ends up as CO_2 in the atmosphere after only one use phase, which often lasts only a few months. For plastics, these end-of-life emissions typically account for more than 50 percent of the life-cycle emissions (cf. Chapter 2.2). A circular economy is a key element to structurally reducing the life-cycle emissions of plastics as well as littering and pollution. The recycling of plastic waste reduces emissions from incineration and reduces the need for raw materials. At the same time, plastic waste can be used as a local resource, leveraging local value creation. Circular economy concepts such as the reuse of chemicals can also play an important role in efficient energy and resource use apart from plastics, including for inorganic chemicals (e.g. leasing and reusing of coolants or solvents). This study, however, focuses on the importance of a circular economy for plastics.

As shown in Figure 13, plastic packaging makes up 27 percent of all plastic products and 59 percent of the plastic waste produced in Germany in 2019 (Conversio 2020). Low recycling rates and high emissions from the incineration of plastic waste result in large CO_2 emissions at the end of life.[18] Theoretically, incinerating all of the plastic

18 Due to regulatory requirements, landfilling of plastic waste no longer plays a role in waste treatment in Germany and is of decreasing relevance across the European Union (2008/98/EC and Directive (EU) 2018/851).

Total plastic consumption and post-consumer plastic waste in Germany in 2019 — Figure 13



Conversio (2020)

consumed in 2019 (12.1 Mt) would result in approximately 34 Mt CO_2.[19] Emissions from the incineration of plastic waste are usually not attributed to the industrial sector but to the power sector, and can only be mitigated by a joint effort along the entire value chain (i.e. primary industry, end product manufacturers and waste management companies). The reform of the EU ETS will include waste incineration in the future, and EU countries will have to measure, report, and verify emissions from municipal waste incineration installations from 2024 onwards. By 2026, the EU Commission intends to present a report on including such installations in the EU ETS from 2028, with a possible opt-out until 2030 at the latest. Further options for reducing emissions include the reduction of the overall amount of plastic produced as well as improving circularity through recycling.

The current legislative approach to a circular economy, i.e. the Closed Substance Cycle and Waste Management Act, has proved to be insufficient to leverage recycling. The German government is currently developing a new national circular economy strategy. In addition to lowering CO_2 emissions, an efficient circular economy reduces reliance on fossil energy imports and enhances local value creation through the efficient use of valuable recyclable waste materials.

Optimising the efficient use of chemicals

In order to reduce emissions related to chemicals, the highest priority is to strengthen the efficient, high-quality and long-term use of chemical products, and to avoid and disincentivise the use of unnecessary and short-lived products. To this end, in addition to banning selected short-lived

19 This is an estimate which assumes that the combustion of one tonne of plastic emits 2.8 tonnes of CO_2. The exact greenhouse gas emissions from the incineration of plastics depends on the composition of the plastic waste among other factors.

and unnecessary plastic products, business models can be strengthened which forgo packaging and are based on reuse and refill. Innovative business models based on sharing and leasing can reduce demand while providing the same level of service (e.g. packaging as a service). Incentivising design for repair can also reduce the amount of waste.[20]

Recycling

Recycling chemical products – particularly plastics – that have reached the end of their useful lives has a double advantage. Firstly, recycling reduces emissions that would otherwise occur when the products were incinerated. At the same time, using recycled material in the production of new products reduces the need for virgin feedstock. Various technologies exist for the recycling of plastics which can basically be classified into mechanical or chemical recycling.

Reported high materials recycling rates in Germany, such as the 39 percent figure reported by Conversio (2020), or the 46 percent reported by Umweltbundesamt (2021a), give a misleading picture: in fact, most of the plastic waste generated in Germany is incinerated.[21] Methodologically, the recycling rate is recorded as the proportion of available, separately collected plastic that goes into the recycling process. However, Material Economics estimates that the initial volume of plastic waste is much higher. For the European Union, it is estimated that plastic waste volumes are about 50 percent higher than is assumed by policy makers and industry (Material Economics 2022). In addition, the high recycling rate often referred to does not take into account recycling process losses. If plastic waste that is not recorded as such is included, it can be assumed that the real recycling rate is significantly lower. At the European level, it is estimated that the real recycling rate for plastics is around 15 percent instead of the reported 35 percent (Agora Industry 2022b). In order to mobilise the full potential of recycling and to set appropriate recycling targets, the methodology for tracking recycling rates needs to be replaced by a "product-to-product" approach that includes all losses as well as low plastic waste collection rates (cf. Chapter 3.2.1).

Mechanical recycling

Today's recycling is almost entirely based on mechanical recycling. Mechanical recycling is the process of remelting sorted plastic waste into new products. This is a particularly efficient process, as the molecular structure of plastics, the polymers, remains intact during the process. However, waste streams are only eligible for high-grade mechanical recycling if they contain only one type of plastic with small levels of impurities. The higher the level of impurities, the lower the quality of the recyclate. At high impurities levels, it is difficult to produce high-quality products from the recyclate. Mechanical recycling of mixed plastic waste mostly results in downcycling – recycling to lower value products. Typical products from downcycling are sound barriers, pallets, cable pipes, and park benches (Huckestein and Plesnivy 2000).

In order to mobilise the potential for mechanical recycling and to tackle downcycling, the collection rates for plastic waste need to be improved. In addition, pre-sorting by the consumer must be incentivised so that more plastic enters sorting and recycling systems (e.g. by enforcing the dual system or deposit refund schemes). At the same time,

20 Little reliable data is available on the CO_2 mitigation potential from eliminating unnecessary packaging and promoting reuse and innovative products. For the European context, a previous study by Agora Industry estimates an emissions reduction potential of 8 Mt CO_2 (Agora Industry 2022b). A study by SYSTEMIQ estimates that 5 Mt of plastic waste, equivalent to emissions of approximately 14 Mt CO_2, can be saved annually by 2030 (SYSTEMIQ 2022). These values represent a reduction of plastic waste by 6 to 11 percent by 2030.

21 Some 39 percent of the separately collected plastic waste in the dual system is reported as being recycled, while 9 percent is exported and more than 50 percent incinerated (Conversio 2020).

sorting systems must be improved so as to generate recyclable mixes.[22]

Even if this happens, multilayer packaging, black and dark packaging, and combining similar polymers in one form of packaging pose major challenges for sorting equipment. Automated sorting of mixed plastic waste almost always results in polymer blends of two or more polymers – which often results in turn in downcycling (Schyns and Shaver 2021, Ragaert et al. 2017). Design for recycling is an approach in which potential recycling at all stages of the life cycle is taken into account in the product design from the outset. Examples of design for recycling are avoiding the use of black plastics or mixed packaging.

One success story with regard to mechanical recycling is the deposit refund scheme for PET bottles. The separate collection and clear standardisation of PET bottles results in very pure waste streams and in consequence a very high recycling rate of 98 percent (GVM 2020). The extension of deposit refund schemes beyond PET bottles offers significant potential for the very efficient recycling of plastic packaging.

Agora Industry estimates that recycling rates for mechanical recycling in the European Union could theoretically be raised from 15 to 35 percent (measured from end-of-life to final product) (Agora Industry 2022b). However, as the process of melting has a degrading effect on the polymer chains, even in the case of pure plastic waste streams, mechanical recycling alone cannot be fully circular. Today, many high-tech composite materials are based on the combination of different components. These composite materials cannot be recycled mechanically, and design for mechanical recycling is unlikely to deliver the required product properties (e.g. low weight and high stiffness for wind turbine blades).

Chemical recycling

Chemical recycling is a term for a group of technologies that can complement mechanical recycling and unlock high rates of circularity. In chemical recycling, plastic waste is not simply melted but broken down into its chemical building blocks. Table 1 gives an overview of recycling approaches. The technologies require different compositions and purities of waste and have the potential to complement each other effectively. As shown in Figure 14, the recycling products from the respective technologies can be fed in at different stages of the chemicals value chain. Chemical recycling technologies are typically more energy-intensive than mechanical recycling and need to be run on renewable energy to ensure CO_2 emissions reduction. Just as with mechanical recycling, chemical recycling involves process losses due to content that cannot be recycled or would require large amounts of energy or disproportionate sorting effort to recycle. This results in a trade-off between materials efficiency, energy efficiency, and cost effectiveness. Thus, the use of chemical recycling is explicitly not an alternative to incentivising design for recycling and improved sorting, but complementary.

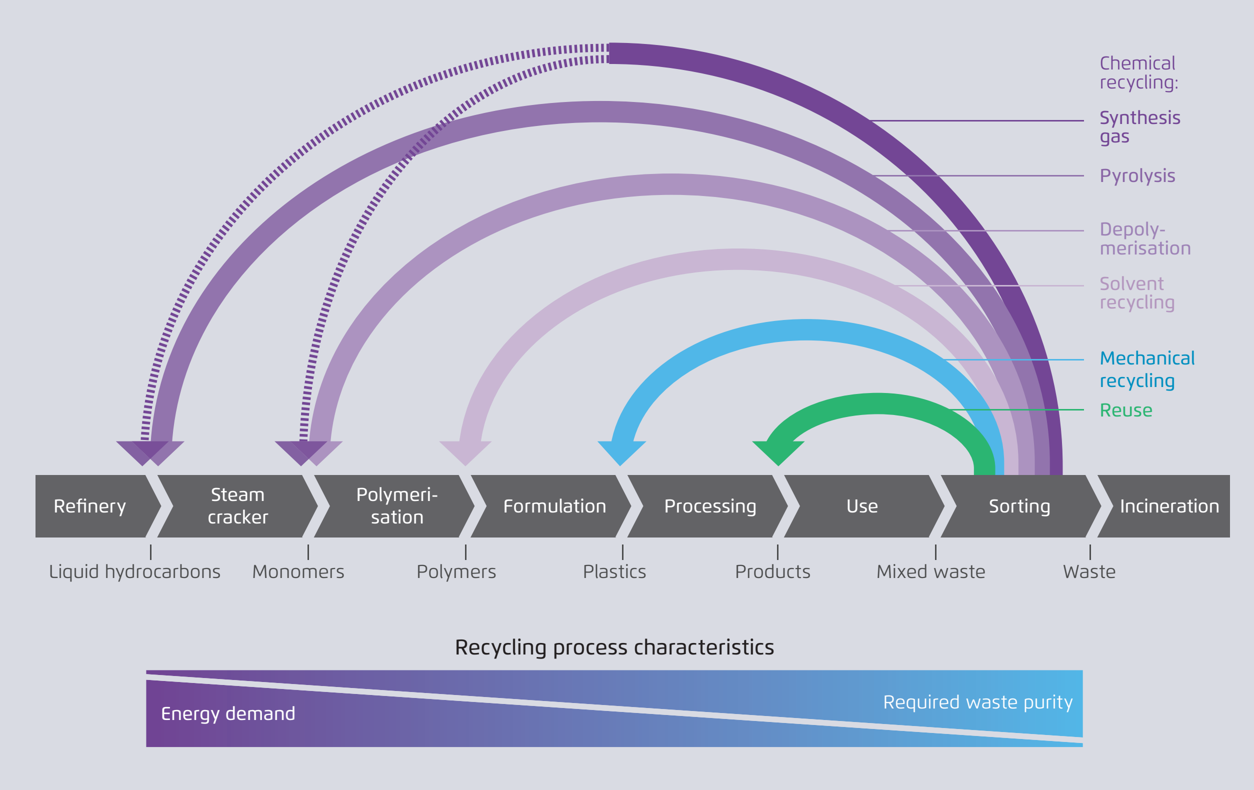
The use of chemical recycling processes with high energy requirements in particular must be carefully weighed up. The process must lead to a significant reduction overall in CO_2 emissions and resource demands. Chemical recycling will create a significant feedstock demand for hydrogen (Agora Energiewende 2021), and the supply of hydrogen must be in line with the decarbonisation of the power sector. The crucial principles here are set out in chapters 3.1.2 and 3.1.3.

Carbon capture and utilisation (CCU) and carbon capture and storage (CCS)

For the remaining waste materials that cannot be recycled (e.g. adhesives, paints, non-recyclable

22 Established sorting systems use various methods such as Fourier-transform infrared spectroscopy, optical colour sorting, sink-float methods and manual sorting (Ragaert et al. 2017). Typically, different sorting methods are combined to achieve the highest possible separation efficiencies.

Complementary recycling technologies for a circular economy — Figure 14



Agora Industry and Carbon Minds (2023)

plastics, etc.), the final technological option for closing the carbon cycle is to incinerate these materials and capture the emitted carbon to use as a feedstock for new processes (CCU). Compared to mechanical and chemical recycling, this is the most energy-intensive option. In developing the circular economy, the focus must be on energy and material efficiency and on a complementary use of technologies. CCU is therefore the "technology of last resort" to prevent CO_2 emissions leaving the carbon cycle, i.e. being emitted into the atmosphere or being stored geologically (carbon capture and storage, CCS).

CCS can be used to prevent CO_2 emissions from non-recyclable chemical waste being released into the atmosphere. The non-recyclable chemical waste can be used as an alternative fuel in industries or incinerated directly at waste incineration plants to produce heat and electricity. The resulting emissions are captured, transported to storage sites and stored long-term underground. CCS should be prioritised for industries that need access to CO_2 infrastructure anyway to deal with non-abatable emissions, such as cement plants with oxyfuel kilns (Agora Industry 2022a). Here, the emissions from incinerating waste materials can be captured efficiently together with the process emissions from clinker production. For CCS to be considered a useful option on the path towards climate neutrality, the carbon capture rate is crucial. However, CO_2 capture rates cannot practicably reach 100 percent, and residual emissions would therefore have to be compensated for elsewhere. Moreover, CO_2 infrastructure

Overview of recycling technologies		Table 1
Recycling technology	**Short description**	**Optimal waste input**
Mechanical recycling	Sorted plastic waste is remelted into new plastic products.	Pure single polymer waste (PET, PE, PP, …)
Solvent recycling	Plastic is dissolved by heat and solvents into a solution of its components (mostly polymers and additives) and separated.	Specific multilayer packages (e.g. PE-Aluminum)
Depolymerisation	Polymers are broken down into their monomers using various solvents and heat (methanolysis).	Polymer groups (polyester), pure single polymer waste
Pyrolysis	Polymers are broken down into liquid hydrocarbons under high temperatures and anaerobic conditions (without oxygen).	Mixed polymers with a high polyolefin share
Gasification	Plastic waste is heated with gasification agents (e.g. steam, oxygen and air) and converted into synthesis gas (hydrogen, carbon monoxide and carbon dioxide).	Mixed polymers

Schyns and Shaver (2021), Saebea et al. (2020), Kusenberg et al. (2022), Zhao et al. (2018)

would need to be built to transport the CO_2 to storage facilities. Finally, only limited CO_2 storage facilities are available (Prognos, Öko-Institut and Wuppertal Institut, 2021). A carbon management strategy is therefore needed that sets clear standards in order to prioritise the access of residual carbon emissions to CO_2 storage facilities. However, CCS is not an alternative to the use of renewable raw materials and must not be used to delay the phase-out of fossil raw materials.

3.2.1 Potential and limitations of a circular economy in Germany

Combining chemical and mechanical recycling has the potential to achieve very high recycling rates – which will however remain below 100 percent. Estimates for achievable recycling rates for the growing volumes of post-consumer plastic waste range from 75 (Agora Industry 2022b) to 85 percent (DECHEMA 2022).[23] However, in Germany, the potential of plastic waste as a resource is limited by three factors:

1. **Plastics that cannot be recycled**
   Many polymers cannot be recycled as they are used as composite materials, for example in adhesives, coatings, and other applications. In such applications, plastic is attached to other materials such as steel, wood, or paper. Separation and recycling of these materials is usually not feasible. Of the 20.2 Mt of total polymer production in 2019, 7.9 Mt are used in such applications (Conversio 2020).

2. **Deficient plastic waste collection**
   Not all plastics that reach the end of their service life end up in the waste recycling system. As mentioned above, Material Economics estimates that the actual volume of end-of-life plastics in the EU is 50 percent higher than what is reported officially (Material Economics 2022).

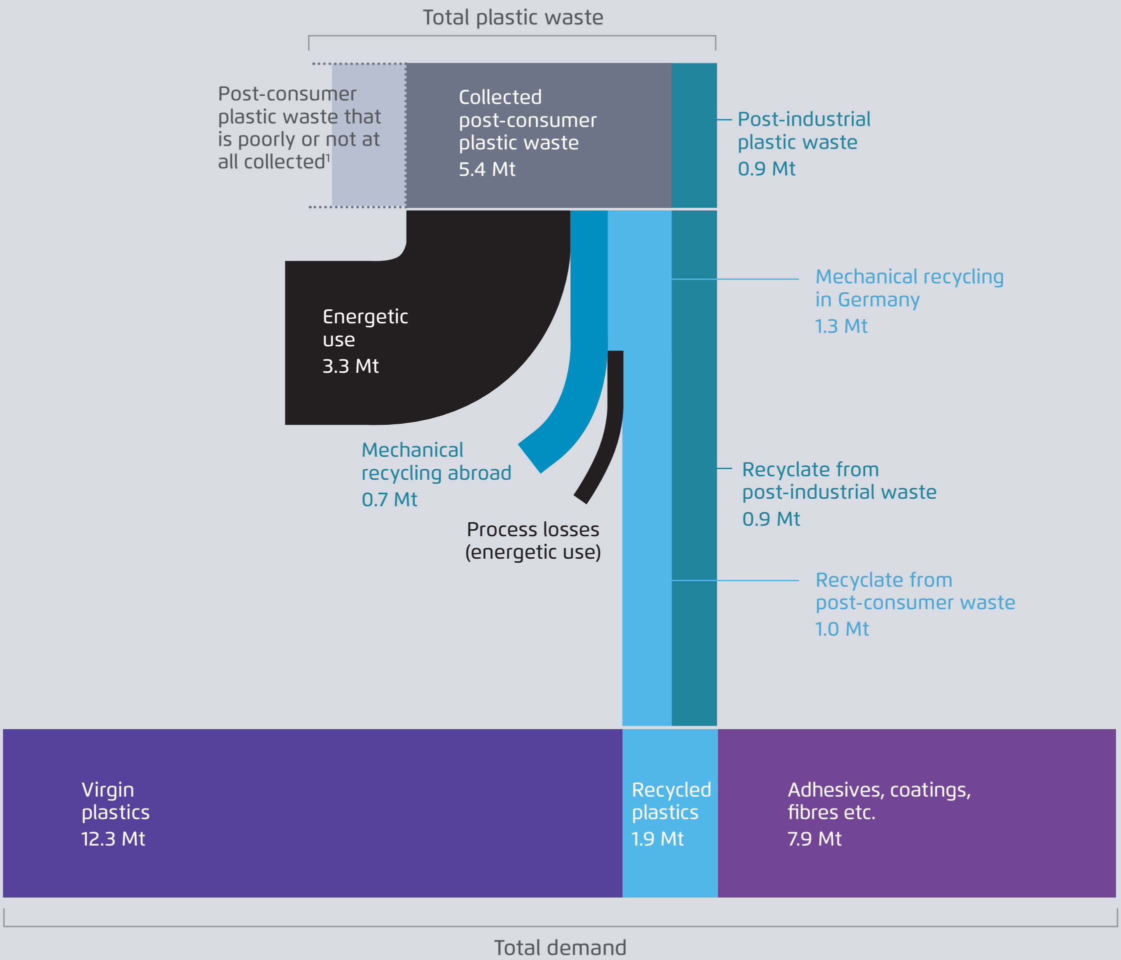
3. **Export of plastic products**
   The German chemical industry is a strongly export-oriented sector. For plastics, the export surplus is around 15 percent. In addition, many products containing plastics are traded abroad and at the end of their service life are not available for recycling in Germany (Conversio 2020).

23 The potential of 75 percent which Agora Industry estimates for the EU is a combination of 35 percent mechanical recycling and 40 percent chemical recycling (Agora Industry 2022b).

As shown in Figure 15, 5.4 Mt of recyclable post-consumer plastic waste were collected in Germany in 2019 – 3.3 Mt (61 percent) were used energetically, 0.7 Mt were exported for recycling abroad, and 1.3 Mt were sent to mechanical recycling. After process losses of 0.3 Mt, 1 Mt of recyclate was produced. In addition to post-consumer waste, 0.9 Mt of post-industrial waste are generated, which is materially recycled at almost 100 percent with very low losses, due to high waste purities (Conversio 2020).

Improving the collection and sorting infrastructure, as well as curtailing the incineration of plastic waste for energy use, can certainly increase the volume of plastic waste available for recycling. However, due to the large export share of plastic and products, the role of plastic waste as a raw material for the chemical industry is limited. Chemical recycling plants in particular require very large quantities of homogenous plastic waste. One option for securing the supply could be the

Plastic waste and plastics production in Germany in 2019 | Figure 15



Agora Industry (2023) based on Conversio (2020). [1] Findings of studies for the EU suggest that the actual amount of waste is higher than the collected amounts (Material Economics 2022). The actual amount in the case of Germany needs to be further investigated. Imports and exports illustrated in simplified form as foreign trade balance.

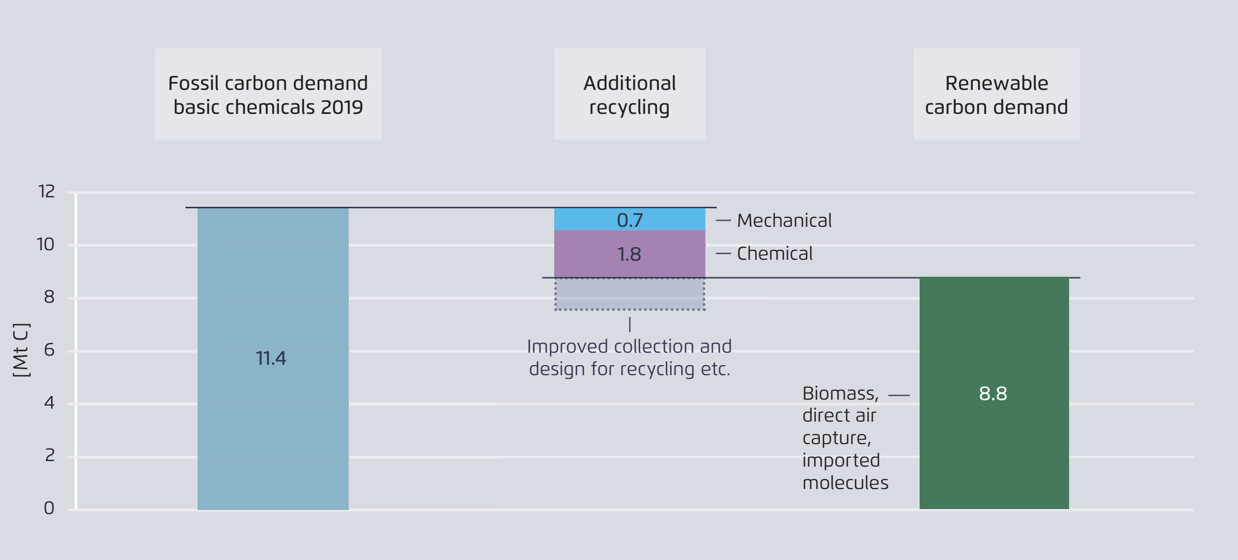
international trade of plastic waste, which is strictly regulated. One reason regulation exists is to strengthen domestic recycling and restrict landfilling in countries with lower environmental standards. When reforming regulatory frameworks for trading waste, it is important to ensure that exports to countries with lower recycling goals and standards are prevented. For this reason, a European approach to recognising plastic waste as a resource is needed.

3.3 Replacing fossil with renewable feedstocks

The chemical industry today is reliant on vast quantities of fossil feedstocks for the production of carbon-based, i.e., organic chemicals and their downstream products, such as most polymers and plastics. Currently, the majority of those fossil feedstocks, around 166 TWh_{LHV} in Germany, are oil-based derivatives (e.g. naphtha) obtained from the refining of crude oil which are then converted in crackers to produce the organic basic chemicals[24] that serve as the building blocks of most chemical products. In terms of carbon inputs, this equates to around 11 Mt of carbon required by the German chemical sector for the production of basic chemicals. Implementing circularity levers along the value chain of chemical products, as discussed in the previous section, reduces the demand for basic chemicals and thus is crucial to reducing the carbon feedstock demand. However, since carbon cycle rates will always be less than 100 percent (due to end products that are difficult to recycle, losses in recycling, and the export of products), new carbon inputs will still be needed by the chemical sector. Even if mechanical and chemical recycling of plastic waste are maximised, around 9 Mt of carbon will still be needed for the industry's current production levels (cf. Figure 16).

24 The organic basic chemicals are ethylene, propylene, methanol, benzene, toluene, xylene (jointly BTX) and C4 chemicals.

Renewable carbon demand of the chemical industry in Germany — Figure 16



Estimated recycling potential based on a maximum post-consumer-waste-to-product recycling rate of of 35% for mechanical recycling and 40% for chemical recycling according to Agora Industry (2022b)

Due to the challenges that the chemical industry is facing, notably the urgent need to address both its GHG emissions and its dependence on fragile fossil supply chains – brought into focus by Russia's war on Ukraine – it is imperative that this feedstock comes from non-fossil carbon sources.

3.3.1 Renewable feedstock sources

There are several alternative carbon sources that could allow the chemical industry to decouple from fossil feedstocks. These fall into two main categories: i) **captured CO_2**, which can be combined with renewable hydrogen to produce hydrocarbons that serve as chemical feedstocks or ii) **biogenic carbon** from various biomass sources, many of which are currently directly burned for energy.

Direct Air Capture (DAC) technologies extract CO_2 from the atmosphere, providing a renewable source of carbon. When combined with renewable hydrogen, this enables the manufacturing of basic chemicals (e.g. via the Methanol-to-Olefins route, as "Direct Air Carbon Capture and Utilisation, DACCU"). However, both the capture of CO_2 out of the atmosphere and the production of hydrogen are highly energy-intensive processes. Relying on renewable feedstocks via DAC to displace the current fossil feedstock inputs of the chemical industry would cause a substantial additional demand for hydrogen and renewable electricity. Since renewable electricity will be a scarce resource for the foreseeable future, its use should be prioritised for the most efficient applications that generate the largest climate and economic value, such as the electrification of industrial and residential heat via power-to-heat technologies and the transformation of the mobility sector. The large energy demand and high costs of DACCU limit its deployment to locations with cheap, abundant renewable electricity, putting its potential as a large-scale solution for the chemical sector in Germany in doubt.

Industrial point source capture (PSC) represents another potential source of CO_2 for the chemical industry. Industrial exhaust gases typically have a higher CO_2 concentration, which makes the capturing process less energy-intensive compared to DAC. In particular, CO_2 point sources from large industrial emitters, such as cement plants, are candidates for Point Source Carbon Capture and Utilisation (PSCCU). However, the emissions from CO_2-intensive industries are expected to reduce in the future as they decarbonise their processes. Providing an offtake destination for their CO_2 emissions risks slowing their transition and locking-in CO_2 intensive processes. Since these industrial processes use fossil feedstocks which generate additional GHG emissions, from the fugitive emissions during the feedstock extraction to incomplete CO_2 capture rates, fossil-based CCU provides a fossil, non-renewable carbon source to the chemical industry. At their end-of-life at the latest, chemicals based on fossil CO_2 point sources will generate CO_2 emissions, as recycling rates as well as carbon capture rates will always remain well below 100 percent. As with DACCU, a PSCCU pathway to make chemicals requires vast amounts of renewable hydrogen, which is responsible for the largest share of energy needed to produce synthetic hydrocarbons from CO_2. In the context of the revision of the EU Renewable Energy Directive 2018/2001/EG and the accelerated transformation towards climate neutrality, it is to be expected that CCU from fossil industrial point sources will not be considered as avoided emissions from 2040 onwards, as set out in the Delegated Act (C/2023/1086) published in February, 2023. CCU can therefore be considered as an add-on technology (especially for the recycling of biogenic carbon), as described in Chapter 3.2, but one that is secondary to mechanical and chemical recycling as well as to more energy-efficient sources of carbon.

Using biomass as a source of carbon can play a key role in defossilising the production of chemicals. Biomass can be considered a potentially renewable, low-CO_2[25] source of biogenic carbon. However, its deployment

25 The CO_2 footprint of biomass depends on the GHG emissions along the value chain of biomass production, as well as the carbon opportunity costs and indirect land use change impacts.

needs to take into account stringent sustainability conditions in order to guarantee its environmental compatibility, including that it benefits biodiversity and contributes to sustainable land use practices (cf. section 3.3.3). In this respect, the source of the biomass, whether for example waste and residual streams from the agricultural and wood processing sectors, bio-waste from households and industry, or primary biomass from agriculture and forestry, is an important consideration. There are different ways biomass can be used by the chemical industry for the production of bio-based chemicals (c.f. Chapter 3.3.2). Depending on the type of biomass and the processing technologies used, this can be far more energy-efficient than making chemicals from CO_2 captured via DAC or PSC.

The use of carbon from biomass, as well as DACCU, has the potential to enable **negative CO_2 emissions across the chemicals value chain**. Long-lived products derived from biochemicals (such as certain building materials or plastics) can function as a temporary stock of carbon in the economy. There is scientific agreement that permanent negative emissions will be required to achieve the climate targets of the Paris agreement (IPCC 2022), and the European Commission is preparing the groundwork for CO_2 removals to be properly accounted for (European Commission 2022). Through the mobilisation of circularity levers, this biogenic carbon stored within the materials stock can be kept within the economy as long as possible, representing a temporary carbon sink. This effect can be maximised through measures such as increasing the lifetime of bio-based products by encouraging reuse, optimising the design of products, and developing mechanical and chemical recycling technologies to enable more extensive recycling. Applying CCUS to waste incinerators for the treatment of non-recyclable products and chemicals would contribute to closing the carbon cycle by storing unavoidable end-of-life CO_2 emissions (CCS) or by combining them with hydrogen (CCU) to reintroduce renewable carbon into the value chain. It should be noted that recycling and capture rates are and will always remain below 100 percent – making it impossible to completely close the loop. However, by combining the use of biogenic carbon with circularity measures and applying CCUS to end-of-life incineration, the carbon sink effect can and should be maximised. Enabling such a closed biogenic carbon cycle would require close collaboration across the whole value chain, from biomass producers to the chemical industry, recyclers, and waste incinerators. Certifying and monetising carbon dioxide removals, within an appropriate monitoring framework, could also provide an additional revenue stream that would financially incentivise circularity measures as well as end-of-life incineration with CCS. However, the operation of CCS technologies is associated with new infrastructure demands and faces the challenge of limited storage sites. It should therefore only be used for residual emissions that cannot be abated by other means, or – in the case of biogenic emissions – can be valorised. The full potential of chemicals production for CO_2 removal will then depend on a comprehensive life cycle assessment of the entire value chain that includes the CO_2 balance of biomass inputs, the production, usage and recycling phases, and end-of-life treatment.

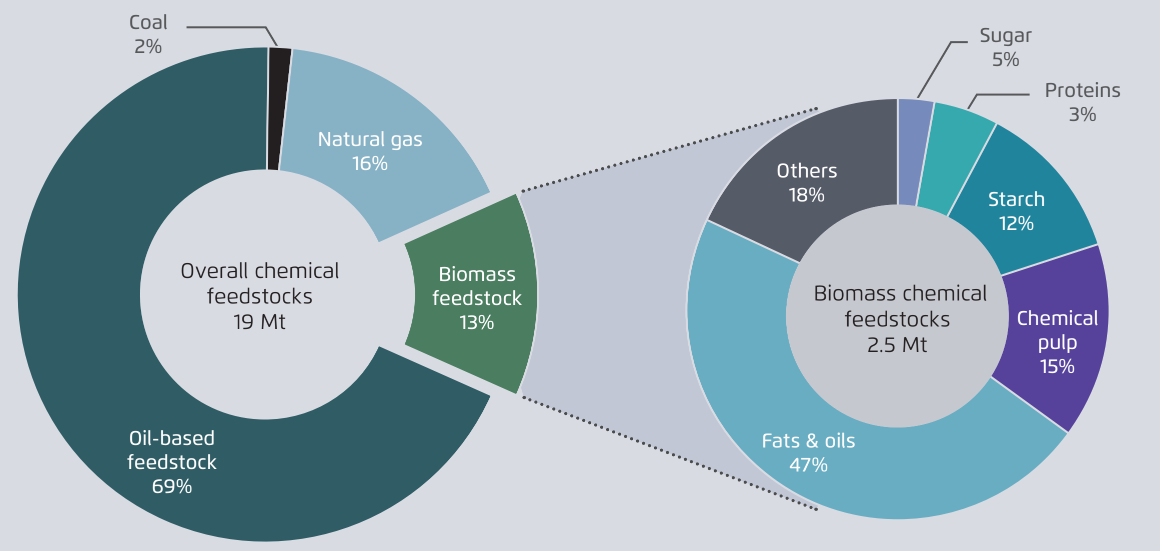
3.3.2 Pathways for bio-based chemicals

Biomass is an important feedstock which can be utilised throughout the chemical industry to replace fossil feedstocks. Currently, biomass makes up a small proportion of the total inputs into the chemical industry, constituting around 13 percent (2.6 Mt) of the total feedstock inputs, which is mainly directly used in the production of specialised chemicals such as detergents, cleaning materials and lubricants (VCI 2021a). Fats and oils, from palm, rapeseed, and sunflower oils among other sources, make up the largest proportion of biomass feedstocks.[26] Other important bio-based feedstock sources are chemical pulps, starches and sugars (FNR 2020).

26 The use of food oil crops can have negative consequences, due among other things to the process of indirect land use change (ILUC). Legislation at European and national level, including the revised renewable energy directive, now aims to limit the use of high ILUC-risk biofuels.

Biomass as a chemical feedstock in 2019 in Germany

Figure 17



Agora Industry and Carbon Minds (2023) based on VCI (2021a) and FNR (2020)

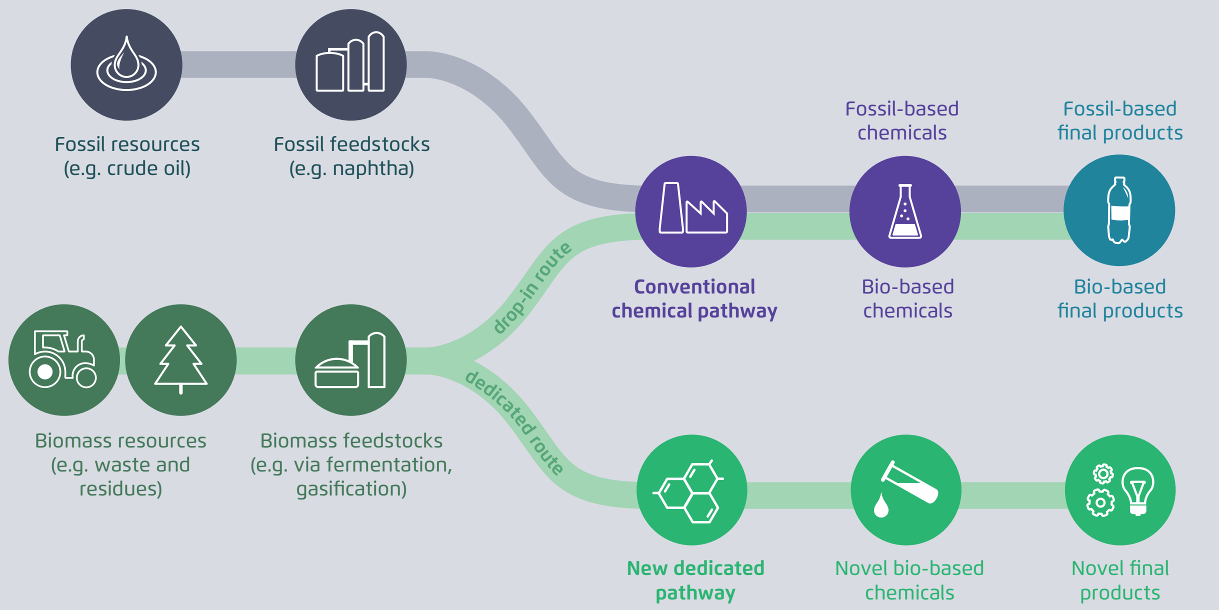
Despite its current marginal use in the industry, there is vast untapped potential for increasing the use of biomass across the chemical industry and integrating the chemicals value chain into a circular (bio-) economy. The use of biomass in the chemical industry can be categorised under two distinct pathways that encompass both the great diversity of biomass types available as well as the variety of different chemicals produced:

Drop-in biochemicals: Under this pathway, the bio-based chemical is chemically identical to an existing fossil-based chemical and can directly replace it within the existing production chain. This "drop-in" technique utilises the existing process pathways and infrastructure, does not require any major process changes, and produces for an existing market. A number of basic chemicals can be produced from biomass in this way with technologies that are already available at industrial scale (JRC 2019). Examples of drop-in chemicals are bio-based ethylene, which replaces fossil-based ethylene in the production of polymers such as PE and PET. However, producing identical substitutes for existing petrochemicals is not necessarily the most efficient way to use biomass, neither in terms of energy efficiency, nor in making use of the natural molecular structure of the biomass. Further R&D may reveal new, faster and more efficient routes to produce drop-in chemicals compared to the existing pathways. This has happened for example with the production of aromatic aniline, an important intermediate in the production of polyurethanes (PUR), which are used as foams in products such as mattresses. Instead of producing aniline via petroleum-based benzene, new pathways are being developed to produce it from sugar fermentation (Winter, Meys and Bardow 2021).

Novel biochemical alternatives: Biomass can also be used to synthesise novel bio-based chemicals and materials that do not have an identical fossil-based counterpart, but have similar, or better, functionalities, properties or end-uses. These chemicals require new dedicated pathways and cannot necessarily take advantage of existing infrastructure and markets. However, because they are tailored to biomass inputs rather

Different pathways towards bio-based chemical products

Figure 18



Agora Industry and Carbon Minds (2023)

than existing fossil-based inputs, these dedicated production pathways can often use biomass much more efficiently and can sometimes result in products with superior properties. Novel, dedicated biochemicals can enable the production of new types of bio-based plastics, cellulose fibres, and bio-based lubricants among other products. The polymer polylactic acid (PLA), for example, produced via the microbial fermentation of sugars, is compostable and can replace fossil-based food packaging. Currently, bio-based plastics are relatively expensive compared to fossil-based alternatives (Meereboer 2020). Further R&D is needed to develop the production pathways and the properties of novel bio-based chemicals, and to bring them to industrial scale. For example, the lack of suitable large-scale and higher-value applications for lignin currently represents a bottleneck for a comprehensive, efficient use of biomass. Unlocking the potential of lignin as a new chemical feedstock for the production of aromatic chemicals via new conversion processes therefore represents a significant opportunity.

Bio-based drop-in chemicals and novel biochemical alternatives can support the transition away from fossil fuel feedstocks in different ways. Drop-in biochemicals utilise existing infrastructure and benefit from commercial, industrial-scale technologies. Even though they may represent a less efficient use of biomass, they can play an important role in displacing fossil feedstocks in the short and medium term. At the same time, it is imperative to scale up the production of alternative biochemical routes that use biomass in an efficient way.

Scaling up the production of bio-based chemicals also faces challenges around infrastructure and logistics. Questions remain about how these new production sites should be organised to optimise their access to feedstocks. Smaller-scale biorefineries could take advantage of the existing logistical infrastructure of biomass, for example the value chain of the pulp and paper industry. Innovative biorefinery concepts already exist that tap into regional forestry-based

Biorefineries: Technological pathways for the processing of biomass

Depending on the type and properties of biomass feedstock, different conversion technologies can be used in biorefineries. These technologies are typically classified as either biochemical processes (e.g. fermentation and anaerobic digestion) or thermochemical processes (e.g. pyrolysis and gasification) (Rathore and Singh 2021).

Biochemical processes such as the fermentation of sugars and starches and the anaerobic digestion of waste and residues are well-established processes for converting biomass to chemicals and fuels such as bioethanol and biogas. Many biomass feedstocks that are more abundantly available and do not compete with food crops, such as wood, forest and agricultural residues, are composed of lignocellulosic structures, which are more difficult to directly process. Lignocellulosic biomass first needs to be pre-treated so as to fraction it into its main constituent parts (cellulose, hemicellulose and lignin) before the sugars obtained from cellulose and hemicellulose can be fermented into a variety of chemicals (IEA 2020). The fractioning of lignocellulosic biomass yields large amounts of lignin as a by-product biomass, most of which is treated as a waste-product or used for energy generation. However, if new value-adding processes currently in R&D are successful and commercialised, lignin could play an important role as a chemical feedstock.

Fermentation processes can play a key part in supplying drop-in biochemicals for existing production pathways, for instance by fermenting the sugars in biomass to ethanol which can then be readily processed into bio-ethylene, identical to fossil-based ethylene. Fermentation can also be used to produce alternative biochemicals, for example by using specific bacteria to ferment the sugars obtained from the hemicellulose fraction of biomass to produce lactic acid, which is the building block of PLA, currently one of the most widely produced biopolymers.

Thermochemical processes can crack the lignocellulosic structure of biomass into its constituent building blocks under high temperature and pressure to produce bio-based chemical feedstocks. During pyrolysis, conducted at high temperatures (500 degrees Celsius) in the absence of oxygen, biomass decomposes into a liquid (pyrolysis oil, also referred to as bio-oil), solid biochar and syngas. As with the pyrolysis of plastic waste, pyrolysis oil from biomass can be used as a feedstock in existing conventional steam crackers – or in future electric steam crackers – for the production of basic chemicals.

Gasification converts organic materials into syngas (a mixture of carbon monoxide and hydrogen) by heating them at high temperatures (>700 degrees Celsius). Syngas can be used as a precursor to biochemical feedstocks such as ethanol, methanol, or even naphtha, which can be further synthesised towards important chemical building blocks such as olefins and aromatics (benzene, toluene and xylene), for instance via methanol conversion (Methanol-to-Olefins; MtO and Methanol-to-Aromatics MtA). It is worth noting that the majority of methanol produced today is based on the catalytic conversion of syngas from fossil fuels and is already used to make olefins via MtO in certain regions.

There is significant scope for developing biorefinery techniques that optimise the production of biochemicals by combining conversion processes and feedstocks in an efficient manner. For instance, both the fermentation of sugars to produce bioethanol and the gasification of biomass to produce syngas yield CO_2 as a by-product. Production pathways that combine this CO_2 with renewable hydrogen to make additional chemical feedstocks such as methanol can increase the efficiency of the total biomass utilisation process. The use of biogenic by-product CO_2 can save large amounts of energy compared to producing chemical feedstocks via dedicated DAC CO_2 while also creating synergies between the chemical and power sectors: if combined with renewable hydrogen, this pathway enhances flexibility in the power system at the same time as efficiently supplying renewable feedstocks to the chemicals industry.

wood supply chains as a raw material, in order for instance to combine the production of bio-based mono-ethylene glycol (a "drop-in" chemical used in the manufacture of PET bottles) and bio-based functional fillers (a bio-based chemical alternative to carbon black, used in the production of rubbers and seals).

3.3.3 Mobilising and utilising biomass sustainably

Biomass is considered a renewable resource, but its availability is limited and it will face increasing demand competition in the future. Competition for land needs to be minimised, as it carries a risk of both direct and indirect land use change (LUC and ILUC) and the intensification of agricultural production. In addition, sustainable forestry practices, including the adaptation of current forest stands to new climate conditions, need to be expanded in order to secure biodiversity, natural carbon sinks, and the long-term productivity of forests. The use of biomass as a renewable feedstock for the chemical industry, integrated within a wider circular bioeconomy, will require a shift in the current usage patterns of biomass.

In Germany, in addition to animal feed and food production, bioenergy production is another large end-user of biomass. As shown in Figure 19, one quarter of the total biomass demand is for bioenergy (48 Mt)[27], sourced from both agriculture and forestry in equal shares. The use of biomass for material applications (38 Mt), by contrast, relies on forestry biomass for 89 percent of its supply (Thünen Institut 2021).

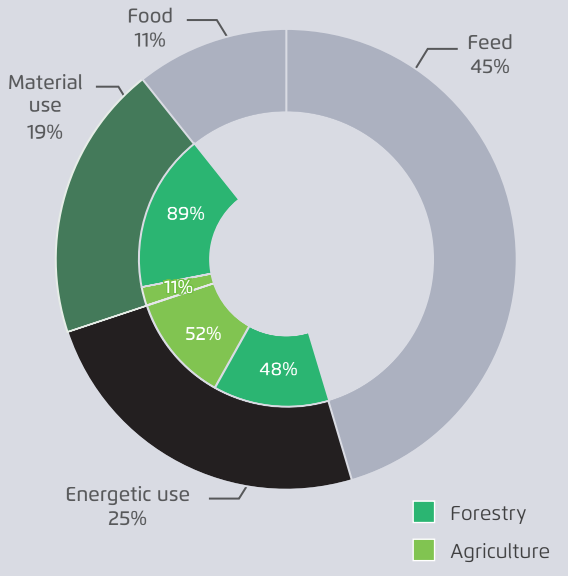
Biomass currently plays a significant role in the German energy system in several different forms and functions – as solid fuel, liquid biofuel or biogas, used to generate heat and power and as fuel for the transport sector. Its principal use is for heat generation (171 TWh in 2021), largely from wood and wood residues (BMEL 2022). In terms of power (50 TWh in 2021) and biofuel (34 TWh) production, the main source is biogas from energy crops (such as maize silage) (BMEL 2022). The use of biomass for energy has in the past been incentivised by EU climate and energy regulations and their respective national implementation policies (biomass is considered carbon-neutral under the EU ETS, and bioenergy contributes to renewable energy targets under RED II).

Due to its limited availability and the increasing competing demands for biomass, it will be necessary to maximise the use of low-risk sustainable applications on the one hand and to prioritise efficient biomass applications on the other.

Prioritising an efficient cascading use of biomass

As society transitions away from a fossil-based economy and further develops its bioeconomy, it is imperative to use the renewable but limited

Biomass usage (and source) in Germany in 2015 — Figure 19



Agora Industry and Carbon Minds (2023) based on Thünen Institut (2021)

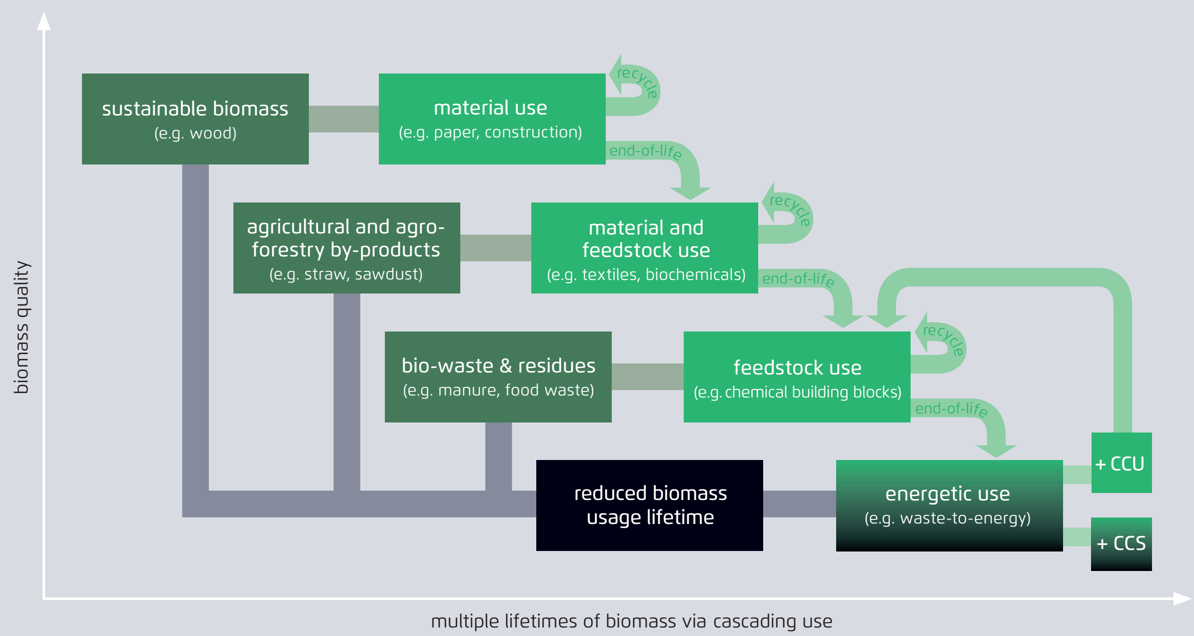
27 The most recent comprehensive data on production and usage of biomass in Germany is from 2015 (Thünen Institut 2021).

resource of biomass as efficiently as possible. In other words, biomass use needs to be **prioritised** to go to those areas where no alternative or more efficient decarbonisation options exist. Furthermore, priority should be given to cases where the biogenic carbon can be integrated into a circular system in which it can be reused over many usage cycles. This enables the biogenic material, and the biogenic carbon, to be kept in the material and economic cycle as long as possible, extending the carbon cycle as described in Chapter 3.2. If the biomass is used directly as a source of energy, it is removed from the material cycle and its many advantageous properties as a versatile material and source of biogenic carbon are not fully exploited. Maximising the circular and efficient use of biomass can be supported by a **cascading use hierarchy** (cf. Figure 20), which targets multiple uses of biomass as a material and/or feedstock, encouraging reuse and recycling of materials and molecules. After several cascading reuse cycles, at the end of their recyclable life, waste products can be incinerated for energy use. As the amount of biogenic carbon used in the chemical sector increases, this will also translate into higher proportions of biomass in future waste streams. Carbon capture and storage technologies applied at the waste incineration plant can then permanently sequester the biogenic carbon in these products, contributing to negative emissions (BECCS), and combining incineration with CCU would enable the biogenic carbon atoms to be recovered and fed back into the material cycle (cf. Chapter 3.2).

In addition to the resource efficiency and emissions reduction benefits a cascading biomass use provides, it can also enhance value creation and generate new local employment, including in rural areas. It is important to note that prioritising and maximising the cascading use of biomass does not entirely

Chemicals production enabling a longer biomass cascade

Figure 20



Agora Industry (2023)

preclude the energetic use of biomass. Rather, it ensures that the material efficiency of biomass is increased over several lifetimes, instead of being restricted to a single, direct energetic use of high-value biomass.

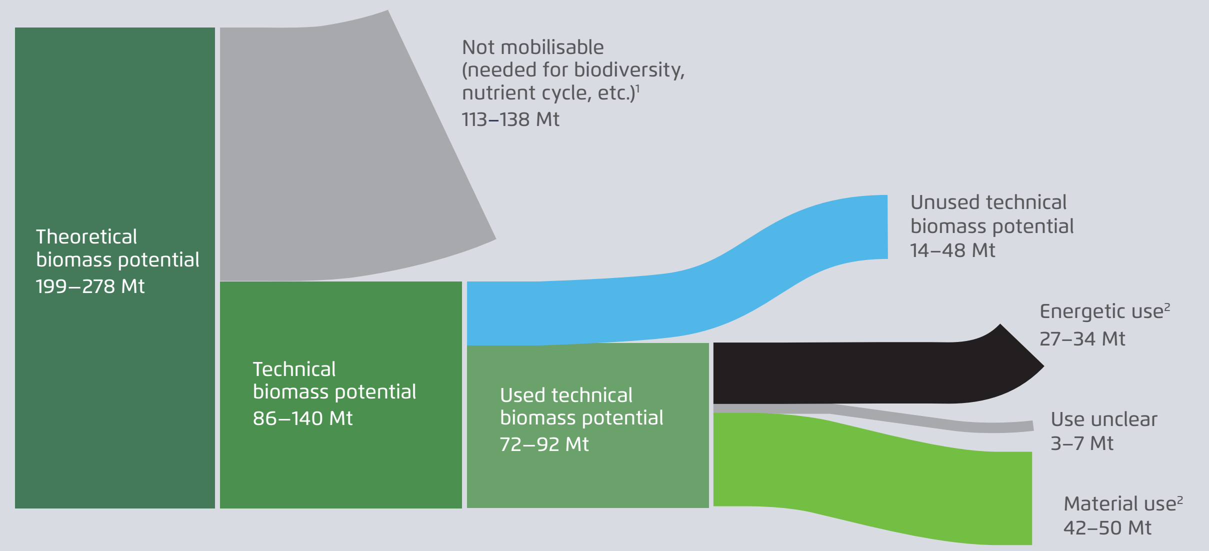
While the cascading use of woody biomass is already established to a certain degree in the forestry and wood sector today, adding the chemical sector can enable the extension of these cascading cycles to a much wider range of biomass via new usage applications. Technologies are developing that can process biomass in new ways, as described in section 3.3.2, for example by making more efficient use of the lignin fraction in lignocellulosic waste biomass or by developing microbial and enzymatic processes to transform biomass waste-streams. The chemicals value chain is particularly well-suited to extending the cascading use of biomass and extracting the most value from various biomass feedstocks.

Biomass potentials of biogenic waste and residues

Biomass from residues and waste streams constitutes a possible no-regret option for use as a feedstock in the bioeconomy, including in the chemical sector, since these sources are not in direct competition with food production and do not pose new additional strains on the environment and ecosystem as they do not require dedicated crops. The sources include forestry residues, agricultural by-products and residues, industrial residual matter and municipal solid waste.

Exploiting the full theoretical potential of residual and waste biomass is problematic because of the important environmental functions it provides, such as humus formation, preserving soil quality and enhancing biodiversity. This restricts the available technical potential to around half of the total theoretical potential. Taking this into account, the technical potential volume of usable biogenic waste and residues in Germany is estimated to be

Residual and waste biomass potentials in Germany — Figure 21



Agora Industry and Carbon Minds (2023) adapted from DBFZ (2019). All values are in million tonnes of dry matter. [1] The use of 50-57% of theoretically available biomass is constrained due to restrictions such as maintaining soil fertility or humus formation. [2] The flow entitled material or energetic use in the original Sankey diagram is here divided equally and added to the respective material and energetic use flows.

between 86 and 140 Mt (dry matter, dm).[28] The vast majority of this potential (up to 84 percent) is residual and waste matter from forestry and agriculture (DBFZ 2019). Around 70 percent of this technical potential is already in use, either as energy or in material applications. This leaves around 14–48 Mt (dm) of waste and residual biomass that is unused and could still be mobilised (cf. Figure 21). It is mainly made up of cereal straw, cattle manure and slurry as well as forestry residues.

28 The biomass waste and residue streams are estimated for the most recent common reference year 2015. The wide range is due to different assumptions and calculation methods, for example on dry matter contents, animal-specific manure or different salvage and removal rates.

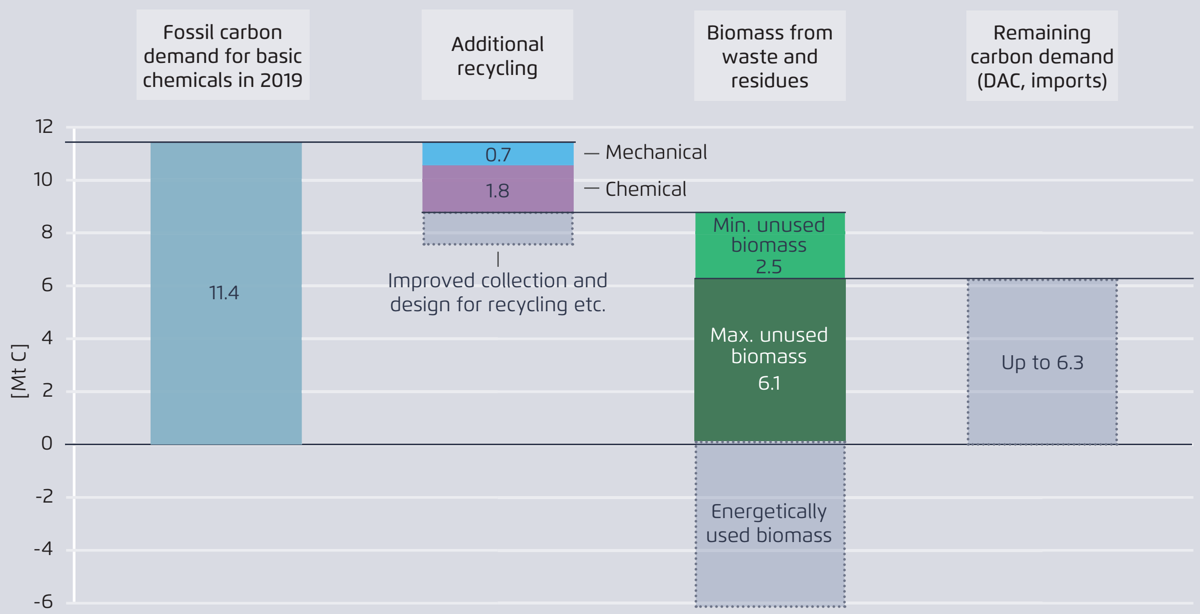
The unused waste and residual biomass potential of 14–48 Mt (dm) corresponds to some 2.5–8.6 Mt of renewable carbon, via an average conversion pathway of gasification to syngas, syngas to methanol and methanol to olefins.[29] This represents between 25 and 80 percent of the estimated carbon feedstock of 11 Mt required by the German chemical industry for the production of the ten basic chemicals in 2019 (cf. Figure 22).

Additionally, another 27–34 Mt (dm) of waste and residual biomass are currently being used energetically. Some of these biogenic residues could be redirected toward a material and feedstock

29 A carbon content of biomass (dm) of 50 percent (wt.) and an average conversion factor (carbon efficiency) of biomass to olefins via gasification and MtO of 36 percent are assumed.

Mobilising the potentials of a circular economy and of waste and residue biomass as a carbon source for chemicals in Germany

Figure 22



Agora Industry and Carbon Minds (2023). Carbon demand based on basic chemicals production in 2019 (VCI 2021). Estimated recycling potential based on a maximum post-consumer-waste-to-product recycling rate of of 35% for mechanical recycling and 40% for chemical recycling according to Agora Industry (2022b); biomass potential based on 2015 data (DFBZ 2019); carbon content of biomass of 50% assumed; average process efficiency of biomass to chemicals of 36% assumed.

application, in line with a cascading biomass utilisation approach. However, it is important to ensure that redirecting biomass flows from energetic applications does not lead to an increased use of fossil fuels, particularly in larger industrial combustion plants. It is imperative that this shift takes into account substitution effects and occurs in parallel with the deployment of renewable energy sources and heat electrification, e.g. via heat pumps (cf. Agora Industry, Future-Camp 2022).

These estimates of biogenic waste and residues streams indicate that by mobilising currently unused potentials and redirecting energetically used biomass towards higher-value use in industry, a large proportion of fossil feedstocks could be replaced by renewable sources.[30] Further quantifying this potential for the chemical sector would require a more granular analysis of the different types of biogenic waste and residues and the technological options to valorise them. It should be noted that as society transitions toward climate neutrality, other sectors will also need renewable sources of carbon – such as the metal industry, which requires carbon for metallurgical processes. In addition to technological innovations, logistics also play an important role

30 Note that this is a snapshot of historic volumes, showing orders of magnitude of supply and demand of renewable carbon. Both the production volume of the chemical industry as well as the availability of waste and residual biomass may change (for instance because of possible changes to agricultural practices and forestry, not least because of the impact of climate change).

Climate-smart land use: synergies for biodiversity and resilience, CO_2 uptake and the supply of biomass

The climate-smart management of forests and agricultural landscapes can combine the production of biomass with safeguarding ecosystem services, improving biodiversity and increasing climate resilience. The forestry and wood sectors are already important pillars of Germany's bioeconomy, providing the bulk of biogenic raw materials. At the same time, Germany's forests are increasingly prone to extreme events linked to climate change, such as severe droughts, windstorms, wildfires and pest invasions. Forest restructuring is already gradually converting Germany's predominantly coniferous forests into mixed forests more resilient to the impacts of climate change. However, this leads to an increasing supply of hardwood, which is less suitable for current material applications, for example as construction timber. The chemical industry can provide new and innovative utilisation options for hardwood, thereby creating value for sustainable forest management (BMEL 2021). If the multiple effects on local biodiversity, climate and soil conditions are taken into account, sustainable selective harvesting can also increase the CO_2-sink effect of forests as well as increasing their resilience and adaptive capacities.

Similarly, climate-smart agricultural concepts can increase the productivity, resilience and climate-benefits of agricultural biomass production. Agroforestry practices, such as hedgerows, "alley cropping" or short-rotation crops for example, can provide a range of environmental benefits, including improving the soil quality, promoting biodiversity, regulating water and nutrient cycles, increasing the CO_2 sink function and creating economic value by combining the production of food with that of biogenic feedstocks. Combining the rewetting of peatlands with paludiculture (agriculture on rewetted peatlands) can also create important long-term carbon sinks while providing an environmentally-friendly source of biomass (WBGU 2021).

in maximising biomass potentials due to the geographic dispersion of biomass. Logistical networks across the entire value chain are needed to bring together decentralised regional biomass sources and biorefineries with larger centralised users in the chemical sector. By creating new demand and exploiting these resources, the chemical sector can contribute towards the development of technological and logistical innovations that increase the use of waste and residual biomass.

Exploiting the full potential of biogenic waste and residues, combined with increased mechanical and chemical recycling of plastic waste, can displace a significant proportion of virgin fossil feedstock. Additional sources of renewable carbon feedstock may be available to the chemical sector in the future. CO_2-based chemical feedstocks produced with renewable hydrogen combined with DACCU, such as naphtha (via the Fischer-Tropsch process) or methanol, could be imported from countries with large renewable electricity supplies. However, increasing the import of biomass or biomass-based feedstocks needs to be considered very carefully with regards to new dependencies and under strict sustainability criteria, because they can be in competition with food and animal feed production and risk exacerbating environmental pressures in exporting countries through direct and indirect land use changes (ILUC).

Finally, the demand for renewable carbon sources can present opportunities for an improved forest and agricultural land use management within Germany which seeks to integrate climate change mitigation and adaptation measures while providing a sustainable supply of biomass.

4 Recommendations for action

Transitioning the chemical sector to climate neutrality requires a regulatory framework aligned with our climate goals. Most importantly, an effective carbon price is vital. The increased level of ambition of the latest reform of the EU ETS requires industry to become climate neutral before 2040. The price signal for industry in Europe, including the chemical industry, is therefore going to become more effective over the coming years. However, an accompanying regulatory framework is needed to push the chemical sector to invest in climate-neutral technologies today. Targets and measures need to address the entire value chain – upstream, midstream and downstream (Agora Energiewende 2020).

1. **Upstream:** The chemical sector needs **reliable access to renewable energy, feedstocks, and basic materials** at competitive prices via new infrastructure. This also requires **additional infrastructure planning**, e.g. for renewable hydrogen and renewable carbon (i.e. biomass, atmospheric CO_2) and for recycling of plastic waste. Increasing the availability of land for renewables expansion and **accelerating planning and permit procedures** is one of the fundamental measures that need to be taken.

2. **Midstream:** Economic and financial conditions should incentivise the development, implementation and operation of key breakthrough technologies and should address the risks of carbon leakage. This includes **special support programmes**, the swift implementation of **Carbon Contracts for Differences** as a supporting measure, and **climate-neutral production standards.**

3. **Downstream:** The chemical sector needs additional **demand and scalable markets** for decarbonised and circular products, markets that have internalised the temporarily higher costs of decarbonised products, and incentives to integrate the circular economy and resource efficiency all along the value chain. For example, setting **clear, ambitious standards** in the EU regulations governing sustainable products would stimulate the demand for sustainable chemical products very effectively.

4.1 Recommendations for direct electrification and flexibility

The electrification of process energy in the chemical industry is a short-term strategy that can significantly reduce both emissions and the reliance on fossil gas imports this decade. The following recommendations are based on the study *Power-2-Heat: Gas savings and emissions reduction in industry* (Agora Industry and FutureCamp 2022).

1. ***Zero-carbon standard* for new investments below 500 degrees Celsius**
   The introduction of a binding ***zero-carbon standard* for new investments** in process heat up to 500 degrees Celsius is indispensable for planning and investment certainty. Especially in the temperature ranges for which there are already commercially available CO_2-free technology options, there should be a legal standard for all new investments. This creates planning certainty for industrial users and plant manufacturers and avoids misplaced investments in fossil fuel systems. In particular, the standard should cover enhanced waste heat recovery, steam regeneration, heat pumps, electric boilers, solar thermal, concentrated solar thermal, geothermal systems and integrated electrification and waste heat technologies. As a rule, the use of biomass and renewable hydrogen should not be included due to the limited availability in the foreseeable future (Agora Industry and FutureCamp 2022).

2. **Mitigating investment risks and closing the cost gap**
   To enable a rapid market ramp-up and scaling of

production and installation, a **special support programme for direct electrification** should be set up. Financial support for lighthouse projects and infrastructure helps overcome financial hurdles and establish direct electrification as the new standard technology. The costs for grid connection, installation and integration into the production site should automatically be eligible for subsidies. Both the use of waste heat (through heat pumps) and electrification measures using the current electricity mix should be eligible for funding. Direct investments in renewable electricity can already provide access to low-cost renewables today. The state should support companies that are signing **corporate green PPAs** and **investing directly in renewable energies**. In the case of PPAs, the state should initially assume the default risks (Agora Energiewende and FutureCamp 2022).

3. **Enabling and incentivising system-serving flexibility**
   Prevailing regulations prevent system-serving flexibility – a key element for a successful energy transition. To change that, **new regulations governing network cost allocation** must be developed. Adjusting the existing grid fee structure will not be sufficient. The requirements for a future grid fee structure were set out in a separate study by Agora Energiewende in 2021 (Agora Energiewende, Consentec, RAP 2021). Furthermore, within the framework of the "climate-neutral electricity system" initiated by the Federal government, **spatially and temporally differentiated electricity price signals** will be needed.

4. **Removing perverse incentives for fossil fuel technologies**
   On the national level, CHP plants benefit from a number of tax exemptions under current law that disincentivise the shift to electrified heating technologies. Tax relief for natural gas or other fuels used in CHP within the framework of energy taxation (§ 53a EnStG) is one of these perverse incentives that must be eliminated. High-efficiency CHP plants are even completely exempt from energy taxation.[31] These **structural advantages for fossil fuel CHP plants need to be dismantled** in order to create a level playing field (Agora Energiewende and FutureCamp 2022).

4.2 Recommendations for circular economy

A circular chemicals (and particularly plastics) economy has three key benefits: 1) it **mitigates end-of-life emissions** and provides a basis for long-term carbon storage; 2) it **minimises feedstock requirements** and associated upstream emissions; and 3) it **reduces import dependence** for virgin feedstocks and instead can provide a resource for local value creation. With the new national circular economy strategy, Germany can lay a robust foundation for this and institute sustainable carbon management. These recommendations are based on the study *Mobilising the circular economy for energy-intensive materials* (Agora Industry 2022b).

1. **Optimising the use of plastics via product requirements**
   The most important and powerful lever for establishing a circular economy is the optimisation of the use of plastics. While the long-term and efficient use of high-quality plastics should be incentivised, for example via **product requirements** (e.g. EU Ecodesign policies), unnecessary uses should at the same time be decreased, for example by **legal bans** (cf. the EU Single-Use Plastics Directive). The goal must be the longest possible service life of products. Other ways of incentivising the efficient use of plastics are combining product regulation with

31 Further perverse incentives are the exemptions for CHP electricity from electricity tax (§ 9 StromStV), explicit subsidies for CHP electricity that is fed into the grid and consumed by the end-consumer (§ 7 KWKG), an exemption from grid charges and levies for self-generated electricity, and the currently still applicable compensation for the grid utilisation charges avoided (§ 18 StromNEV).

extended end-product responsibility and introducing **embodied carbon requirements**.

2. **Incentivising design for recycling and developing green markets**
   Products and business models need to be designed in a way that 1) enables high proportions of recycled content in production and 2) facilitates the separation of materials and thus enables high rates of energy- and material-efficient recycling, especially mechanical recycling. A prime example of how to design for recycling is PET bottles: the German **deposit refund scheme,** combined with stringent **specifications regarding colours and additives**, enables recycling rates of 98 percent (GVM 2020). In the development of a green market for recycled PET, **recycled content quotas** have been key. Green markets are important for promoting high-quality recycling and avoiding downcycling. Combining policies that incentivise or enforce design for recycling with policies for green markets, and extending them to a wider range of products, maximises CO_2 reduction and energy and material efficiency.

3. **Transparent statistics, tracking methods and ambitious recycling targets**
   For appropriate targets to be set and progress to be measurable, the transparency of plastic flows needs to be improved in two ways. 1) Better statistics need to be developed, including for estimating the volumes of plastic **wastes that are not disposed of properly**. 2) In the future, recycling rates must include both collection and sorting losses as well as process losses. Circularity must be tracked in the form of a **product-to-product recycling rate**.

4. **Regulatory recognition and market ramp-up of chemical recycling as a complementary measure to maximising mechanical recycling**
   Particularly high recycling rates can be achieved through the complementary use of mechanical and chemical recycling. Mechanical recycling is a proven and particularly energy- and material-efficient technology which should be prioritised. In order to mobilise the potential of mechanical recycling, **separate post-consumer collection for end-of-life products** needs to be further incentivised (e.g. via product design) and **sorting infrastructure needs to be improved** (e.g. via support measures). Chemical recycling must be recognised as a valid material recycling process that complements mechanical recycling. It is important to ensure that chemical recycling is as energy-efficient as possible and operated with renewable energies and does not compete with mechanical recycling for recyclable materials. Chemical recycling is still in the early stages of adoption. In order to accelerate its implementation, **funding for research and development** as well as for **lighthouse projects** and the necessary infrastructure will help to quickly gather hands-on experience.

4.3 Recommendations for renewable feedstocks

For a successful transition from fossil to renewable feedstocks, both a coherent long-term vision and a comprehensive set of policy instruments are needed. The upcoming German biomass strategy needs to consider the use of biomass as a renewable feedstock for the chemical industry within a wider circular bioeconomy, requiring a shift in current usage patterns for biomass. Most importantly, this implies a **shift away from a purely energetic biomass use**. Guided by a clear set of priorities, existing and new **regulation needs to be harmonised** across all policy areas – including energy, agriculture, forestry, biodiversity, and the environment. These currently seem to be not aligned but rather pulling in different directions.

1. **Removing perverse incentives for pure energetic use and promoting cascading use**
   Current regulations, such as the EU Renewable Energy Directive and the EU ETS, treat biomass as a carbon-neutral energy source but neglect its

potential to replace fossil feedstocks and to create CO_2 sinks. This regulatory imbalance incentivises low-value energetic use instead of promoting a cascading use hierarchy and needs to be corrected. To enable this, the sustainability criteria for biomass need to **take into account its full carbon footprint and environmental impacts**. Regulations on carbon dioxide removal should only incentivise the storing of biogenic carbon within products if they are kept within the economy as long as possible via circularity strategies, thereby creating a temporary carbon sink. These products can only be considered long-term carbon sinks if **permanent carbon storage** is ensured, e.g. if their end-of-life incineration is combined with CCS.

2. **Transparent monitoring of biomass potentials**
   More data and analysis are needed regarding the availability and usage potentials of biomass, including on the type and quality of biomass as well as on current and future flows. **Biomass availability and demand are expected to shift** in the future, due to dietary changes as well as the shift from combustion engines (in part fuelled with biofuels) to e-mobility in the transport sector and increased electrification replacing bioenergy use for heating in buildings and industry. Moreover, due to the multiple functions and services provided by natural ecosystems and their impact on our climate, biodiversity and nature restoration goals, it will be necessary to leave more biomass unharvested in some ecosystems, while in others sustainable landscape management will be preferable. These changes in biomass flow and availability will need to be monitored, and their impact on the **availability of biomass for high-value uses will need to be assessed**.

3. **Funding R&D and pilot projects**
   Funding for pilot **projects that connect biomass growth and harvest, collection, transport and processing logistics** and its use as an industrial feedstock is needed at national and EU level in order to incentivise the creation of new value-chains for biomass. These projects must be in line with biodiversity goals and should aim to create new **win-win alliances** (e.g. on the basis of paludicultures). Access to R&D financing should be increased for technologies aimed at **developing the use of waste and residual feedstocks**. The focus should be on innovations for efficient pathways towards biochemicals as well as pilot, demonstration and first-of-a-kind **projects linked to cascading biomass use**. Furthermore, dialogue or exchange platforms between suppliers and users can enhance the development of logistics infrastructure, provide support for SMEs and small-scale biorefineries and create planning certainty and new business models for biomass producers. A **bioeconomy alliance via industrial associations** can create biomass supply-and-usage networks and clusters and enable the sharing of promising business models.

4. **Green markets for bio-based chemicals**
   Green markets must be created for renewable carbon- and bio-based chemicals and downstream products in line with **robust sustainability criteria** for the biomass feedstock. Transparent accounting of the full life-cycle emissions of chemicals is crucial to stimulating market demand; they must **include end-of-life emissions**, so that the emissions savings compared to the use of fossil resources are clear. End-of-life emissions could be estimated by combining the fossil or non-fossil carbon content of a product with the current average end-of-life treatment method, which today is predominantly waste incineration. In addition, several green lead market instruments could be considered, such as the introduction of mandatory **bio-based content quotas** or of **embedded carbon limits** based on the total life-cycle emissions of specific products. In designing these instruments, care must be taken to ensure that they 1) do **not undermine the level of ambition for recycling**, and 2) are consistent with climate-smart land use practices and do **not lead to land use intensification or direct or indirect land use change** with detrimental effects on ecosystems and carbon cycles.

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Mit Zukunftsinvestitionen die fossile Inflation bekämpfen

Durchbruch für die Wärmepumpe
Praxisoptionen für eine effiziente Wärmewende im Gebäudebestand

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Schutz in der fossilen Energiekrise
Optionen für Ausgleich und Entlastung

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Klimaneutrales Stromsystem 2035 (Vollständige Studie)
Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann

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About Agora Industry

Agora Industry is a division of Agora Energiewende that develops strategies and instruments for climate-neutral industrial transformation – in Germany, the EU and globally. Agora Industry works independently of economic and partisan interests. Its only commitment is to climate action.

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