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Position Paper

Towards a Climate-neutral Germany
Policy Options for the Technological Transition, Reducing Consumption and Carbon Management

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Towards a Climate-neutral Germany

Policy Options for the Technological Transition, Reducing Consumption and Carbon Management

Preface

In its Biennial Report published at the end of 2022, the German Council of Experts on Climate Change concludes that the emission reduction rates to date are far from sufficient to achieve the climate protection targets for 2030. Even with the policy instruments implemented by 2021, the sector target will not be met in any sector. While issues such as energy security and affordability have come to the fore as a result of the current energy price crisis, they must not be allowed to overshadow climate action, especially at such a critical juncture.

How can a climate-neutral energy supply be achieved? This question was addressed by a working group of the Academies' Project "Energy Systems of the Future" (ESYS). The working group reviewed the current literature and simulated its own scenarios.

The working group's experts regard efficiency and sufficiency as key strategies for reducing energy demand and thus preventing greenhouse gas emissions. In addition, it will be necessary to transition to a fully renewable energy supply. However, in order to achieve climate neutrality, it will also be essential to reduce hard-to-abate industrial process emissions. This is especially true of the energy-intensive steel, chemical and cement industries that are responsible for a large proportion of industrial emissions. The experts argue that a three-pronged approach of circularity, material efficiency/substitution and climate-neutral processes will be key to achieving the relevant targets in industry.

In their study, the experts also conclude that negative emissions will make an indispensable contribution to tackling climate change. Both technological and land-based carbon dioxide removal methods will be needed to counterbalance hard-to-abate emissions so that Germany can achieve climate neutrality by 2045.

All of these areas will require policymakers to develop measures – such as an active sufficiency policy – that complement existing market mechanisms, especially carbon pricing. The experts argue that the necessary widespread transition to climate neutrality in the energy system and in industry can only be achieved through a combination of far-reaching measures in every sector. If these strategies are pursued concurrently, missed targets in some areas can be offset by successes in others.

We would like to express our sincere thanks to the scientists and reviewers who contributed to this paper.

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Contents

Abbreviations, acronyms and units

BECCS	Bioenergy with Carbon Capture and Storage
BECCU	Bioenergy with Carbon Capture and Utilisation
BEHG	Brennstoffemissionshandelsgesetz (Fuel Emissions Trading Act)
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
DACCS	Direct Air Capture and Storage
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)
EU ETS	European Emissions Trading System
EV	Electric vehicle
GHG	Greenhouse gas
GW	Gigawatt(s)
HVC	High Value Chemical
HGV	Heavy goods vehicle
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied natural gas
LULUCF	Land Use, Land-Use Change and Forestry
MW	Megawatt(s)
PV	Photovoltaic(s)
RED	Renewable Energy Directive
SDG	Sustainable Development Goal
TRL	Technology Readiness Level
TW	Terawatt(s)

Glossary

Active mobility	Forms of transport based on human physical activity, especially cycling and walking.
Agrivoltaics	The simultaneous use of land for agriculture and solar power generation.
Backup power plants	Flexible power plants used as a backup for the electricity supply rather than to produce electricity continuously. They are only used for a few hours a year, for example at times when not enough wind and solar power is being fed into the grid.
BECCS – Bioenergy with Carbon Capture and Storage	How it works: plants extract CO_2 from the atmosphere through photosynthesis and convert it into energy-rich carbon compounds. When these compounds are used to produce electricity, heat or fuel, the CO_2 is released again. But instead of going back into the atmosphere, it is captured and permanently stored underground. This results in the net removal of CO_2 from the atmosphere.
Blue hydrogen	Hydrogen produced from natural gas by steam reforming. The CO_2 generated by this process is captured and stored underground (CCS).
Capacity markets	In capacity markets, suppliers are paid for providing capacity rather than for the quantity of electricity generated. They are paid regardless of whether electricity is actually fed into the grid.
Carbon Border Adjustment Mechanism	Carbon Border Adjustment Mechanisms are sometimes referred to as "climate tariffs". They aim to prevent industry from relocating to regions with less ambitious climate policies (carbon leakage) by compensating for the global competitive disadvantages of carbon pricing. Imported goods are subjected to a carbon levy equivalent to the carbon price applicable to domestically produced goods. The European Union is currently discussing the introduction of a European Carbon Border Adjustment Mechanism for iron, steel, cement, fertiliser, aluminium and electricity.
Carbon Contracts for Difference (CCfDs)	Carbon Contracts for Difference are an instrument that can be used to help climate-friendly industrial technologies compete with conventional technologies that have negative climate impacts. How it works: a company wishing to switch to a climate-friendly technology signs a CCfD with the government. The contract establishes a fixed carbon price for the lifetime of the new asset in order to compensate as far as possible for the cost to the company of reducing CO_2 emissions. If the market price of carbon credits falls below the carbon price agreed in the contract, the government pays the company the difference. If the market price is higher than the carbon price agreed in the contract, the company pays the difference to the government.
CCS – Carbon Capture and Storage	CO_2 is captured from energy or industrial installations and permanently stored underground, mainly in exhausted oil and natural gas reservoirs and deep saline aquifers.

CCU – Carbon Capture and Utilisation	CO_2 is captured from an industrial process and used e.g. in chemical processes. Synthetic fuels (synfuels) made from hydrogen and CO_2 are one example. CCU can be used to produce various products that contain carbon, such as plastics and chemicals. The CO_2 replaces oil or gas as the source of carbon.
DACCS – Direct Air Capture with Carbon Capture and Storage	A carbon dioxide removal technology. DACCS facilities use chemical binding agents to capture CO_2 from the air. The CO_2 is subsequently compressed and stored underground.
Distributional effect [of carbon pricing]	The distributional effect describes the impact of policy measures, in this case carbon pricing, on income and wealth distribution in society. The burden or benefits for different demographic groups can vary depending on how a measure is designed.
Ecosystem services	The benefits provided by ecosystems to humans. Examples include the provision of water, the reproduction of animals and plants used for food, the provision of building materials such as timber, medicinal resources, and the pollination of crops by insects. An attractive environment that provides opportunities for recreation and is aesthetically pleasing is also an ecosystem service.
Feedstocks	In this context, feedstocks are chemical and biogenic energy carriers (hydrogen and hydrocarbons) that are used as raw materials for the production of plastics or chemicals rather than to produce energy. Today, most are either fossil feedstocks like natural gas or refinery by-products like naphtha. In the future, it will be necessary to use climate-friendly feedstocks such as biomass or green hydrogen and synthetic hydrocarbons derived from green hydrogen. A climate-neutral source of carbon will be required to synthesise the hydrocarbons.
Final energy	The energy consumed by end users (households, businesses, industry), e.g. in the form of electricity, petrol and heating oil. Final energy is calculated as the primary energy used to produce the final energy carrier minus the losses incurred during transport and conversion.
Flexibility (electricity supply)	There will be a need for technologies capable of compensating for the intermittent nature of wind and solar power in order to maintain a balance between the amount of energy fed into and drawn from the power grid. These technologies include batteries, flexible power plants with rapidly adjustable outputs, and consumers able to at least partly defer their electricity consumption to times when a lot of wind and solar power is being fed into the grid.
Floating PV	PV modules that can operate on the surface of unused waterbodies.
Grandfather clauses	Provisions in laws or contracts that exempt pre-existing assets from new legal requirements. For instance, if tougher emission limits were introduced, they would only apply to new assets, whereas old assets covered by a grandfather clause would remain subject to the limits that were in place when they were licensed.
Green hydrogen	Hydrogen produced with renewable energy. In most cases, it is produced by electrolysis using wind or solar power. The electrolysis process that splits water into hydrogen and oxygen requires large amounts of electrical energy.
Grey hydrogen	Hydrogen produced from natural gas by steam reforming. Unlike blue hydrogen, instead of being captured and stored underground, the resulting CO_2 is released into the atmosphere, generating CO_2 emissions. This is the most common way of producing hydrogen today.

High-value chemicals (HVCs)	The term "high-value chemicals" refers to olefins and aromatics, the main products of steam cracking. These "platform chemicals" are used to produce plastics, paints and coatings, solvents and other products. Steam cracking breaks down long-chain hydrocarbons, principally naphtha from oil refineries, into smaller hydrocarbons. Future climate-neutral HVC production will call for alternative production methods based on hydrogen and climate-neutrally produced carbon.
Interconnector capacity	Line capacity for cross-border power transmission.
Intermittent renewable energy	Renewables that depend on the weather, primarily wind and solar power.
Material substitution	The replacement of a material that is problematic – for instance because it is expensive, scarce or damaging to the climate – with another, less problematic material. Examples include the substitution of timber for cement and steel in the construction industry and the replacement of cement clinker with alternative binders in cement production.
Micromobility	Transport using small, lightweight vehicles. The vehicles may be electric, conventional or non-motorised. Examples include bicycles, pedelecs, kick scooters and e-scooters. These vehicles can help to reduce freight and passenger transport emissions if they replace larger vehicles or are used in conjunction with rail transport for the "last mile".
Modal shift	Climate-friendly mobility will require a shift away from motorised private transport (especially private cars) towards public transport and active mobility (cycling, walking). The freight sector can reduce its climate footprint by shifting from road transport to rail and inland waterways.
Negative emissions	Carbon dioxide removal, for example through bioenergy with CCS or afforestation. The total emissions are net-negative if the total amount of CO_2 removed from the atmosphere is greater than the total amount emitted, thereby reducing atmospheric CO_2.
Parking management	Charging or time restrictions for parking space use.
Price sensitivity	Price sensitivity is a measure of how strongly consumer purchasing behaviour is affected by changes in a product's price.
Process emissions	Greenhouse gas emissions from industrial processes arising from the chemical conversion of feedstocks into products. The term is used to distinguish these emissions from energy-related industrial emissions arising from the production of the energy required to power production processes (mainly electricity and heat).
Reallocation charge	"Reallocation charges" are used to finance energy transition measures by passing on their cost to consumers using a fixed allocation formula. In Germany, reallocation charges are used e.g. to pay the feed-in tariff for renewable electricity promoted under the Renewable Energy Sources Act (EEG) or Combined Heat and Power Act (KWKG).
Rebound effect	Energy efficiency improvements can lead to changes in consumer behaviour that prevent the efficiency measures from achieving the hoped-for energy savings. The rebound effect occurs because efficiency improvements are often associated with cost savings for consumers. When the cost of a more efficient energy service falls, demand for it increases. This is referred to as a direct rebound effect. An indirect rebound effect occurs when the money saved as a result of efficiency improvements is spent on other products or services that also consume energy.
Redispatch	In order to relieve imminent grid congestion, grid operators instruct power plants and storage facilities up- and downstream of the grid bottleneck to adjust their operating schedules (dispatch).

Residual emissions	The greenhouse gas emissions, mainly from farming and industry, that remain after all available measures to reduce CO_2 emissions have been deployed. To achieve climate neutrality, it will be necessary to counterbalance these difficult or impossible to avoid residual emissions through carbon dioxide removal (negative emissions).
Re-use	The re-use of products after their first use for the purpose that they were originally designed for. Examples include reusable containers and second-hand goods. Products that are durable and repairable support the widespread adoption of re-use practices.
Ridesharing	Carpools and lift sharing arrangements, usually with private cars.
Ridepooling	Ridesharing that uses digital systems to combine individual routes.
Sector coupling	Sector coupling involves connecting the electricity, heating and mobility energy sectors to create an integrated energy system that provides the necessary energy services to domestic, commercial and industrial customers. Sector coupling aims to increase the use of renewable energy, especially solar and wind power, in the heating and transport sectors and in industry. This involves the use of direct electrification technologies (such as electric vehicles and heat pumps) and indirect electrification technologies (the use of electricity to produce hydrogen or synfuels that replace fossil fuels in the relevant applications).
Sufficiency	Sufficiency is a strategy for enabling an absolute reduction in consumption and production while still guaranteeing minimum standards. It is achieved first and foremost through social innovation and behavioural change. It is thus distinct from (energy) efficiency, which refers to a relative reduction in the energy consumption of a given energy service.
Synfuels	Synthetic fuels produced using electricity generated from wind or solar power. How it works: water is split into hydrogen and oxygen by electrolysis, an energy-intensive process powered by electricity. The hydrogen is then combined with CO_2 to produce carbon-containing compounds such as methane or liquid fuels. Synfuels are sometimes also referred to as e-fuels.
Technology Readiness Level (TRL)	Technology Readiness Level is based on a scale from 1 to 9 for evaluating the maturity of new technologies. It helps to estimate how long it will be before a technology is ready to go to market.
Windfall profits	Unexpected profits resulting from events outside a company's control that cause a sudden and unanticipated change in the market.

Summary

To meet Germany's current climate targets, far-reaching measures will need to be taken concurrently in every sector.

1. If current **energy consumption patterns** continue, renewable energy and other technologies will need to be rolled out at an extremely rapid rate that will be very difficult to achieve. As well as improving energy efficiency, it is thus vital to reduce demand for energy services.

2. **Achieving this reduction in demand will require policy measures** to create an appropriate framework that involves more than just carbon pricing. **Good, climate-friendly alternatives** for housing and mobility will be key to enabling a socially equitable transformation.

3. **Climate-neutral production** must go hand in hand with **sustainable consumption**. Product demand can be reduced by sharing goods, using them for longer, and reusing and reconditioning them. Climate-neutral production can be achieved through new production processes using green hydrogen and electricity, closed material cycles and zero-carbon raw materials.

4. **A rapid transition to a one hundred percent renewable energy supply, widespread direct electrification and a ramp-up of hydrogen production and imports** will all be necessary, even if energy consumption is reduced.

5. Residual emissions will need to be counterbalanced by **carbon dioxide removal**. It will be necessary to revisit the option of **geological CO_2 storage** for this and for unavoidable process emissions captured from industry.

Methodology and focus

The latest version of the Federal Climate Change Act sets a deadline of 2045 for Germany to achieve net greenhouse gas neutrality. The aim of this study is to identify transformation pathways for meeting this target. While its focus is on the German energy system, it also considers how Germany fits into the wider European context and discusses imports of hydrogen and other electricity-based energy carriers.

The findings presented in this paper were arrived at using the following three methodologies:

1. the working group's own simulations,
2. a systematic review of existing scenarios for a climate-neutral Germany, and
3. expert discussions in an interdisciplinary working group.

The **working group's own simulations** used the REMod energy system model developed by the Fraunhofer Institute for Solar Energy Systems. A **review of climate neutrality scenarios in seven German studies** was carried out in parallel. The review aimed to contextualise the results of the working group's own simulations and identify the areas where the experts largely agree on the main aspects of the pathway for transitioning to climate neutrality. It also sought to identify the areas that are more contentious – i.e. where there is still considerable uncertainty about the technologies most likely to deliver the desired results.[1] Conclusions are also drawn about areas not covered by the REMod simulations, primarily industrial process emissions and carbon dioxide removal technologies used to counterbalance hard-to-abate residual emissions. The **expert discussions** provided an opportunity to reflect on the findings of the working group's simulations and the meta-analysis and formulate recommendations for policy measures and instruments based on the overall picture presented by the different scenarios.

The study focuses on the following aspects:

1. the **importance of reducing demand** in order to meet the climate targets,
2. the role of **faster technology rollout** in helping to meet the targets,
3. the assumptions that would allow a **climate-neutral energy supply** to be achieved **before 2045**,
4. the strategies required to achieve climate neutrality in **industrial production**, and
5. how **net-negative emissions** can help to achieve climate neutrality.

1 However, it should be stressed that most of these transformation pathways are scenario-based projections (i.e. "what-if" simulations) and not forecasts.

Previous scenario studies have barely considered the extent to which **reducing demand** for energy services could create some leeway if the technology rollout targets are not met, or even help to meet the climate targets a few years earlier. Consequently, this was addressed in the working group's own simulations. In order to explore the full extent of the leeway in the transformation pathways, extreme assumptions were deliberately chosen both for demand reduction and for **faster technology rollout**.

It has become apparent that the sum of current national climate targets will not be enough to meet the targets set out in the Paris Climate Agreement. Consequently, it is urgently necessary to enable the possibility of achieving a climate-neutral energy system in Germany even sooner than 2045. This was investigated by simulating the achievement of a **climate-neutral energy supply by 2040**. The energy system model was only able to identify a transformation pathway that meets this deadline by assuming either a very strong reduction in demand or an even faster technology rollout than in the main scenario, which already assumes an ambitious rollout rate. However, regardless of the deadline for meeting the targets, these simulations should not mislead anyone into thinking that the transition to climate neutrality can be achieved without a tremendous effort and far-reaching transformation.

If Germany is to stay within a carbon budget that is **compatible with the 1.5 degree Celsius target** and also reflects equal global per capita distribution, it will need to reduce its emissions to almost zero by 2035. This scenario was also modelled and was only found to be achievable if the technological transition happens even faster and final energy demand is reduced even more quickly. During their discussions within the working group, the experts concluded that it would be impossible or almost impossible to achieve the rate of technology rollout and conversion required by this scenario. They reached a similar conclusion about the feasibility of the required rate of behavioural change throughout society as a whole.

In addition to accelerating the transformation of the energy system, the achievement of climate neutrality will also call for a greater focus on reducing industrial process emissions and greenhouse gas emissions from farming wherever possible. Regardless of the measures taken, however, some residual emissions will always be unavoidable. These will need to be counterbalanced by **carbon dioxide removal**. Accordingly, one of the working group's key priorities was to undertake a specific, separate analysis of options for achieving net-negative emissions.

Key message 1: The transition to climate neutrality will require extensive social and policy changes

Our continued existence on this planet will be in jeopardy unless we transition to a climate-neutral lifestyle and economy within a few short decades. Integrated social, technological and economic solutions will be key to achieving the far-reaching changes that are required. This will call for overarching packages of measures that enable the transformation by fundamentally promoting technologies and behaviours that prevent CO_2 emissions.

Overarching policy options: policy areas (PAs)
PA 1: Define wider targets and pursue a wider range of solutions for a sustainable energy transition To achieve climate neutrality, it will be necessary to use renewable resources instead of fossil resources, implement closed-loop material cycles, improve energy and material efficiency and reduce demand for energy services. The significance of these measures is even greater if, in addition to the climate effects, other planetary boundaries and the global impacts of energy and resource consumption are also taken into account.
PA 2: Address the energy transition as a social process The energy transition is much more than a technological transformation – it is also about how we shape the future socially, culturally and as a society. It is about reconciling a high standard of living with long-term environmental sustainability. The policy framework should aim to make climate-friendly behaviour the easiest option and to actively promote sufficiency. Transparent processes, opportunities for active participation and a perception that the benefits and burdens are shared fairly are all key to achieving public acceptance.
PA 3: ”Getting the Price Right” to achieve climate neutrality A sufficiently high carbon price across all sectors is key to eliminating the use of fossil fuels. Grandfather clauses and the importance of reliable forward planning mean that carbon prices usually start off at a moderate level before subsequently rising. Consequently, additional support may be needed for technologies that are still in the early stages of development and will therefore be more expensive at the start of the transition. The phasing out of this support should also be planned for from the outset. Future carbon price increases must also be predictable for businesses. Carbon Contracts for Difference (CCfDs) can help companies to plan ahead with confidence and support new technologies during their market rollout phase. Current subsidies for fossil fuel use undermine carbon pricing and should be ended.
PA 4: Upgrade the key network infrastructure in good time Because of its long lifespan and planning timeframe, new network infrastructure should be built with an eye on future requirements. The electricity transmission and distribution grids are in particular need of upgrading. Increased sector coupling will call for an overarching system development plan geared towards the integrated development of the electricity, gas, hydrogen and CO_2 networks. This will require close cooperation at European level. It will also be important to find ways of overcoming the multiple barriers to network expansion associated with local opposition to specific projects.

Overarching policy options: policy areas (PAs)
PA 5: Establish transparent and consistent guidelines for the deployment of electrification, hydrogen, PtX and biomass In many cases, renewable electricity, green hydrogen and its derivatives and biomass can be used as alternatives for the same applications. Energy scenarios indicate that a high percentage of direct electrification results in a more efficient and cheaper overall system. The limited potential of sustainably produced biomass and climate-neutral hydrogen should be preferentially used in applications where there is no direct electric alternative, for example certain industrial processes, shipping, aviation and some types of heavy goods transport. The use of biomass as a raw material should be prioritised over its use as an energy source.
PA 6: Strengthen energy transition skills among industry professionals and provide free information A training campaign for the relevant manual and technical professions could help to meet the urgent need for more skilled professionals to implement the transition. Continuing professional development can help to keep installers and consultants up to date with the latest developments in the field. Among other things, this is important because they often have a significant influence on private purchasing decisions (e.g. for heating systems). Information campaigns that include sufficiency options can also help households with their choices in the housing, mobility and consumer sectors.
PA 7: Continuously monitor policy effectiveness Achieving the goal of climate neutrality by 2045 will call for a rapid, concurrent transition in every sector. It is no longer enough to start by focusing only on cheap measures. An early indicator system can help to quickly identify where targets are likely to be missed so that corrective measures can be taken.

Table 1: Overarching policy options: policy areas (PAs)

Key message 2: It will be almost impossible to meet the climate targets without reducing demand

The simulations indicate that a strategy focused predominantly on technological solutions would require an extremely extensive and rapid transition and would also necessitate the use of particularly costly technologies. For instance, it would call for extremely rapid and extensive modernisation of the entire building stock. If current behaviour patterns remain unchanged, the implementation of a purely technology-focused transformation would be associated with huge pathway risks. The requirements for land and other resources as well as the availability of imports would also be very challenging. Consequently, the technological transition must be accompanied by an active sufficiency policy that promotes climate-friendly behaviours and creates the conditions for a significant reduction in energy service demand. This should not be interpreted as a call to reduce demand through individual "sacrifice" driven mainly by price signals. Instead, it is necessary to create an overall framework that is geared towards people's needs, creates accessible climate-friendly alternatives for everyone, and can thus enable positive side effects over and above demand reduction. New housing, mobility, consumption and production concepts can play a particularly important role in this regard.

Policy measures for reducing consumption: policy areas (PAs)
PA 8: Strengthen scientific research on the integration of strategies to reduce consumption Previous transition scenarios for Germany have barely considered sufficiency strategies. Policy advice in particular should place greater emphasis on them, with a view to quantifying the potential, limitations and timeframes of strategies to reduce consumption and formulating appropriate policy options.
PA 9: Reimagine mobility The efficiency gains achieved thanks to technological advances in the transport sector have not translated into a reduction in CO_2 emissions. This is because they have been accompanied by an increase in passenger and freight transport use and in average vehicle size and weight. Consequently, rather than simply relying on technological developments, it will be vital to develop an integrated strategy that defines mobility as a means of accessing particular destinations such as workplaces, social activities and shops. The strategy should aim to reduce motorised private transport by promoting high-quality public transport, cycling and walking and by making the appropriate long-term urban planning and settlement structure policy choices. Economic regionalisation could help to reduce freight transport.
PA 10: Focus on housing quality, land use and climate adaptation In addition to heating systems, the building sector's environmental footprint is also determined by building materials' resource consumption and embodied emissions, i.e. the greenhouse gas emissions arising from the materials' production. Other factors include land use and soil sealing. Reversing the trend towards higher per capita living space is key to reducing the building sector's climate and environmental footprint. This could be facilitated by more flexible use of existing buildings, enabled for example by senior-friendly refurbishments or house swapping services, and by greater use of communal areas. While this is a long-term goal, the relevant policy decisions should be made as soon as possible. Adaptation to rising temperatures and other impacts of climate change should also be addressed in long-term strategies for the building sector.
PA 11: Reduce energy demand through sustainable consumption and production Systematic pricing of climate impacts and other externalities can reduce demand for products that are damaging to the climate. Policy measures can ensure that climate-friendly alternatives are accessible to all social groups. This can be supported by simple and transparent labelling of products' climate impacts and by incentives to produce products that are durable and repairable.

Table 2: Policy measures for reducing consumption: policy areas (PAs)

Key message 3: The technological transition must happen much faster

Both the scenario study meta-analysis and the working group's own simulations indicate that various technologies will need to be rolled out much faster if climate neutrality is to be achieved by 2045. Wind and solar power, technologies for producing hydrogen and synfuels, electric mobility, heat pumps and building modernisation measures will need to be rolled out at rates that, in some cases, are at the limit of what the experts currently deem possible. The relevant technologies will still have to be rolled out extremely quickly even if there is a strong fall in demand as a result of extensive sufficiency measures. It is thus vital to implement the most efficient system solutions without delay.

Modernising the energy supply: policy areas (PAs)
PA 12: Transition to a one hundred percent renewable electricity supply as soon as possible The electricity supply will need to be almost one hundred percent renewable by 2035. This will call for a significantly faster expansion of wind and solar power. It will also be necessary to upgrade electricity grids and storage systems in order to optimise the integration of renewables. In addition to financial measures to incentivise investment in the necessary technologies, it will be necessary to expedite planning and licensing procedures and make sufficient land available for their expansion.
PA 13: Enable a rapid ramp-up of the hydrogen and synfuel markets in areas where they can deliver system benefits A rapid ramp-up of the hydrogen market will play a particularly important role in helping industry to meet its climate targets. This will require the development of both domestic hydrogen production and the relevant import relationships and infrastructure. Supply and demand side support for hydrogen production and use will be necessary until such a time as the projected reductions in the cost of electrolysis are achieved through economies of scale and a liquid market has been established for green/low-emission hydrogen. In the future, hydrogen derivatives such as methanol will be required, primarily for use as fuels in the international aviation and shipping sectors but also as raw materials in the chemical industry. In addition to hydrogen, in the long term a climate-neutral source of carbon will also be needed to produce these derivatives. The scenarios analysed all agree that most of Germany's demand for hydrogen derivatives will be met by imports.
PA 14: Switch to a climate-neutral heating supply Key requirements for a climate-neutral heating supply include more favourable conditions for the widespread adoption of centralised and decentralised heat pumps, a higher building modernisation rate, the expansion of heating networks, compulsory connection of waste heat sources and the use of deep geothermal energy. Mandatory municipal heating planning, as promised in the German government's coalition agreement, is a key instrument for the development of an efficient, long-term heating supply strategy that reflects local conditions, and should therefore be introduced as soon as possible.
PA 15: Drive the technological transition to a climate-neutral transport sector A shift from private car use to cycling, walking and public transport will be key to achieving climate-neutral mobility. This will call for the redistribution of traffic space in urban areas. Ambitious measures must also be introduced to accelerate the switch to battery electric vehicles in the passenger car sector. Further expansion of the charging infrastructure will be crucial, as will systematic leveraging of the potential to improve electric vehicle efficiency. In the freight transport sector, close coordination will be required at European level. In principle, both direct electric solutions in the shape of battery-powered vehicles and overhead line systems have potential in this sector. However, it will also be important for the rail freight system to take over as much freight transport as possible. This will require investment in and extensive digitalisation of the European rail network. In the international shipping and aviation sectors, synfuel quotas can kickstart the market diffusion of climate-neutral fuels that will be vital in the long term.

Table 3: Modernising the energy supply: policy areas (PAs)

Key message 4: Industry requires a three-pronged approach of climate-neutral processes, circularity and material efficiency

The long lifespan of production assets and the imperatives of global competition mean that it will be particularly challenging for industry to achieve climate neutrality by 2045. Pan-European regulatory solutions will be required to prevent offshoring to regions with lower climate standards.

Strategies for climate-neutral industry: policy areas (PAs)
PA 16: Climate-neutral processes Since approximately one third of industrial emissions are process emissions, it is not enough simply to replace fossil fuels with renewables. Instead, it will be necessary to completely redesign industrial processes. In steel production, for example, blast furnaces will need to be replaced with direct reduction by hydrogen. In the long term, fossil feedstocks such as the gas and oil used to produce plastics will have to be replaced by biogenic alternatives or feedstocks made with green hydrogen and CO_2 removed from the atmosphere. Appropriate instruments such as Carbon Contracts for Difference and investment support schemes will be needed to stimulate new investment in climate-neutral processes. Emissions that cannot be prevented in this way, especially in the cement industry, will need to be captured using carbon capture and storage technology or counterbalanced by negative emissions. If the captured CO_2 is used to produce goods, the entire chain will only be climate-neutral if the products have a very long lifespan, if recycling keeps the carbon in a closed-loop system for a very long time, or if the CO_2 released when the product is incinerated at end-of-life is captured and stored geologically.
PA 17: Creation of a circular economy The creation of a circular economy can significantly reduce resource consumption and industrial emissions. Policymakers can draw on a wide range of instruments to implement a circular economy. In order to achieve closed-loop material cycles and enable efficient recycling, manufacturers could be required by law to design products that are simple to disassemble into easily recyclable components. Take-back obligations for manufacturers and better collection and logistics systems could also improve the supply of raw materials for secondary production. Quotas for the use of secondary materials in production could reduce demand for primary raw materials.
PA 18: Promote material efficiency and material substitution Mandatory carbon footprint labelling covering every stage of a product's life would create transparency and help consumers to make climate-friendly choices. Quotas or binding sustainable procurement rules could be introduced in the public sector. The use of climate-friendly building materials will require some aspects of building and product standards to be updated.
PA 19: Strengthen carbon price effectiveness and investment security In the current system, where free carbon allowances are allocated to industry, there is a danger that carbon prices will not always be fully reflected in production costs. However, since many companies compete in global markets, the goal of more effective carbon pricing must be balanced against the need to prevent carbon leakage, i.e. the relocation of production to regions with lower climate standards. Between now and 2030, Carbon Contracts for Difference could encourage companies to switch to climate-neutral production processes even while carbon prices are still relatively low. At EU level, it will be necessary to develop a version of the Carbon Border Adjustment Mechanism that the member states can agree on, but that still provides effective incentives for the transformation of industry.

Table 4: Strategies for climate-neutral industry: policy areas (PAs)

Key message 5: Carbon dioxide removal is necessary as well as but not instead of preventing CO_2 emissions

Carbon dioxide removal from the atmosphere will be necessary to counterbalance unavoidable emissions and stay within the Paris Climate Agreement temperature limit. The carbon dioxide removal strategy should be coordinated at European level and form an integral part of an overarching carbon management strategy that also encompasses carbon utilisation (CCU) and the geological storage of fossil CO_2 emissions (CCS) that cannot be reduced sufficiently within the required timeframe.

In some cases, there is still considerable uncertainty about the potential of carbon dioxide removal and the cost, threats to the environment and social impacts of different CDR methods. Consequently, climate action strategies should not be over-reliant on carbon dioxide removal and should prioritise the prevention of CO_2 emissions wherever possible. In other words, carbon dioxide removal should not be used instead of emission prevention.

Carbon management: enabling the transition to net-negative emissions: policy areas (PAs)
PA 20: CDR – removing carbon from the atmosphere It is important to ensure that the ambition of measures to prevent CO_2 emissions is not diminished by the prospect of carbon dioxide removal (CDR) at some point in the future. CDR is associated with numerous risks and uncertainties in terms of its potential, cost, and environmental and social impacts, as well as the length of time that the carbon will remain stored. The introduction of a statutory target for the ratio of emission reduction to CDR would ensure that the prevention of greenhouse gas emissions was prioritised. There is an urgent need for further research into the different CDR methods. These must also be trialled on an industrial scale and evaluated in a broad public debate process that addresses their potential and risks. The risk of stored CO_2 escaping back into the atmosphere varies depending on the method used. For instance, it can be released by forest fires where afforestation has been used as a carbon sink. It will therefore be necessary to develop appropriate accounting rules. Temporary, technology-specific funding will be required to help bring methods that are still under development to market.
PA 21: CCS – geological carbon storage Until a few years ago, CCS was primarily seen as a solution for CO_2 emissions from coal-fired and gas-fired power plants. Today, on the other hand, it is mainly viewed as a means of dealing with emissions that are difficult to avoid (for example from the cement industry and waste incineration) or carbon dioxide that has been removed from the atmosphere in order to counterbalance residual greenhouse gas emissions (especially from farming). This change calls for a new public debate about the extent to which CCS should be implemented in Germany and where the carbon should be stored – e.g. in Germany or in other European countries, and onshore or offshore. The development of a European CO_2 storage and transport infrastructure should commence as soon as possible.
PA 22: CCU – climate-friendly carbon utilisation It is also necessary to find replacements for the fossil carbon used as a raw material for products like plastic (Carbon Capture and Utilisation – CCU). Potential climate-neutral carbon sources include biomass and CO_2 that has been removed from the atmosphere. In contrast, if CO_2 derived from fossil fuels is utilised, the entire chain is not carbon-neutral, since the CO_2 is released into the atmosphere at the end of the product's life. Regardless of where the carbon comes from, the length of time that it remains locked away is key – the longer this time, the greater the climate benefits. Accordingly, incentives for CCU should be based on the actual climate benefits delivered rather than simply on carbon utilisation per se.

Table 5: Carbon management: enabling the transition to net-negative emissions: policy areas (PAs)

1 Introduction

While the transformation of the German and European energy systems is steadily gathering momentum, it needs to happen even faster. The transition is already being driven by the amended Federal Climate Change Act, which defines Germany's national contribution to limiting global warming and mitigating the devastating consequences that it is likely to have for our existence on this planet. The need for a far-reaching transformation is not confined to the energy supply – it affects every sector, including industry. This has become all too apparent in the light of the recent developments in Europe's energy markets, which have been severely exacerbated since the start of the war in Ukraine.

While the current **energy crisis** and **natural gas supply issues** could delay the energy transition, they could also accelerate it. High energy prices are an incentive to reduce consumption and thus curb fossil fuel use. They also create better market opportunities for renewable energy technologies. On the other hand, there is a danger that strategies and investments designed to prevent supply shortages in the short to medium term and mitigate high energy prices could cause emissions to rise, for example if more coal is used to replace Russian gas. This could even result in fossil fuel technology lock-in if new natural gas fields are developed or regasification plants and pipeline extensions are built without taking future hydrogen infrastructure requirements into account. Moreover, measures to tackle the current crisis are tying up capital and other resources that are needed for the transformation of the energy system, while rising raw material prices are affecting production of the necessary energy technologies. These factors could prevent the relevant technologies from being rolled out as fast as necessary and delay other measures such as building retrofits.

This position paper is based on a wider analysis of scenarios and policy options for achieving a climate-neutral energy supply and industrial sector that was carried out by a previous ESYS working group. It addresses the fundamental question of how to achieve a climate-neutral energy supply and industrial sector in Germany, expanding on the findings of the ESYS working group on Coupling Different Energy Sectors as presented in the 2017 study "Sektorkopplung – Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems" [2] (German only) and the position paper "Coupling the different energy sectors – options for the next phase of the energy transition"[3]. This working group investigated ways of reducing CO_2 emissions by up to ninety percent compared to 1990 levels, but did not address industrial process emissions. The current position paper adopts a wider perspective by including industrial production in its discussion of the climate neutrality goal. Where relevant, it

2 Ausfelder et al. 2017.
3 acatech/Leopoldina/Akademienunion 2017-1.

also discusses how the implications of the recent energy price crisis could affect the previous conclusions.

This ESYS working group also analysed **demand-side solutions** for preventing greenhouse gas emissions in greater detail than many previous climate neutrality scenario studies, where stable or even increasing demand for energy services is set exogenously. Both energy efficiency measures and the reduction of demand for energy services are addressed in this paper. This is an area that has received more attention as a result of recent efforts to reduce reliance on Russian energy imports. However, even before the latest turn of events, the IPCC's Sixth Assessment Report devoted the first ever chapter to demand for energy services and the social aspects of climate change mitigation. The inclusion of social and demand-side aspects in the IPCC report is based on scientific evidence showing that energy savings are not necessarily at odds with welfare and quality of life and may even improve them if these dimensions are included in the energy-saving measures' design. In other words, energy scenarios that include a reduction in demand are entirely compatible with sustainable development. Moreover, they make further transgression of planetary boundaries less likely. As well as posing less of a threat to the environment than many supply-side technologies, they reduce the need to remove CO_2 from the atmosphere at some point in the future ("negative emissions"), a process associated with multiple challenges and uncertainties. Demand-side solutions can also help to meet short-term climate change mitigation targets. Nevertheless, it should be emphasised that there are limits to the potential of demand-side solutions. In some cases they can take a long time to deliver and be challenging to implement (for example due to public acceptance issues, conflicts with established economic interests or complex actor structures). Achieving the goal of climate neutrality will call for ambitious strategies for every aspect of the system's transformation.

Although the German energy system is the main focus of this paper, it is embedded within the wider European context and cannot be considered in isolation. Many of the policy options for promoting the energy transition must be coordinated within the European regulatory framework, and the policy options proposed in this paper take this into account.

The **methodology** used for this position paper comprised **the working group's own simulations**, a **systematic analysis and comparison of existing energy scenarios for achieving climate neutrality by 2045/2050** and **expert discussions in an interdisciplinary working group**. This process is illustrated in Figure 1.

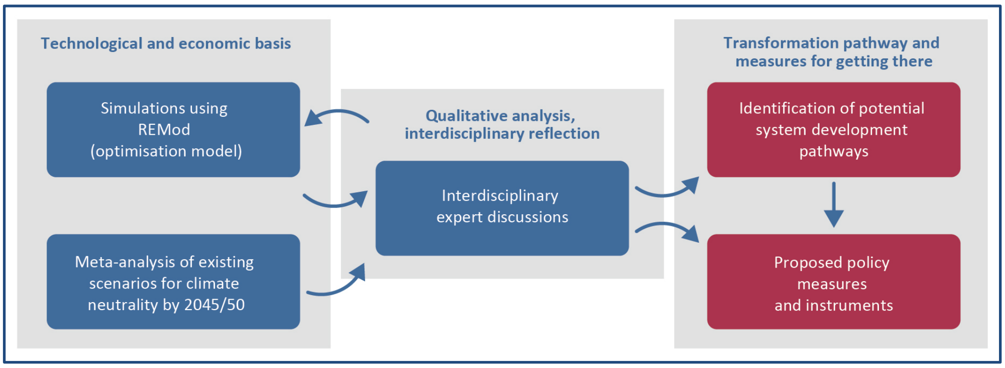

Figure 1: Working group methodology

The working group's own simulations used the REMod energy system model developed by the Fraunhofer Institute for Solar Energy Systems. This model uses cost-based optimisation to calculate a target pathway for the energy system transformation that stays within a given energy-related CO_2 emission budget. Energy conversions in the industrial, transport and building sectors and the conversion sector itself can be modelled in different levels of detail. The scenario modelled using REMod is hereafter referred to as "ESYS KN2045". It comprises a main scenario and additional specific scenarios (referred to as focus scenarios) that model a stronger reduction in final energy demand and a faster market rollout of the relevant energy technologies. The focus scenarios investigate the leeway that can be created through significantly greater efforts on these two fronts. This leeway can help to reduce the existing implementation risks along the transformation pathway.

The unavoidable residual emissions associated with certain activities – primarily farming, waste management and some industrial processes such as cement production – mean that climate neutrality cannot be achieved without **negative emissions**. Consequently, a comparatively large amount of space is devoted to this topic. The role of carbon dioxide removal is discussed, together with the options for its implementation.

A favourable framework and key policy decisions will be essential for enabling the multiple measures that the scenario analysis identifies as necessary for achieving a climate-neutral Germany. This position paper outlines the available **policy options** and identifies measures that can confidently be expected to make a major contribution to achieving climate neutrality. Chapter 2 summarises the key findings of the analysis, contextualising the policy options and explaining the background to them. The following chapters outline overarching policy options for promoting the energy transition (Chapter 3), and more specific options in the fields of demand reduction (Chapter 4), technological modernisation of the energy system (Chapter 5), transforming industrial production (Chapter 6) and carbon management through net-negative emissions (Chapter 7).

2 Transformation pathways for a climate-neutral energy supply and climate-neutral production

2.1 Energy demand: starting from the end of the conversion chain

Energy demand trends and their key drivers were investigated in a meta-analysis (see Meta-analysis: study overview).

Meta-analysis: study overview

In addition to the working group's own simulations, the scenarios of the following seven German studies of pathways to greenhouse gas neutrality were analysed and compared. In these scenarios, carbon dioxide from burning fossil carbon and hydrocarbons is only available for a limited transition period, if at all.

- Umweltbundesamt (UBA) 2019 "Wege in eine ressourcenschonende Treibhausgasneutralität – RESCUE-Studie", *hereafter: UBA 2019*[4]
- Bundesministerium für Wirtschaft und Energie (BMWi) 2021 "Leitstudie – Langfristszenarien und Strategien für den Ausbau der Erneuerbaren", *hereafter: BMWi LFS3 2021*[5]
- Prognos, Öko-Institut, Wuppertal-Institut 2021 "Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann", summary commissioned by Stiftung Klimaneutralität, Agora Energiewende and Agora Verkehrswende, *hereafter: Agora 2021*[6]
- Deutsche Energie-Agentur GmbH (dena) 2021 "dena-Leitstudie Aufbruch Klimaneutralität – Klimaneutralität 2045 – Transformation der Verbrauchssektoren und des Energiesystems", *hereafter: dena 2021*[7]
- Kopernikus-Projekt Ariadne 2021 "Ariadne-Report – Deutschland auf dem Weg zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich", *hereafter: Ariadne 2021*[8]
- Bundesverband der Deutschen Industrie (BDI) 2021 "KLIMAPFADE 2.0 – Ein Wirtschaftsprogramm für Klima und Zukunft", *hereafter: BDI 2021*[9]
- Forschungszentrum Jülich 2021 "Strategien für eine treibhausgasneutrale Energieversorgung bis zum Jahr 2045", *hereafter: Jülich 2021*[10]

4 UBA 2019.
5 BMWI 2021-1.
6 Agora 2021.
7 dena 2021-1.
8 Ariadne 2021-1.
9 BDI 2021.
10 FZJ 2021.

In all of the scenarios analysed, **final energy demand falls** from a baseline figure of 2,317 TWh in 2020 to between 1,863 and 2,245 TWh in 2030 and between 1,056 and 1,791 TWh in 2045/2050.[11] Essentially, a reduction in final energy demand can be achieved through efficiency and sufficiency strategies. These strategies are employed to different extents in the studies analysed.

Figure 2 presents an overview of energy demand reduction strategies across the chain stretching from energy service demand to final energy demand. Sufficiency strategies for reducing final energy consumption can aim to reduce demand for energy services. For instance, they might seek to cut demand for transport by reducing the distance people have to travel to work. Another strategy involves shifting to a qualitatively different technology (i.e. with some differences in terms of the benefits provided[12]) in order to meet demand for a given service. An example of this would be a shift to cycling as an alternative to the private car. Efficiency strategies can also be employed to reduce final energy demand. An example would be the development of more efficient drive systems in the transport sector.

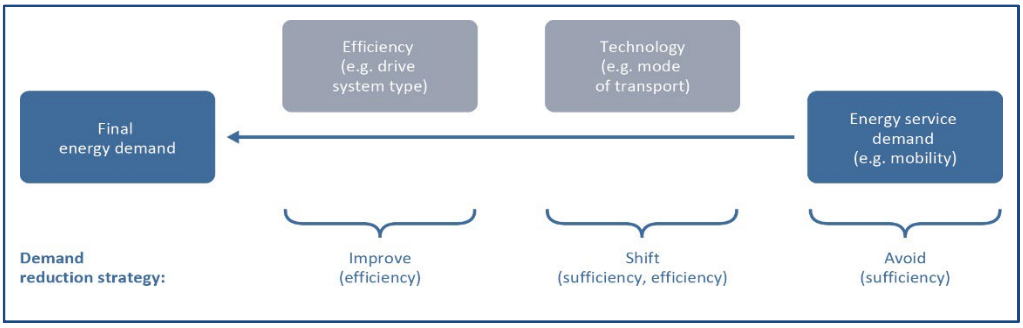

Figure 2: Strategies for reducing final energy consumption along the conversion chain to energy services, as illustrated by the transport sector. Source: working group's own illustration based on Creutzig et al 2018[13]

In the meta-analysis scenarios, this reduction in final energy demand is **mainly achieved through assumed efficiency gains**. Very few studies consider the impacts of policy-driven changes in behaviour that can be grouped under the heading of "sufficiency" strategies – such as reductions in commuter traffic as a result of different residential patterns. The studies calculate the change in final energy demand from sector models, based on projected energy service demand, technologies used and efficiency. Policy measures promoting efficiency and in particular sufficiency strategies are not explicitly modelled or quantified. Despite this, most of the studies propose policy options based on the scenario outcomes. One exception is the transport sector in BMWi LFS3 (but not the building and industrial sectors). In this instance, various policy measures are included as an input in the sector models. While some of these can be categorised as sufficiency measures (five percent congestion charge increase, ten percent reduction in long-distance train journey times), the majority involve efficiency policies such as tax breaks for electric company cars. The outputs of the transport sector model include transport use, modal split and vehicle model.

11 These figures show the full range of values. Figure 4 also shows the quartiles and median of the distribution across the different scenarios.

12 Fischer et al. 2013.

13 Creutzig et al. 2018.

The following sections focus on individual sectors, comparing current final energy demand and how this evolves in the different scenario studies. The policy options proposed in the studies are summarised and categorised on the basis of strategy type and timescale of impact. This makes it clear whether the measures are best suited to meeting short-term, medium-term or long-term climate targets. A detailed discussion of the measures and categorisation of their strategy (avoid, shift, improve efficiency) and impact timescale can be found in the study accompanying this position paper. It should be noted that, in many cases, the measures should not be regarded as alternatives to each other – the energy savings occur when several measures are implemented as a package. Consequently, this position paper does not attempt a qualitative evaluation of the individual measures proposed in the studies.

2.1.1 Transport

The current (2020) final energy consumption of the transport sector is 637 TWh, accounting for 27 percent of total final energy consumption. This figure falls in all the scenario studies, to between 187 and 516 TWh by 2045/50.

In the scenario studies, the **passenger transport** sector's climate targets are met through a **combination of electrification of motorised private transport and modal shift**. Some scenarios also assume **a reduction in domestic air travel**. The UBA 2019 GreenLife and GreenSupreme scenarios are the only ones to also include a reduction in international air travel. These strategies account for different percentages of the emission reductions in the scenarios. This is illustrated by the wide spread of assumptions for the modal share of motorised private transport in 2045, which range from 58 percent to 82 percent. The upper figure of 82 percent is the same as the figure for 2019. Modal shift is generally set exogenously in the studies – the strategies and policy measures for its implementation are not specified. The sole exception is the long-term scenarios (BMWi 2021 LFS3), where policy measures and price trends are inputs for the model and transport demand and modal split are determined endogenously on the basis of a transport model. Nevertheless, possible policy options for promoting modal shift are identified in the meta-analysis studies and widely discussed in the literature. Frequently cited key measures include reorganising traffic space in urban areas to promote ecomobility, i.e. walking, cycling and local public transport (policy area 9.2), and the promotion of public transport as an alternative to private cars (policy area 9.1). Both of these measures can be supported by the removal of financial incentives or even the introduction of financial disincentives to use motorised private transport. The technological transformation of motorised private transport is discussed under policy area 15. Only a few of the scenarios consider the possibility that people might travel less – **most of the studies assume that total travel demand will remain more or less the same in years to come**. However, the UBA 2019 study does consider a reduction in travel demand as a means of reducing transport and energy demand, and proposes possible policy options for enabling this reduction (policy area 9.3).

In the **freight transport** sector, almost all the scenarios project an **increase in freight transport** from the current figure of 679 billion tonne-kilometres to between 853 and 995 billion tonne-kilometres in 2045/2050. This is largely based on the assumption of continued economic growth. The UBA 2019 GreenSupreme and

GreenLife scenarios are the only exceptions. They assume that a reduction in consumption accompanied by economic regionalisation will result in a fall in freight transport to between 584 and 619 billion tonne-kilometres by 2050. However, the main strategy for reducing freight transport emissions in all the studies involves **policy measures to promote an increase in the percentage of rail freight** (policy area 9.4). Indeed, the volume of rail freight almost doubles in some scenarios. Many of the scenarios also include the use of electric trucks, while just a few consider the use of overhead line trucks.

Most of the policy options proposed for passenger and freight transport in the meta-analysis scenario studies only reduce final energy consumption in the medium to long term. In response to the 2022 energy crisis, more recent publications have also increasingly discussed short-term policy options that would take immediate effect (for example motorway speed limits). If these measures are maintained, they can also reduce emissions in the medium to long term. Table 6 provides an overview of the policy options identified in the meta-analysis scenario studies and in more recent publications, as well as showing the timescale for each option to deliver its potential energy savings.

Sector	Short-term impact (1–3 years)	Medium-term impact (2030 climate targets)	Long-term impact (2045 climate targets)
Transport (pass-enger)		Travel shorter distances to access amenities (urban and rural areas)	
	Enable “digital mobility” (home working, digital business trips, e-government)		
	Short-term increase in local public transport capacity	Develop local public transport system offering good geographical and timetable coverage, including sharing and on-demand solutions	
	Incentives to increase local public transport use, e.g. cheap tickets and user-friendly booking		
	Pop-up cycle lanes and footpaths	Reorganise traffic space to promote cycling and walking	
	Temporary long-distance bus services	Expand national and international long-distance train services	
	Financial incentives to switch away from cars, removal of passenger car subsidies		
		Incentives for higher vehicle occupancy, e.g. promotion of ridesharing and smaller vehicle sizes	
		Improve drive system efficiency (conventional and electric)	
		Incentives to switch to EVs, e.g. expand charging infrastructure	
	Speed limits		
Transpor t (freight)		Avoid, e.g. through policy measures to reduce demand and regionalisation	
		Incentives to shift to (hybrid) overhead line trucks, rail and shipping (e.g. infrastructure development, financial incentives)	
		Improve efficiency of aircraft, ships and HGVs	
	Increase percentage of electric trucks, e.g. through emission-based HGV toll		

Table 6: Meta-analysis – options for reducing energy consumption in the transport sector, categorised according to timescale of impact and strategy type: avoid (blue), shift (orange), and improve efficiency (green). Source: working group’s own illustration; policy options taken from scenario studies[14] and studies of short-term policy options published in response to the 2022 energy crisis.[15]

2.1.2 Buildings

In 2020, the final energy consumption of the building sector was approximately 1,023 TWh (accounting for 44 percent of total final energy consumption). In the different system transformation scenarios, this figure falls to between 494 and 748 TWh by 2045/2050. Most of the energy consumed in the building sector is for **heating**. The energy required for heating is mainly determined by the total area heated (primarily living space) and by building envelope and heating system efficiency. UBA 2019 GreenLife and GreenSupreme are the only scenarios to consider a reduction in per capita living space from its 2021 level of 47.7 square metres. These scenarios assume that it will decline to 41.2 square metres per capita by 2050. All the other scenarios assume that it will increase to between 49.4 and 57.4 square metres per capita in 2045, continuing the current trend towards higher per capita living space. Most of the studies focus on **modernisation** measures to improve building envelope efficiency. Virtually all of them assume that heating systems will switch to different power sources and that the existing building stock will be modernised much faster and more extensively – from

14 Ariadne 2021-1, Agora 2021, BDI 2021, dena 2021-1, BMWI 2021-1, UBA 2019.
15 Greenpeace 2022, Öko-Institut 2022, UBA 2022, Agora 2022, DIW 2022, FZJ 2022

a rate of 1.1 percent in 2019 to between 1.6 percent and 3.9 percent in 2045. It is assumed that annual space heating demand will fall from 100 kWh/m² in 2019 to between 61 and 40 kWh/m² in 2045.

As well as reducing energy consumption, a reversal of the trend for rising per capita **living space** would also reduce demand for new housing. In the medium to long term, this could be achieved through more flexible use of existing housing stock, building conversions and a reduction in the number of vacant properties. Additional shorter- to medium-term measures include **lowering the room temperature** in heated buildings and a general improvement in the **efficiency of appliances and heating and air conditioning systems** (policy option 10.1). While reducing heating energy demand is clearly a priority both for the modernisation of existing housing stock and for new builds, heat protection measures can also help to reduce future cooling energy demand (policy option 10.2). This will become increasingly important in a warming climate. Table 7 provides an overview of the policy options identified in the scenario studies and the timescale for each option to achieve its impact. Figure 6 shows the range of figures for the number of additional heat pumps that will need to be installed by 2050 according to the working group's own simulations.

Sector	Short-term impact (1–3 years)	Medium-term impact (2030 climate targets)	Long-term impact (2045 climate targets)
Buildings		Policy measures promoting conversion, sharing, communal use and swapping of existing properties	
	Enable or require lowering of heating temperature in (non-)residential buildings, especially public buildings		
	Information campaigns on efficient ventilation, heating and showering		
		Include climate adaptation measures in urban and building planning	
	Information campaigns on quick insulation measures	Policy measures to drive modernisation of existing building stock	
	Optimise operation of existing heating systems	Improve efficiency of (new) appliances and heating and air conditioning systems	
		Policy measures promoting a switch to resource-efficient building materials (e.g. recycled building materials, renewable raw materials)	

Table 7: Meta-analysis – options for reducing energy consumption in the building sector, categorised according to timescale of impact and strategy type: avoid (blue), shift (orange), and improve efficiency (green). Source: working group's own illustration; policy options taken from scenario studies (Ariadne 2021-1, Agora 2021, BDI 2021, dena 2021-1, BMWI 2021-1, Jülich 2021, UBA 2019) and studies of short-term policy options published in response to the 2022 energy crisis (Greenpeace 2022, Öko-Institut 2022, UBA 2022, Agora 2022, DIW 2022, FZJ 2022).

2.1.3 Industrial and consumer sectors

In 2020, the final energy consumption of the industrial sector was 657 TWh, accounting for 28 percent of total final energy consumption. There are significant differences in the scenario studies regarding the sector's future development, with the assumptions for final energy demand ranging from 554 to 739 TWh in 2030 and from 375 to 963 TWh in 2045/50. All the scenarios assume that industrial final energy demand and emissions will be reduced through major efficiency gains enabled by better technology, electrification and increased material recycling. There are major differences between scenarios in terms of how production volumes change due to the use of alternative materials and reduced consumption. The example of steel production illustrates the extent of these differences. The specific final energy demand per unit of production in the steel industry falls by between 27 and 50 percent by 2045/2050 compared to 2015. Some scenarios assume a significant drop in production volumes ranging from -7 percent (where the focus is on more efficient material use in products) to -11 percent (where the focus is on reduced consumption) and -21 percent (in the scenario combining reduced consumption and material efficiency). Other scenarios assume that production volumes will remain virtually unchanged (-3 to +5 percent), while others still assume that there will be a substantial increase of ten percent by 2045/2050 compared to 2015. Table 8 provides an overview of the efficiency and sufficiency strategies for reducing industrial final energy demand proposed in the scenario studies.

Strategies for reducing production include policy incentives **to use products more efficiently and intensively (e.g. through sharing models) and to increase their lifespan and repairability** (policy area 11.2). For materials that cannot be produced in a climate-friendly manner, another option is to **use policy measures to promote alternative materials. This can be supported by carbon pricing**. Alternative materials must be less energy- and resource-intensive, easier to recycle, or renewable (policy area 11.1). The technological transformation in the industrial sector is discussed in Chapter 6.

<table>
<tr><th>Sector</th><th>Short-term impact
(1–3 years)</th><th>Medium-term impact
(2030 climate targets)</th><th>Long-term impact
(2045 climate targets)</th></tr>
<tr><td rowspan="7">Industrial and consumer</td><td>Incentives to use existing products for longer and repair them</td><td colspan="2">Create conditions for the development and widespread use of durable, repairable, recyclable products</td></tr>
<tr><td>Incentives for shared use and reuse of existing products</td><td colspan="2">Create structures for widespread sharing systems and product reuse</td></tr>
<tr><td></td><td colspan="2">Policy measures promoting shift to products that use fewer materials and resources and less energy-intensive, renewable materials</td></tr>
<tr><td>Policy measures promoting easily implemented process electrification, e.g. low temperature processes, mechanical energy</td><td colspan="2">Create conditions for widespread process electrification</td></tr>
<tr><td>Easily implemented efficiency measures</td><td colspan="2">More efficient technologies and process optimisation</td></tr>
<tr><td></td><td colspan="2">Create conditions to increase recycling rates</td></tr>
</table>

Table 8: Meta-analysis – options for reducing energy consumption in the industrial and consumer sectors, categorised according to timescale of impact and strategy type: avoid (blue), shift (orange), and improve efficiency (green). Source: working group's own illustration; policy options taken from scenario studies (Ariadne 2021-1, Agora 2021, BDI 2021, dena 2021-1, BMWI 2021-1, UBA 2019) and studies of short-term policy options published in response to the 2022 energy crisis (Greenpeace 2022, Öko-Institut 2022, UBA 2022, Agora 2022, DIW 2022, FZJ 2022).

2.2 Scenarios for a climate-neutral energy supply

The working group simulated its own scenarios and compared them against the scenarios in the literature. The panel "Meta-analysis: study overview" lists the studies that were analysed. An overview of the working group's own scenarios and their key outcomes is provided in section 2.3. These scenarios aim to investigate the significance of demand reduction and faster technology rollout for meeting the climate targets, and the conditions that would need to be met in order to achieve a climate-neutral energy supply before 2045. A detailed description of the assumptions and outcomes of the scenarios is provided in the study that accompanies this position paper.[16] Since this position paper focuses on Germany, the only scenarios considered were those where Germany is the main country investigated. Nevertheless, the studies analysed also model the rest of Europe and allow for imports from non-European countries. It should also be noted that some of the studies have different system boundaries. For example, some studies fail to account for ambient heat in the building sector or international aviation and shipping in the transport sector.

Since the original scenarios were simulated in 2021, an additional sensitivity analysis was carried out to investigate the impacts of higher gas prices on the original outcomes. The results of this sensitivity analysis are summarised in the panel “Interpreting the outcomes in the context of sustained high gas prices” on page 41.

All the scenarios indicate that a **significantly faster rollout of various technologies** will be required in the energy sector in order to achieve climate neutrality by 2045. Even if there is a substantial reduction in demand as a result of widespread sufficiency measures and other factors, the relevant technologies will still need to be rolled out much faster than the current rate. To illustrate the necessary technology rollout rate, Figure 3 shows the required installed capacity for solar and wind power in 2030 and 2045/50. Although there are differences between the scenarios, all of them agree that extremely high rollout rates will be necessary for these technologies. However, many of them (with the exception of the Ariadne scenarios) have solar PV rollout rates that are lower than the German government targets for 2030. The government targets for onshore wind fall within the range of values in the scenario studies, while for offshore wind they are slightly above the scenarios’ average. While the government targets thus seem in line with what is required, they are nonetheless ambitious and will need to be enabled by an appropriate legal framework.

All of the studies highlight the importance of making the electricity system more flexible so that it is able to integrate a high percentage of intermittent renewable energy. In addition to strengthening European electricity retailing coordination and increasing storage capacity, it will be necessary to increase load flexibility in all consumption sectors. Sector coupling technologies have significantly greater potential to support flexibility than conventional forms of electricity usage. Smart EV charging and the operation of electrolysers[17] and heat pumps in a way that delivers system benefits can make a major contribution to power grid stability.

16 Ragwitz/Weidlich 2023.

17 In addition to the use of electrolysis to enable more flexible hydrogen production, in many studies the reconversion of hydrogen into electricity also plays an important role in guaranteeing security of supply in the electricity system.

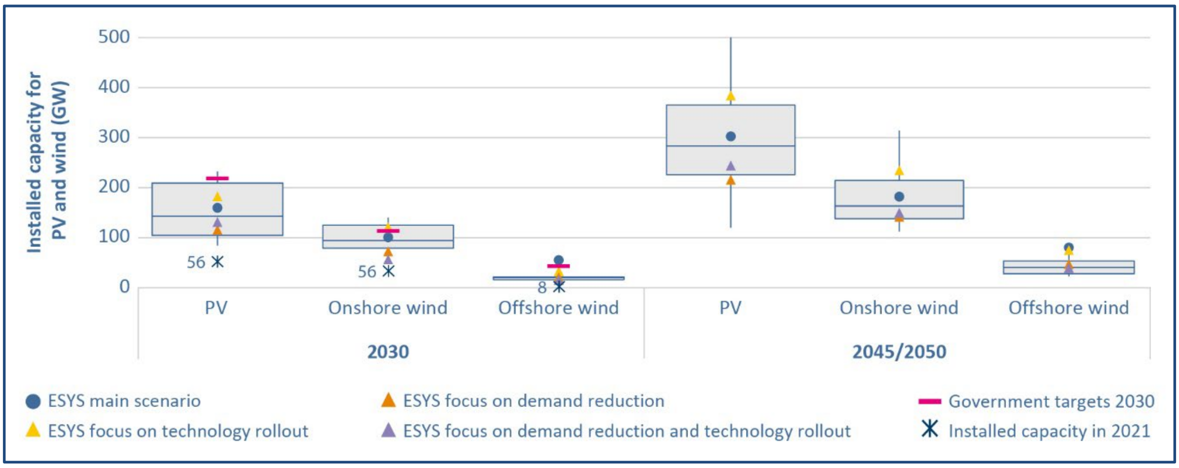

Figure 3: Increase in installed capacity for solar PV, onshore wind and offshore wind in the scenarios analysed. Target year 2050 for UBA 2019 and BMWI 2021-1, target year 2045 for all other scenarios. Ariadne scenarios relate to hybrid model. Source: ESYS meta-analysis.

In addition to the need for rapid technology diffusion, the scenario studies and Figure 4 indicate that it will be necessary to **reduce energy demand in every sector**, albeit to different degrees. The meta-analysis studies assume a reduction in total final energy demand of between 18 and 54 percent by 2045/2050, compared to the current level.[18] Energy efficiency measures play an important role in all the scenarios, while some scenarios (such as *UBA GreenSupreme*) also include extensive sufficiency measures. In the *main scenario ESYS KN2045*, total final energy demand for 2045 is at the higher end of the values in the meta-analysis studies, while it is at the lower end of the range in the *focus on demand reduction* and *focus on demand reduction and technology rollout* scenarios. Figure 4 also suggests that **direct electrification is often the best option** where it is technically and economically feasible. This is because it is often significantly more efficient and generally also less expensive than alternative technologies. All the studies assume an increase in direct electrification. Electricity accounts for 21 to 31 percent of total final energy demand in 2030 and 32 to 63 percent in 2045/2050. Synthetic fuels are necessary in many industrial processes, for instance as a reducing agent in steelmaking, and as fuel for the international shipping and aviation sectors. In these sectors, renewable fuels (hydrogen, synfuels and biofuels) are used instead of fossil fuels. The percentage of renewable fuels rises from 2-14 percent in 2030 to 15-51 percent in 2045/2050. Other energy carriers such as district and ambient heat play a smaller but nonetheless important role in achieving climate neutrality in the final energy sectors.

18 According to AGEB, final energy demand in 2020 was 2,317 TWh.

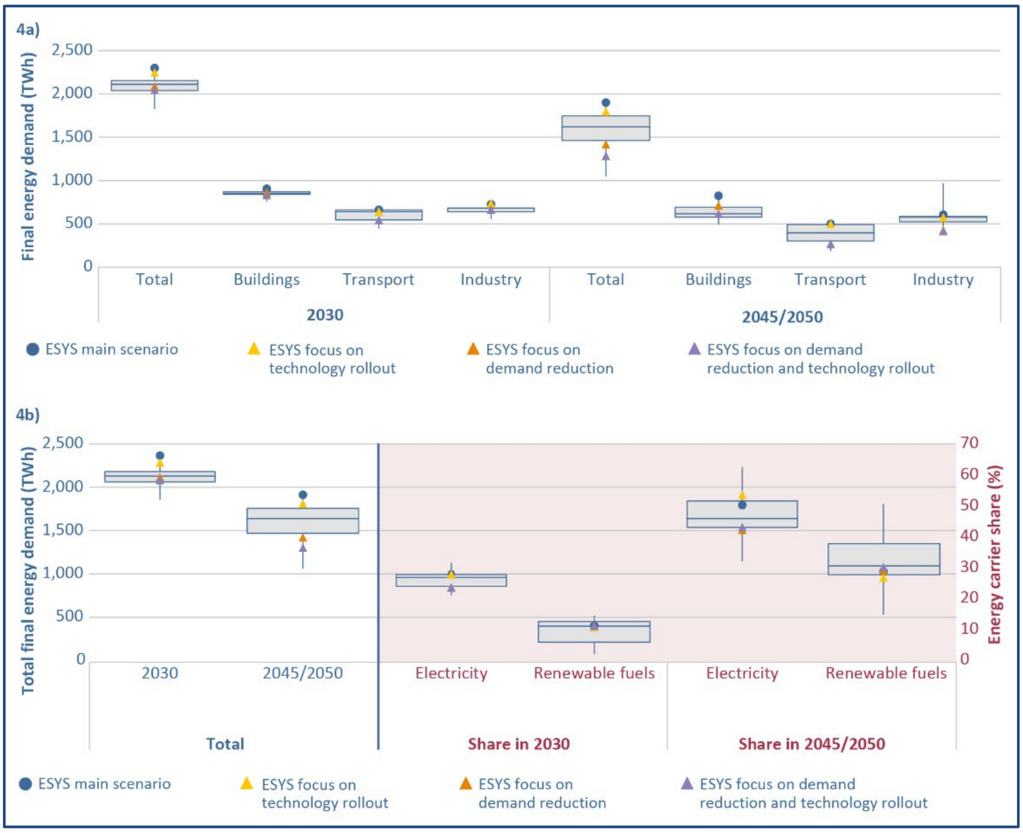

Figure 4: Total final energy demand for 2030 and 2045/2050 (in TWh, left) by sector (top) and by energy carrier share (bottom in percent, centre and right) in the different scenarios. Data for 2050 in *UBA 2019* and *BMWi LFS3 2021*, and for 2045 in all other scenarios. *Ariadne 2021* scenarios relate to hybrid model; Source: ESYS meta-analysis.

The following sections discuss further conclusions for the building, transport and industrial sectors and for the ramp-up of the hydrogen market. The findings for the industrial sector are discussed in greater detail in section 2.4.

2.2.1 Climate neutrality in the building sector

In all the meta-analysis scenarios and in the working group's own scenarios, three trends emerge as key to the achievement of climate neutrality in the building sector. Building **modernisation rates** are much higher than at present, **district heating networks** are expanded and upgraded, and there is a very strong focus on **heat pumps** for individual heating systems.

Figure 5 shows final energy consumption in the building sector (residential, industrial, commerce and services) in the meta-analysis and the working group's own scenarios. Even in 2030, electricity is used to provide a high percentage of heating as well as to power domestic appliances. By 2045/50, electricity finally becomes the main final energy source for heating, owing to its use in conjunction with ambient heat to power heat pumps. It is also the main energy source for district heating networks.[19] Biomass, hydrogen and synfuels are also used for heating, to a varying but limited degree. The two BMWi long-term scenarios "hydrogen" (BMWi LFS3 H2) and "synthetic hydrocarbons" (BMWi LFS3 PtG/PtL) have particularly high percentages of

19 There is still some uncertainty regarding the future role of geothermal energy in this context. Geothermal may prove to be the best option in areas with good potential.

these fuels. However, these scenarios specifically investigate the prioritisation of hydrogen and synfuel use, even though this would result in higher total system costs than the preferred option of direct electricity use investigated in the long-term scenario “electricity” (BMWi LFS3 Strom). The final energy demand in the ESYS scenarios is at the upper end of the range of figures in the meta-analysis. This can be attributed to conservative assumptions for per capita living space trends and modernisation rates that, while still ambitious, are lower than in other studies. Whereas many studies establish fixed pathways for modernisation, in the REMod model it is a variable in the cross-sectoral optimisation. The fact that modernisations are very expensive means that the model tends to select them as the last of the available options, preferring further expansion of renewables or measures in other sectors. However, this optimisation is focused entirely on finding the most cost-effective way of staying within a given emission budget. As with most of the meta-analysis studies (except for UBA 2019), it does not consider other aspects such as land use, raw material consumption and ecosystem impacts. These aspects should be taken into account when making real-world pathway choices between increased building modernisation rates and further expansion of renewables.

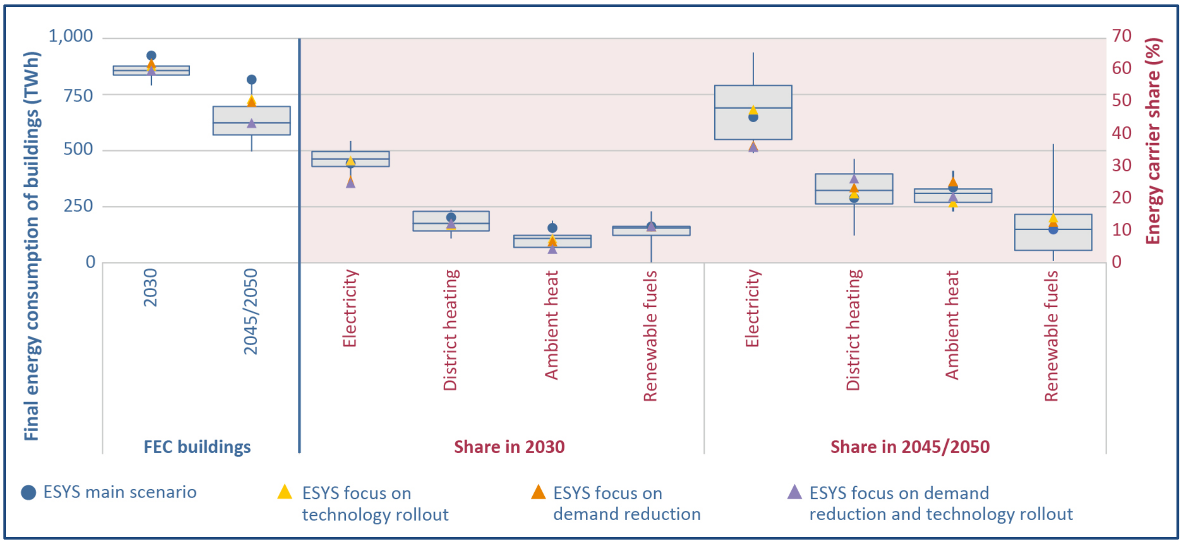

Figure 5: Total energy demand of buildings (residential, industrial, commerce and services) (in TWh, left) and main energy carrier shares (in percent, centre and right) in the scenarios analysed for 2030 and 2045/2050. Data for 2050 in the UBA and BMWi scenarios and for 2045 in all other scenarios. Jülich and dena scenarios do not include ambient heat. Ariadne scenarios relate to hybrid model; ambient heat and solar thermal energy included under “district heating”. Source: ESYS meta-analysis.

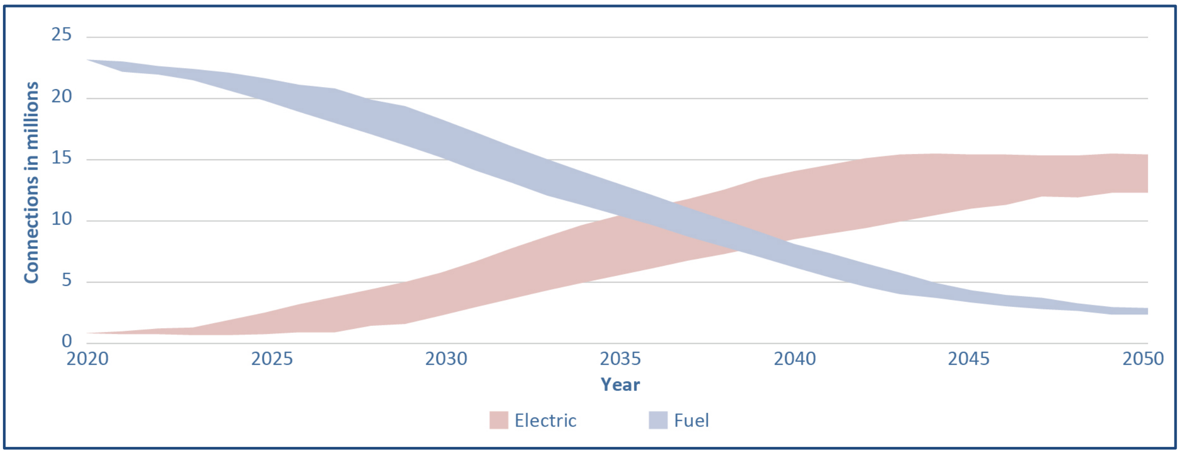

Figure 6: Corridors in the four ESYS scenarios for the number (in millions) of electric and fuel-powered heating connections[20] from 2020 to 2050

2.2.2 Climate neutrality in the transport sector

While various technologies are used to achieve climate neutrality in the transport sector, all the scenario studies conclude that **electric mobility is the most cost-effective and efficient solution for motorised private transport**. As the only means of achieving the necessary energy densities, hydrogen- or biomass-based liquid fuels are used for international aviation and shipping in all the scenarios except *Jülich TS2045*, which does not include international aviation and shipping. However, the scenarios differ with regard to heavy goods transport. While all the scenarios assume a stronger shift to rail freight, the percentage of battery electric, overhead line and hydrogen-powered vehicles used for road transport varies.

Figure 7 shows the breakdown of final energy demand in the transport sector in the different scenarios. The significant differences in the composition of final energy demand can be attributed to the specific focuses of the different scenarios (for example hydrogen, synfuels) and to different assumptions about demand for transport services. As far as the ESYS scenarios are concerned, there are clear differences between those that focus on demand reduction and those that don't. While the main scenario makes the conservative assumption that road traffic will increase, the scenarios that focus on demand reduction show significant changes in mobility behaviour (for example switching to cycling, rail or working from home, etc.). This explains why some of the ESYS scenarios are at the upper end of the range of analysed studies with regard to final energy demand, while others are at the lower end. The ESYS scenarios assume a rapid and widespread rollout of battery electric cars (see Figure 8). The relatively high percentages of fuels in 2045 are partly due to the low efficiency of the internal combustion engine – in the ESYS scenarios, the ICE continues to be used with synfuels in the HGV sector. Pathway choices for HGVs are thus highly sensitive to energy carrier and technology cost assumptions. However, future synfuel import prices and the cost of battery electric, overhead line and fuel cell truck technologies are very difficult to predict with any certainty. This means that it is not currently possible to identify robust pathways for HGV transport from the available studies.

20 District heating connections are not shown in the illustration.

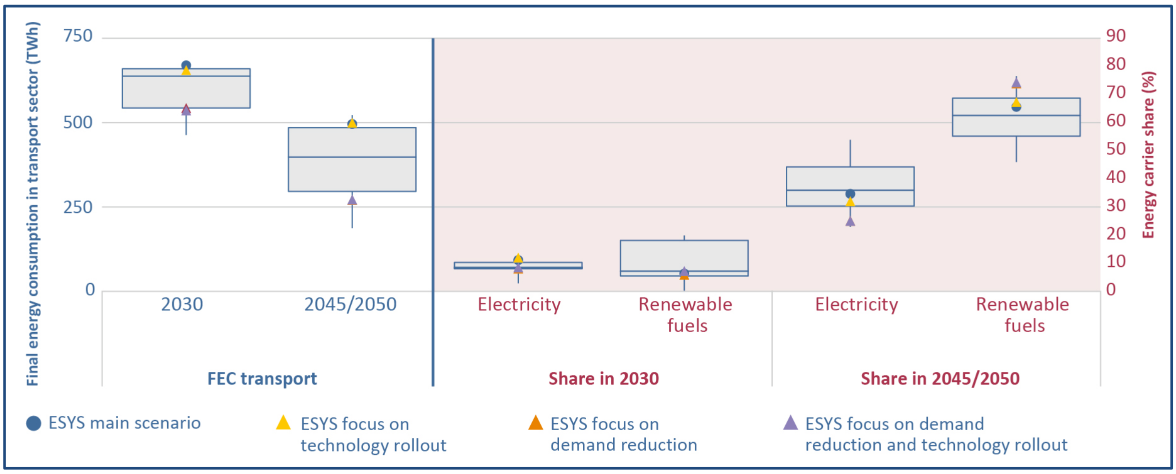

Figure 7: Total energy demand in the transport sector (incl. international aviation and shipping) (in TWh, left) and main energy carrier shares (in percent, centre and right) in the scenarios analysed for 2030 and 2045/2050. Data for 2050 in *UBA 2019* and *BMWi LFS 2021*, and for 2045 in all other scenarios; the scenario *Jülich TS2045* in *Jülich 2021* does not include international aviation and shipping. The scenarios in *Ariadne 2021* relate to the hybrid model. Source: ESYS meta-analysis.

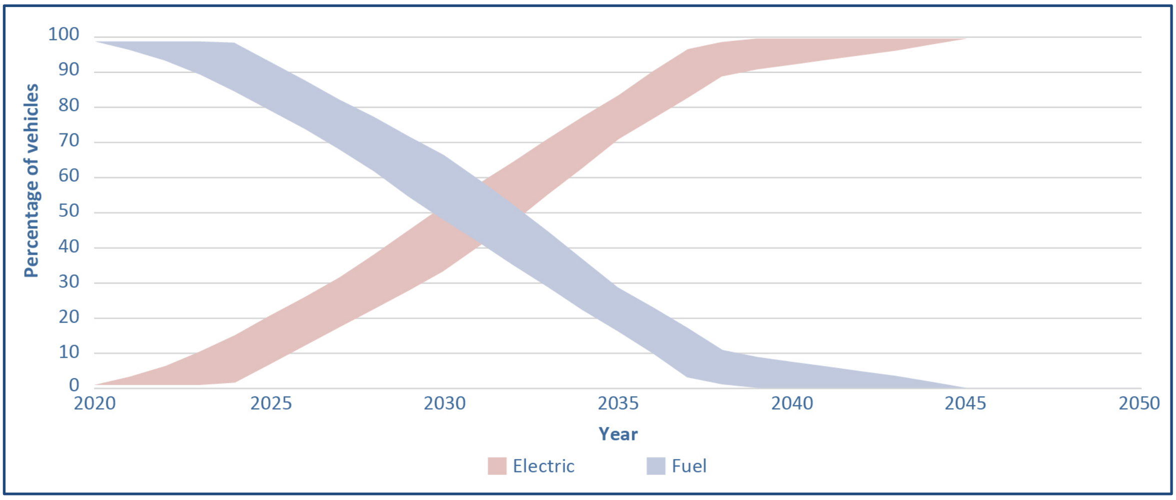

Figure 8: Corridors in the four ESYS scenarios for the percentage of battery electric and fuel-powered cars from 2020 to 2050.

2.2.3 Climate neutrality in industry

Switching to climate-neutral processes and raw materials in the industrial sector is one of the toughest challenges involved in decarbonisation. In addition to increasing direct electrification wherever this is technically and economically feasible, it will also be necessary to use renewable fuels, for example as a reducing agent or to generate high-temperature process heat. In all the scenarios analysed, hydrogen plays a key role both in steel production and as a raw material in the chemical industry.

Figure 5 shows that industrial energy demand declines between 2030 and 2045 in the majority of scenarios.[21] The one exception is the *Jülich TS2045* scenario, which projects an increase in energy demand as a result of higher gross value added and goods production in the industrial sector. Industrial demand in the *ESYS KN2045 main scenario* is at the upper end of the range in both 2030 and 2045/2050. While energy demand in 2030 is also at the upper end of the range in the scenarios that focus on demand reduction and on demand reduction and technology rollout, it then declines sharply and is at the lower end of the range by 2045/2050.

The target of completely phasing out fossil fuels by 2045/50 results in a continuous increase in demand for electricity and renewable fuels. In 2030, 27-44 percent of final energy demand is accounted for by electricity and 1-14 percent by renewable fuels (primarily biofuels), depending on the scenario. By 2045/50, these figures have risen to 35-75 percent electricity and 8-55 percent renewable fuels. Electricity demand is high in all the ESYS scenarios, in part due to the increased use of electrode boilers to generate high-temperature process heat. Section 2.4 discusses industrial processes in more detail.

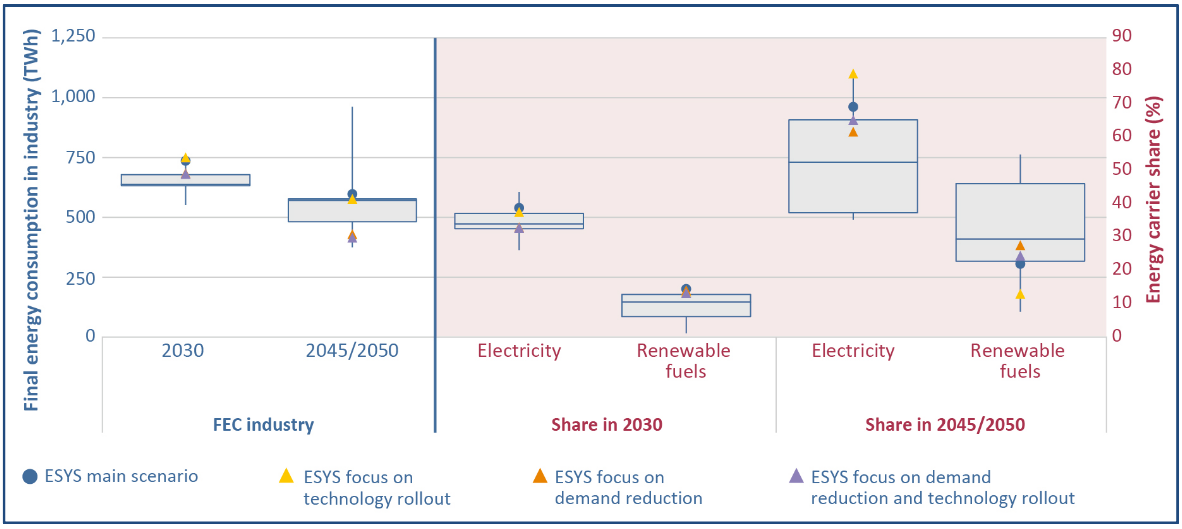

Figure 9: Industrial energy demand (in TWh, left) and main energy carrier shares (in percent, centre and right) in the scenarios analysed for 2030 and 2045/2050. Data for 2050 in *UBA 2019* and *BMWi LFS3 2021*, and for 2045 in all other scenarios; the scenarios in *Ariadne 2021* relate to the hybrid model. Source: ESYS meta-analysis.

2.2.4 Market ramp-up of hydrogen and hydrogen derivatives

All the scenarios indicate that hydrogen and hydrogen-derived synfuels will be key to achieving climate neutrality. The way that hydrogen is produced has implications for the associated requirements, consequences and risks. *Blue hydrogen*[22] is produced by reforming natural gas and capturing the resulting carbon. The captured CO_2 requires long-term storage, methane leakage throughout the natural gas supply chain generates residual emissions, and energy is also required to power the carbon capture process. *Green hydrogen* is produced by electrolysis. This calls for additional renewable electricity generation capacity, resulting in increased material consumption and land

21 A detailed description of the scenarios is provided in Ragwitz/Weidlich 2023.

22 Some studies regard blue hydrogen as a bridge technology that can support the transition to hydrogen-based processes until green hydrogen is available in sufficient quantities. However, this pathway has become increasingly uncertain as a result of the natural gas shortage and the likelihood of gas prices remaining high in the long run.

requirements (either in Germany or abroad if the hydrogen is imported). Consequently, direct electrification should be prioritised wherever possible.

Table 9 shows the sectors where hydrogen and other chemical fuels including biomass could be used in the future, the sectors where direct electrification is feasible and advantageous, and the sectors where there is still some uncertainty. R&D advances in recent years have led to a general increase in the number of sectors where direct electrification is a realistic option.

	Industry	Transport	Buildings[23]
Fuels (incl. biomass)	Feedstocks in steel and chemical industries	Intercontinental aviation and shipping	to some extend buildings that are difficult to modernise
Mix of technologies probably favourable	High-temperature process heat	Long-distance heavy goods transport Aviation and shipping within Europe	District heat generation (large heat pumps: electricity, combined heat and power plants: fuels)
Electricity probably favourable	Medium-temperature process heat	Public road transport Light commercial vehicles Short and medium distance heavy goods transport	Buildings that can be modernised
Electricity definitely favourable	Low-temperature process heat	Private cars, passenger rail	New buildings

Table 9: Future suitability of electricity and fuels for different areas of application, based on analysed scenarios

Only limited quantities of **hydrogen and hydrogen derivatives** are likely to be available, at least in the medium term. Electrolysis capacity will need to increase at an extremely ambitious rate, faster than the growth rates achieved for solar PV in the past. Moreover, the scenarios assume that it will be possible to **import a significant proportion of the hydrogen and synfuels**, with synfuel imports in particular coming from outside Europe. Very ambitious growth pathways for synfuel production are assumed here, too. The scenarios prioritise use of the limited fuel resources in those sectors where there are no realistic alternatives (industry, long-distance transport).

23 As well as electricity and fuels, final energy in the building sector is also obtained from solar thermal and geothermal energy. Geothermal energy has particular potential for meeting future heating requirements.

Interpreting the outcomes in the context of sustained high gas prices

The energy system studies in the meta-analysis and the working group's own simulations using the REMod model were carried out before raw material markets were impacted by the war in Ukraine. To address this, the working group subsequently simulated two additional scenarios in order to investigate the medium- to long-term impacts of the energy crisis on pathways for the transition to climate neutrality. Although the shortages are likely to abate in the medium term, long-term gas prices will probably remain significantly higher than before the current crisis. In most previous energy system studies, natural gas played an important role as a bridge technology in the transition to climate neutrality. Accordingly, the sensitivity analysis aims to investigate potential medium- and long-term changes in the transformation pathways as a result of higher gas prices. The model's original natural gas price assumption of €23/MWh was therefore increased to €70/MWh in one scenario and €150/MWh in another. All other parameters were taken from the main scenario. The model outputs remained relatively stable despite these higher gas prices, with most of the differences occurring in 2030. There were only minor changes to the climate-neutral system in 2045, since this system no longer uses fossil gas.

Significant differences in natural gas consumption only occur when the price of gas rises to €150/MWh. In this scenario, natural gas demand in the model falls by a total of approx. 170 TWh in 2030, a reduction of around 22 percent compared to the main scenario. Some of the natural gas is replaced by oil, especially for high-temperature process heat in industry and some parts of the building heating sector. However, none of this fundamentally changes the need for a very rapid expansion of renewables and an ambitious rollout of sector coupling technologies. Indeed, the rollout of heat pumps in the building sector actually occurs even faster, reaching a million additional connections by 2030.

In the medium to long term, natural gas prices only have a small impact on electricity generation. Based on the scenarios' gas and carbon price assumptions, by 2030 it does not make financial sense to replace flexible gas-fired power plants with coal-fired power plants to cover peak loads due to the latter's long heat-up times and higher CO_2 emissions. However, this finding says nothing about the need to use coal-fired power plants to maintain a secure energy supply between 2022 and 2025. In the scenario where the price of gas is €150/MWh, the electricity sector's natural gas consumption in 2030 falls slightly by 25 TWh due to a somewhat slower rollout of electric mobility. However, electric mobility still plays an important role in this scenario, with twenty million battery electric vehicles on the road by 2030.[24]

The sensitivity analysis thus suggests that the transformation pathways outlined in this paper are robust in the medium- to long-term (2030-2045). The ESYS discussion paper on security of supply[25] takes a closer look at the short-term situation (2022-2026). It shows that the pursuit of an ambitious climate mitigation pathway with rapid expansion of renewables and climate-friendly technologies can help to significantly reduce electricity prices and maintain a secure natural gas supply. Consequently, the policy areas and measures described in this paper remain valid in both the short and the longer term.

24 Fewer than one million battery electric vehicles are currently registered in Germany (https://de.statista.com/statistik/daten/studie/265995/umfrage/anzahl-der-elektroautos-in-deutschland/).

25 acatech/Leopoldina/Akademienunion 2022-1.

2.3 Can a climate-neutral energy supply be achieved before 2045 through faster technology rollout or a reduction in energy demand?

The working group simulated its own scenarios using the REMod energy system model developed by the Fraunhofer Institute for Solar Energy Systems. Among other things, the scenarios were used to investigate the importance to the development of resilient transformation pathways of both a reduction in demand achieved through efficiency and sufficiency measures and of faster technology rollout, especially on the supply side (renewable energy, hydrogen technology). The possibility of achieving climate neutrality before 2045 through even more ambitious demand reduction and faster technology rollout was also investigated.

To do this, the working group defined **one main scenario and three focus scenarios**. The main scenario makes assumptions about the rollout rates of supply-side and efficiency technologies that were regarded as achievable by the working group's experts. The focus scenarios go further, assuming that particular efforts to accelerate the transition will be made in specific areas:

- In the "focus on demand reduction" scenario, demand for energy services is reduced through sufficiency measures such as reducing per capita living space, lowering heating temperatures and reducing transport use. This scenario also assumes a huge increase in energy efficiency across all sectors. The technology rollout assumptions are the same as in the main scenario.

- The "focus on technology rollout" scenario assumes that the relevant technologies will be rolled out faster than in the main scenario. This involves a faster expansion of wind and solar power and hydrogen technologies, a faster rollout of heat pumps and electric vehicles, and a higher capacity for building modernisations.

- The third focus scenario combines the ambitious assumptions of the "focus on demand reduction" and "focus on technology rollout" scenarios.

In view of the fact that some industrial process emissions and agricultural greenhouse gas emissions are harder to avoid, reducing energy-related emissions to zero a few years before the 2045 deadline would help Germany to achieve climate neutrality by this date. Accordingly, all four scenarios were simulated with the goal of achieving a climate-neutral energy system by 2040 as well as by 2045.

The main scenario assumes an emission budget for energy-related emissions of 7.8 Gt CO_2 from 2020. The scenario that aims to achieve climate neutrality by 2040 assumes a budget of 6.2 Gt. The emission budget used in the main scenario (2045) is based on the greenhouse gas reduction pathway set out in the 2021 Federal Climate Change Act. The total emissions estimated on this basis are comparable to the residual national budgets calculated and proposed by the German Advisory Council on the Environment based on per capita distribution of global budgets. The scenarios based on the Federal Climate Change Act would limit global warming to approximately 1.75 degrees Celsius. However, these budgets are significantly higher than the budget needed to limit warming to 1.5 degrees Celsius.[26] Consequently, an additional scenario

26 Sachverständigenrat für Umweltfragen 2022.

investigates the changes in demand and technology rollout rates that would be required to stay within a carbon budget that limits warming to 1.5 degrees Celsius with equal per capita distribution. Figure 10 provides an overview of the simulated scenarios, while the different scenarios' climate targets are summarised in Table 10. The assumptions and outputs of the scenarios are described in detail in the study that accompanies this position paper.[27]

Extreme assumptions were deliberately chosen for both demand reduction and faster technology rollout in order to explore the full **leeway in the transformation pathways**. The aim was to provide answers to "what-if" questions such as "How fast must renewables be expanded even if demand for energy services is dramatically reduced?" and "When might climate neutrality be achieved if there is a dramatic reduction in demand and the relevant technologies are rolled out faster than the experts think realistically possible?".

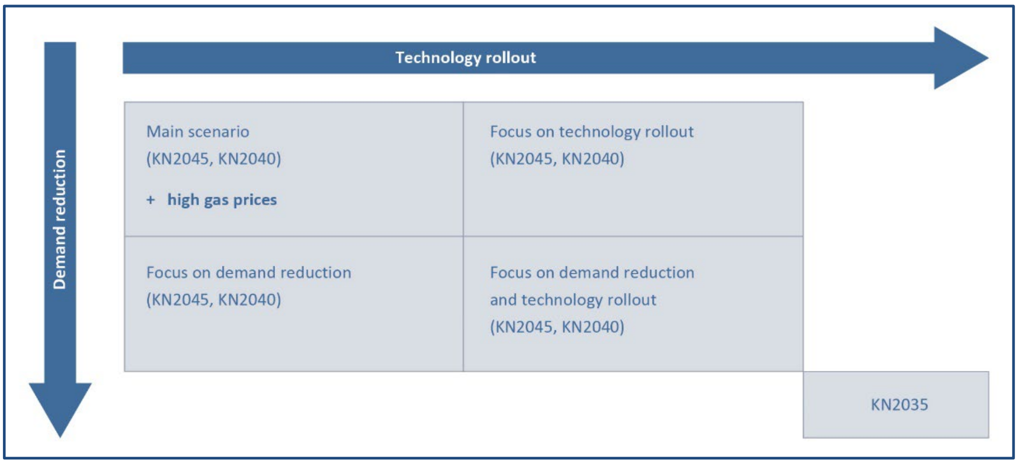

Figure 10: Simulated scenarios. Starting from a main scenario, the working group simulated one pathway that focuses on faster technology rollout and one that focuses on stronger demand reduction. These two pathways were also combined in a third focus scenario (KN = climate neutrality).

Scenario	Energy-related CO_2 emissions
Climate neutrality 2045	Budget of 7.8 Gt_{CO2} with -65 percent in 2030 and -100 percent in 2045
Climate neutrality 2040	Budget of 6.2 Gt_{CO2} with -65 percent in 2030 and -100 percent in 2040
Climate neutrality 2035	Budget of 4 Gt_{CO2}, -100 percent in 2035

Table 10: Climate targets in the scenarios. The carbon budgets refer to the period from 2020.

The scenarios indicate that **it will not be possible to achieve a climate-neutral energy system by 2040 with the assumptions in the main scenario**. Meeting this target will require either a major reduction in demand or an even faster technology rollout than in the main scenario, which already contains ambitious assumptions for the rollout rate and for synfuel imports. **If demand for energy services cannot be reduced through sufficiency measures, it will be particularly vital to increase the rate and extent of building modernisations.** Thus, in the "focus

27 Ragwitz/Weidlich 2023.

on technology rollout KN2040" scenario, almost all buildings are modernised by 2040, most of them to the KfW 40 standard (roughly equivalent to the Passivhaus standard). Unless this happens, it will not be possible to expand renewables fast enough to meet energy demand.[28] In the absence of sufficiency measures, more than 200 GW of solar power, 125 GW of onshore wind power and 30 GW of offshore wind power will be required in 2030, even if these very ambitious building modernisation measures are implemented. In view of the slow rollout rate in recent years and the numerous barriers[29] to rapid expansion, it is far from certain that this faster rollout rate can be achieved.[30] There are similar doubts about the feasibility of the rate and extent of building modernisations required by the "*focus on technology rollout KN2040*" scenario.

A climate-neutral energy system can be achieved by 2045 under the assumptions in the main scenario. However, a reduction in demand for energy services makes the transition much easier in this instance, too, since the required rollout rate for onshore wind and the necessary levels of hydrogen and synfuel imports are all lower. In fact, energy imports are more than 200 TWh lower in the "focus on demand reduction" scenario than in the main scenario. This creates a more resilient transformation pathway, since a temporary failure to achieve a target in one area can be compensated for by exceeding a target in another area.

Last but not least, **an active sufficiency policy could also reduce the costs associated with the transition**. In the "*focus on technology rollout KN2040*" scenario, extremely widespread use is made of the most expensive technologies, especially extensive building modernisations. Importantly, a reduction in demand for energy services also reduces the need for more renewable energy installations and flexibility technologies such as storage systems. This also means that fewer raw materials are needed to build the necessary installations.

Even a combination of the assumptions in the "*focus on technology rollout*" and "*focus on demand reduction*" scenarios is not enough for Germany to contribute its fair share to staying within a carbon budget compatible with the 1.5 degree Celsius target with equal per capita distribution while also achieving climate neutrality by 2035. To do this, energy-related emissions would need to fall to virtually zero by 2035. This can only happen if demand for energy services is drastically reduced within the space of just a few years and if multiple technologies are rolled out concurrently at an even faster rate than in the "*focus on technology rollout KN2040*" scenario. An additional 33 GW of solar and 16 GW of wind power would need to be installed every year between now and 2030. By way of comparison, just 1.4 GW of wind power and 4.8 GW of solar were installed in 2020. All oil boilers for heating buildings would need to be phased out by 2025 and all gas boilers by 2034. This would involve **replacing a large number of heating systems before the end of their life.** According to the experts in the working group, it will be virtually or completely impossible to achieve the rollout and

28 The exogenously set constraints for renewable energy rollout rates are based on historical data, licensing process requirements, land availability and supply chains. While a faster rollout may be possible, it is considered to be highly unrealistic, at least in the short to medium term.

29 For a detailed analysis of the barriers to the expansion of wind and solar power and policy options for overcoming them, see acatech/Leopoldina/Akademienunion 2022-2.

30 The installed wind and solar capacity in 2030 in the KN 2040 scenario is more or less the same as the German government's current targets. However, the rollout rates achieved by 2030 in most of the analysed scenarios from the current literature are significantly lower (see Ragwitz/Weidlich 2023, Chapter 3.2.2).

conversion rates required by this scenario. The same applies to the prospects of effecting the necessary widespread behavioural change within the required timeframe.

Overall, the scenarios indicate that **even the target of achieving a climate-neutral energy system by 2045 will call for an extremely ambitious technology conversion programme**. Without a concurrent reduction in demand for energy services, there is almost no leeway to compensate for missed targets in individual areas – the transformation pathway is extremely narrow. **An active sufficiency policy would strengthen the transformation pathway's resilience and make it possible to achieve a climate-neutral energy system a few years earlier.** In view of the fact that the sum of current national climate targets will not be enough to meet the targets of the Paris Climate Agreement, this policy option should be given urgent consideration.

2.4 Strategies for climate-neutral industry: transforming processes and saving resources

Alongside an absolute reduction in output (see 3.1 – Industry), there are three key strategies for preventing industrial greenhouse gas emissions:

- circularity,
- material efficiency and substitution, and
- switching to climate-neutral processes.

The **energy-intensive steel, chemical and cement industries** are responsible for a large proportion of industrial emissions and are therefore discussed in detail in all the studies. The studies clearly indicate that achieving climate neutrality in industry is a major challenge that cannot be met through individual measures in individual industries. Instead, the **three-pronged approach of climate-neutral processes, circularity and material efficiency** referred to above must be implemented in all three energy-intensive industries. Table 11 provides an overview of how the three strategies can be implemented in the steel, chemical and cement industries. The same principles apply to other energy-intensive industries such as the non-ferrous metal, glass and paper industries, etc.

	Circularity	Material efficiency and substitution	Climate-neutral processes
Steel	• Increase secondary steel production by improving scrap availability • Product design • Separate collection and sorting of scrap steel	• Efficient product design • Reduce waste in component production • Lightweight construction using textile-reinforced or carbon concrete	• Replacement of blast furnaces with direct reduction by hydrogen

Chemi-cal	• Mechanical recycling • Chemical recycling • Increase percentage of secondary production • Design products that are easier to recycle (e.g. single-layer packaging or packaging with easily separable layers)	• Product design, e.g. material-efficient packaging	**Ammonia** • Produce from hydrogen instead of natural gas **High-Value Chemicals (HVCs)** • Replace steam cracking with methanol-to-olefins process • Electrify steam crackers if applicable **Steam generation** • Switch to hydrogen, biomass or direct electrification
Cement	• Separate waste streams • Mandatory selective building demolition • Building and product design that facilitates recycling • Use crushed concrete sand as alternative additive and potentially reuse as binder	• Reduce amount of clinker in cement through use of alternative additives • Reduce amount of cement in concrete without compromising its strength • Use carbon concrete and structural geometry to enable efficient concrete use • Innovative concretes with cement alternatives • Use wood and other organic materials instead of concrete	• Switch to biomass or hydrogen as a fuel • Capture and geological storage (CCS) of process emissions (and fuel emissions e.g. from waste incineration)

Table 11: Implementation of three-pronged approach comprising circularity, material efficiency/substitution and climate-neutral processes as illustrated by the steel, chemical and cement industries.

2.4.1 Circularity

The literature is very clear on the subject of circularity, especially in the steel industry. It is considered absolutely essential to increase the percentage of recycled steel in the steel industry by as much as possible. Recycling steel is much more energy-efficient than primary production. Moreover, secondary steel production employs an established and proven electric technology, namely electric arc furnaces. **Accordingly, optimised collection of secondary materials is a key area for policy action** (policy area 17.2). Increasing the percentage of secondary production also constitutes a robust pathway in the non-ferrous metal industry (metals like aluminium and copper).

The current situation in the chemical industry is more heterogeneous and it is difficult to model the complex multitude of products and processes. Only two studies consider chemical recycling for the production of high-value chemicals (HVCs). Most of the studies only include less energy-intensive mechanical recycling as an assumption for reducing production volumes. Consequently, it is difficult to quantify the impact/contribution of circularity in the chemical industry on the basis of these studies. From a qualitative perspective, however, all the studies agree that changes to the processes used in the chemical industry must be accompanied by measures to promote higher plastic waste recycling rates. **These measures include production standards that make it easier to sort and recycle plastic and metal waste** (policy area 17.1).

2.4.2 Material efficiency and substitution

In the meta-analysis studies, concrete measures to increase material efficiency are particularly focused on the cement industry, where material efficiency is a key means of reducing process emissions. It can be implemented in three stages across the production/value chain: reduction of the amount of clinker in cement by using alternative additives; reduction of the amount of cement in concrete; and the use of smart structural geometries and carbon concrete instead of ferroconcrete to enable more efficient concrete use in the construction sector. Material substitution can also make a contribution in the cement industry – the studies discuss the use of innovative cement types to replace high-emission cement clinker and the replacement of concrete itself, for example by timber structures. **In order to implement these measures, it will be necessary to create transparency and incentives** (policy area 18.1) **and to amend the regulatory framework, for example for building standards** (policy area 18.2). As well as helping to address hard-to-abate process emissions, efficient material use can also help to reduce energy demand across all industries. In the studies, this is modelled by falling production volumes.

2.4.3 Switching to climate-neutral processes

Certain robust pathways for the switch to climate-neutral industrial processes are identified in all of the studies. One example is the transformation of the steel industry. All the studies specify a complete switch from blast furnaces (currently the most widespread production method) to direct reduction by hydrogen by 2045/2050. In the chemical industry, the methanol-to-olefins process is emerging as a partial or complete replacement for current high-value chemical (HVC) production methods. The reinvestment cycles will be key in both cases. **All the studies agree that this transformation must begin right away and that reinvestment in technologies such as conventional blast furnaces must be avoided** (policy area 16.3).

Both of these examples clearly illustrate the importance of hydrogen and synfuels such as methanol in industry. **Their use as a raw material is a no-regret option** (policy areas 16.1 and 16.2). However, some of the studies also attribute a major role to hydrogen and synfuels in the generation of high-temperature process heat, although demand for their use as an energy source is closely linked to the extent of biomass use. Some studies favour the use of biomass instead of hydrogen to generate high-temperature process heat – often in conjunction with bioenergy with carbon capture and storage (BECCS) to produce negative s. Some studies (*BMWI 2021*, *Ariadne 2021*) also assume that biomass will make a significant contribution to the transport sector in the form of biofuels. There is thus no clear consensus in the current literature about where the limited biomass resources should be deployed.

The use and scale of direct electric generation for high-temperature process heat, for example using electric rotary kilns in the cement industry, is strongly dependent on the assumptions regarding the relevant technologies' availability and economic viability. While these assumptions vary significantly between studies, different assumptions are also made within individual studies, depending on the focus of the different scenarios. **Further research into the availability and economic parameters of different technologies is required in order to clarify the situation** (policy area 16.4).

The studies clearly show that direct electrification in the form of heat pumps will play a key role in the generation of low- and medium-temperature process heat. **Consequently, access to affordable renewable electricity for industry is a top priority** (policy areas 16.3 and 3.2). District heating and waste-based fuels will also play an important role in the generation of industrial process heat.

In addition to changing specific processes in individual industries, the studies also stress the need to optimise the energy efficiency of technologies used across all industries (pumps, lighting, etc.). As in the other sectors, efficiency is improved by making greater use of direct electric technologies. These measures lead to a reduction in the industrial sector's final energy demand in all the studies except *Jülich 2021*.

2.5 Carbon dioxide removal: long-term sequestration of hard-to-abate greenhouse gases

The climate scenarios for Germany analysed by the working group indicate that **it will not be possible to achieve climate neutrality by mid-century without removing and storing carbon from the atmosphere**. Since some non-CO_2 emissions from agriculture and industrial process emissions are very difficult or impossible to avoid, the use of carbon dioxide removal will be essential. Moreover, according to the IPCC global scenarios, rather than simply counterbalancing hard-to-abate emissions, in the long run it will be necessary to achieve net-negative[31] CO_2 emissions if longer-term warming is to be limited to a maximum of 1.5 degrees Celsius despite this limit being temporarily exceeded in the short term. The main reason for this is that the remaining global carbon budget for limiting warming to 1.5 degrees Celsius is now so small that greenhouse gas emissions can no longer be reduced fast enough, even in the most ambitious climate action scenarios. Consequently, it will be necessary to remove the excess CO_2 emissions from the atmosphere.[32]

Carbon dioxide can be removed using various methods that work in different ways. The study accompanying this position paper[33] discusses six **carbon dioxide removal** methods:[34]

- Afforestation
- Soil carbon sequestration
- Biochar use
- Bioenergy with Carbon Capture and Storage (BECCS)
- Direct Air Carbon Capture and Storage (DACCS)
- Enhanced weathering

One way in which these methods differ is their storage medium. Afforestation, soil carbon sequestration, biochar use and enhanced weathering store carbon in the form of stable carbon compounds in vegetation or the soil. DACCS and BECCS, on the other hand, store it as CO_2 by injecting it underground.[35]

Other differences include the (projected) cost, the potential quantities of carbon that can be stored, the length of time that the carbon remains locked away, possible environmental impacts, technology readiness level and public acceptance. Since most of these methods are still in the early stages of development, it is only possible to

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31 Net-negative means that, overall, the amount of CO_2 removed from the atmosphere is greater than the amount emitted. See also Erlach et al. 2022.

32 IPCC 2022.

33 For details of these methods, see Ragwitz/Weidlich 2023.

34 In addition to these six methods, there are a number of other approaches such as ocean fertilisation and ocean alkalinity enhancement. However, these methods are highly controversial due to their environmental impacts and are therefore not discussed further in this paper.

35 For a more detailed description of the carbon dioxide removal methods, see also Erlach et al. 2022.

provide estimates for many of the above parameters. Nonetheless, certain risks and competing uses are already becoming apparent and are outlined below.

Woodland already absorbs large amounts of CO_2 from the atmosphere and will continue to make a significant contribution to future carbon dioxide removal in many of the scenarios. However, this method cannot guarantee that the carbon will be stored permanently. Human activities such as logging and other hazards such as forest fires and pests – which are exacerbated by anthropogenic climate change – mean that this form of storage is highly reversible, i.e. the stored carbon can be released back into the atmosphere. **This makes it particularly important to define clear accounting rules for calculating the carbon removal performance of different carbon dioxide removal methods** (policy area 20.2).

As well as the economic and ecological aspects, evaluations of the different carbon dioxide removal methods should also consider how they interact with the energy system and with farming and forestry. Most of the carbon dioxide removal methods described above require **large areas of land**. This could result in competition for land between the different methods. Afforestation projects could conceivably end up competing with biomass cultivation for BECCS, for example. There is also competition for biomass within the wider energy system, since it has other potential energy uses apart from BECCS, especially for biofuels in the transport sector. Land use competition could also arise between carbon dioxide removal and food production, animal feed production and the cultivation of renewable resources for material use. Last but not least, increased land use pressures could cause conflicts with ecosystem and biodiversity protection.

The low CO_2 concentration in the atmosphere means that direct air capture uses a lot of energy. This could result in higher demand for fossil fuels during the transition to a fully renewable energy supply.

Competition for land, biomass and energy, the negative environmental impacts outlined above and a possible lack of public acceptance mean that the different carbon dioxide removal methods all have limited potential and are associated with risks that require further research. **Consequently, it will be necessary to carry out a more detailed ecological, economic, technical and social evaluation of the different methods over the next few years** (policy area 20.3). **If they are deemed suitable, it will then be necessary to create a regulatory framework to incentivise and regulate the development and implementation of the different carbon dioxide removal methods** (policy area 20.4).

It is important to stress that the prospect of negative emissions at some point in the future should not diminish efforts to reduce greenhouse gas emissions. **The development and deployment of carbon dioxide removal methods should form part of a whole-system strategy that clearly defines the role of CDR, for instance by setting separate CO2 avoidance and removal targets** (policy area 20.1).

While all the meta-analysis studies conclude from their scenarios that carbon dioxide removal will be necessary, they differ with regard to its extent (which depends on the residual emissions in each scenario) and the methods employed. The studies use very different assumptions for the level of removals by the LULUCF sector. [36] This highlights the difficulty in carrying out accurate accounting for the LULUCF sector due to the reversibility of the removals achieved in this way. Seven of the eight studies use BECCS and DACCS carbon dioxide removal technology, the only exception being the Federal Environment Agency's Rescue study. All of these scenarios make use of BECCS, from as early as 2030 in some cases. DACCS is only employed in three scenarios and is generally rolled out later and more slowly (except in the Forschungszentrum Jülich study).

Most of the scenarios analysed use geological carbon storage (CCS) to sequester fossil CO_2 emissions from the cement and chemical industries. This technology only prevents emissions, it does not achieve negative emissions like BECCS and DACCS. The scenarios assume that CCS will only be used for otherwise unavoidable process emissions and explicitly exclude its use to deal with emissions from fossil power plants. It is vital to stress this in the public debate, since some previous studies have viewed CCS as a means of achieving net zero without phasing out fossil power generation. The most recent studies, on the other hand, all conclude that it will be necessary to transition to one hundred percent renewable electricity in the long run. Nevertheless, even the **exclusive use of CCS for process emissions will require a broad public debate about the benefits, challenges and risks associated with this option** (policy area 21.1).

Due to differences in the suitability of local conditions for carbon capture and storage, the European and international communities must start planning the rollout of CCS technology as soon as possible, **especially the necessary CO_2 transport and storage infrastructure** (policy area 21.2).

Carbon is used as a raw material for numerous products and will continue to be needed in the long term for products such as plastics, medicines and fertiliser. In order to enable a greenhouse gas neutral energy supply and industrial sector, it will be necessary to create sustainable closed carbon cycles. Possible sources of sustainable carbon include biomass and CO_2 that has been captured from the atmosphere (DACCU, Direct Air Carbon Capture and Utilisation) or from biomass (BECCU, Bioenergy with Carbon Capture and Utilisation). In contrast, if the CO_2 used is derived from fossil fuels or chemical processes, the entire chain is not carbon-neutral, since the CO_2 is released into the atmosphere at the end of the product's life. Nevertheless, CCU with CO_2 from fossil sources can still be employed as a medium-term bridge technology to tackle climate change if it is used instead of processes with higher CO_2 emissions. That said, it will eventually be necessary to replace these fossil CO_2 sources with CO_2 from biomass or the atmosphere if a climate-neutral overall system is to be achieved. **Consequently, the individual CCU processes should be assessed in detail and integrated into an appropriate regulatory and economic framework based on their respective climate impacts** (policy area 22.1).

36 Land Use, Land-Use Change and Forestry.

3 Overarching policy options

This chapter outlines the overarching policy areas that cannot be assigned to any of the specific topics covered in the subsequent chapters (energy demand, energy system transformation pathways, climate-neutral industry and negative emissions) and must be addressed from a whole-system perspective.

Comprehensive, evidence-based assessments of effectiveness, cost and side effects are not yet available for some of the measures and instruments outlined below. Where possible, these knowledge gaps should be plugged through further research in order to enable an evidence-based impact assessment before measures are implemented and prevent potentially valuable measures from being ruled out because there are no studies of their effectiveness. This also applies to the policy areas discussed in Chapters 4 to 7.

Policy area 1: Define wider targets and pursue a wider range of solutions for a sustainable energy transition

PA 1.1 Sufficiency, efficiency and consistency: use all available strategies for the energy transition

Sufficiency, efficiency and consistency are generally regarded as the three key strategies for achieving sustainability. “Sufficiency” is a demand-side strategy that involves reducing energy service consumption. “(Energy) efficiency” is a predominantly technology-based strategy focused on using technology to increase efficiency so that a given energy service can be provided with less energy. Efficiency uses technological means to deliver a *relative* reduction in energy consumption for a given energy service. Sufficiency, on the other hand, seeks to achieve an *absolute* reduction in the use of energy services through social innovations, behavioural change, etc. “Consistency” is a strategy focused on the use of renewable resources instead of fossil resources and on closed-loop material cycles. All three strategies are key enablers of climate neutrality.

It will be necessary to use all three strategies concurrently if the ambitious overall goal of climate neutrality is to be achieved. Focusing primarily on technological solutions, for example, would seriously jeopardise the chances of meeting this goal. Employing all three strategies can create synergies and also help to achieve wider sustainability goals, since reducing consumption (through behavioural change) also reduces the amount of resources and land required to transform the system.

PA 1.2 Keep the global dimension in mind

While Germany's efforts to achieve climate neutrality and implement the energy transition obviously require local decisions and action, they also have a global dimension. This includes factors such as technology development, competitiveness, the use of global resources and the ongoing safeguarding of global supply chains.[37]

Germany's current emissions accounting only considers sources of emissions within its borders (territorial or source principle, production-based emissions). **Accounting based on the polluter pays or population principle**, on the other hand, includes all the emissions caused by the population in a given area (consumption-based emissions). This provides a picture of the emissions associated with the goods consumed in Germany by including embodied emissions such as the climate impacts of producing imported building materials and consumer goods. The emissions associated with a country's domestic consumption are important for determining whether an energy transition pathway supports efforts to achieve climate neutrality globally rather than just within Germany. In order to enable informed decisions about a country's contribution to meeting global climate targets, the annual emissions balance based on the territorial principle should be supplemented by an emissions balance based on the polluter pays principle that includes embodied emissions. Sweden is planning to implement this approach, with a proposal currently being debated in the Swedish parliament.

PA 1.3 Consider wider environmental impacts

Our planet has limited resources and land. In addition to the climate crisis, life on earth could also be threatened if **other planetary boundaries** are transgressed. Most scenario studies outlining pathways for the transition to climate neutrality in Germany only focus on the most cost-effective means of reducing Germany's reported national greenhouse gas emissions. However, energy systems also have major impacts on other ecological, social and economic dimensions (both at home and abroad, as discussed in the previous section). One particularly critical example is biodiversity loss, which is strongly impacted by resource and land use. When evaluating transformation pathways, the ecological dimension should be included as part of a multi-criteria analysis. While this does increase the complexity of the analysis and of identifying "optimal" pathways, an effort should nonetheless be made to model land and resource use as particularly relevant factors in scenario studies and to evaluate these dimensions of energy transition strategies.

As far as the energy and climate pathways are concerned, this means also developing and implementing **climate and sustainability criteria for planned and hoped-for synfuel imports**. Imports can only form part of a German climate action strategy that makes a fair contribution to global climate protection if they are produced using low-emission – and, from 2045, climate-neutral – technologies. Moreover, they must not delay the achievement of climate neutrality in the exporting country. Import standards should include a range of sustainability criteria relating to

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37 There is currently a debate about whether, in order to improve supply chain reliability, the state should subsidise the establishment of a German or European production capability for key components such as PV modules, thereby reducing reliance on individual supplier nations (see ESYS position paper acatech/Leopoldina/Akademienunion 2022-2). Extraction in Europe is also an option for diversifying the supply of critical raw materials (see ESYS position paper acatech/Leopoldina/Akademienunion 2017-2). Another advantage of European production over imports is that it is easier to guarantee high environmental and social standards.

resource and land use and social issues. In this context, it is necessary to identify where synfuel import agreements can already be concluded today.

Policy area 2: Address the energy transition as a social process

PA 2.1 Approach the energy transition's goals and transformation pathways as a social change process

The energy system transformation is a social change process, the scope of which extends beyond the purely technological and economic dimensions. The analysis and evaluation of potential transformation pathways in terms of their climate goals, technological basis, systemic relationships and economic costs is a key part of the policymaking process. However, discussion of the associated social processes – for example public acceptance of the energy transition's technological enablers – should not be left until after the decisions have already been made.[38] Instead, the energy transition should be approached as an integrated process in which the **societal, social, institutional and cultural aspects** are all discussed and addressed right from the outset.

The energy transition should thus be understood as more than a predominantly technological transformation. It should be seen as a means to the end of creating a future with quality of life at its centre. For instance, the transition to a sustainable transport system in general and from the internal combustion engine to electric mobility in particular can also be used as an opportunity to improve quality of life in urban areas by promoting alternatives such as cycling. Modernisation measures and the switch to widespread heat pump use are key to the systemic transformation of the building sector. At the same time, however, it is also necessary to address the wider question of which housing types are suited to the needs of different lifestyles and how to create and promote solutions that also include the use of communal and public spaces. These needs-based, more flexible ways of using living space are often also climate-friendlier. In the consumer sector, demand for durable, repairable products will increase if their resource-efficient and climate-friendly credentials are reflected in their price and if it is easier and cheaper to repair a product than to buy a new one.

While energy services such as heating for our homes and mobility are essential to quality of life, their impacts – for example the consequences of climate change, pollution, or the risk of traffic accidents – can also be detrimental to it. Ideally, the energy system transformation should ensure that the balance between these two aspects is fair to everyone. In other words, as well as being a technological issue, the energy transition is also a social question – how do we wish to live and what type of future do we want? It is important to be aware that even an energy transition that takes the societal dimension into account could result in at least temporary hardships that affect some demographic groups more than others. Higher energy prices have a greater impact on low-income households, while the transformation of individual industries will have different implications for different regions. To avoid putting social cohesion

38 The factors influencing public acceptance of more widespread deployment of wind and solar installations are discussed in detail in the ESYS position paper "Accelerating the Expansion of Wind and Solar Power" (acatech/Leopoldina/Akademienunion 2022-2).

at risk, it will be vital to consider whether a given measure could cause social hardship and how this can be prevented.

PA 2.2 Create the conditions to make energy-saving behaviour the easiest option

The expansion of renewables and the implementation of energy efficiency measures are strongly conditional on the policy framework. The same is true of sufficiency strategies aimed at reducing absolute energy consumption. Consumer choices are driven by the prevailing framework, attitudes and social context – individuals have only limited influence. Thus, although moral suasion and information campaigns can help to promote sustainable, energy-saving practices, they do not usually result in widespread, enduring and far-reaching change. However, a reduction in energy consumption can be driven by **social trends**. Some **pioneering social groups** already practise energy- and resource-saving behaviours and by doing so help to raise awareness of sustainable lifestyles. Regardless of the policy framework, these trends may get stronger due to growing public awareness of the climate crisis, and they can be further reinforced by sufficiency strategies.

The current framework often promotes individual behaviours and consumer choices associated with high energy consumption. Examples include tax relief for people with long commutes to work coupled with high property prices in towns and cities, subsidies for aviation fuel that make flying the cheapest option, and car-focused urban planning that makes it less attractive for people to switch to cycling or public transport. Creating a framework that promotes energy-saving and more generally environmentally-friendly behaviours will require a mix of policy instruments that includes financial and fiscal incentives, information campaigns, education, research and regulation. Achieving an absolute reduction in energy consumption will also call for an **active sufficiency policy from the municipal to the European level**. Its aim should be to enable climate-friendly and resource-efficient behaviours and make them the new normal, i.e. the easiest, most attractive option. For instance, car-free zones in urban areas can improve quality of life by reducing noise and pollution and improving road safety. However, these benefits only prevail if local residents can manage comfortably without owning their own car and their mobility does not suffer as a result. In other words, sufficiency policies require appropriate planning and the provision of decentralised infrastructure such as medical care, shops and educational institutions. They can enhance quality of life, for example thanks to improved road safety as a result of fewer motor vehicles or the health benefits arising from an increase in active mobility. Consequently, strategies for reducing energy consumption should not simply be included as an abstract potential in energy and climate scenarios. Instead, they should be treated as a policy area that is just as important as accomplishing the technological transformation through consistency and efficiency. When incorporating sufficiency policies into strategies for achieving the climate targets, it is important to consider the time required for different measures to take effect. Some sufficiency polices can achieve short-term reductions, for example reducing commutes to work through increased home working. Others, such as the urban and regional planning changes outlined above, take a long time to implement and can thus only help to achieve long-term climate targets (for an overview of the timescales of different measures' impacts, see Tables 6 to 8). It is also important to remember that an active sufficiency policy should not be pursued instead of other system transformation strategies –

achieving the ambitious climate targets will require a massive effort across every dimension of the energy transition.

PA 2.3 Address the distributional effects of the energy transition

In order to ensure that the energy transition is socially inclusive, it will be important to address different dimensions of justice both at the strategic level and in the concrete measures. In particular, it will be necessary to **ensure that the benefits and drawbacks of the energy transition are shared fairly**. As a rule, more affluent social groups contribute disproportionately to total emissions because their per capita energy consumption is much higher (for example because they have larger homes, travel more frequently or buy more energy-intensive, higher-emission products). High carbon prices combined with adequate repayments of carbon pricing revenue can make these high-emission lifestyles more expensive while also tackling energy poverty.

Another way of trying to achieve fairer consumption and cost distribution is through progressive energy tariffs that charge a lower rate for basic energy requirements but a significantly higher rate for additional usage. However, this approach could prove difficult to implement, especially when it comes to determining basic energy requirements in general and taking the different energy needs of different households into account.

Another example of how climate policies can support distributive justice is a mobility policy that ensures everyone has access to transport infrastructure. The frequent current focus on motorised private transport tends to disadvantage social groups that use cars less often. These include children, older people and low-income groups. A mobility policy that focuses on providing basic access to mobility for all social groups rather than on the selective promotion of particular modes of transport can help to tackle climate change and also support distributive justice.

Energy justice should also address **procedural and recognition justice**, both of which can be key to achieving public acceptance of the energy transition. Procedural justice means implementing the energy transition transparently, based on clear rules and in a way that gives all the stakeholders a fair say. This is important when it comes to the siting of infrastructure such as wind turbines. Recognition justice relates to how the transformation is communicated – decisions must be explained, information must be easily accessible, and the needs of all social groups must be recognised, including groups that could be particularly susceptible to the drawbacks of the energy transition.

PA 2.4 Create incentives for the public to actively participate in the energy system transformation

The decentralisation of the energy system gives members of the public the opportunity to actively participate in its transformation. For instance, they can generate electricity by installing solar panels in their homes and help to counteract the intermittent nature of renewable energy by using storage batteries or through flexible electric vehicle charging. In order to leverage this potential, the regulatory and economic framework should create incentives for investments that deliver system benefits and encourage the relevant actors to operate their assets in a way that supports the system as a whole. For example, incentives should be created for people to cover as much suitable roof space as possible with solar panels rather than only installing as many panels as they require for their own energy needs.

The wide range of actors who can generate energy as a result of energy system decentralisation will be key to public acceptance of the energy transition. Prosumers, energy cooperatives and other types of community energy company will all play an important role. However, small, decentralised installations will not be enough to generate and distribute the necessary quantities of energy. It will also be essential to increase the number of large renewable energy installations such as offshore wind and ground-mounted PV farms and to expand the distribution grid.[39]

Policy area 3: Get the price right

In order to achieve climate neutrality, it will be necessary to actively phase fossil energy out of the energy system. Price signals will play an important role, and must provide a strong enough incentive to use low-carbon and zero-carbon energy carriers. This can be achieved by strengthening existing measures and introducing new ones.

PA 3.1 Ensure effective carbon pricing in all sectors

Most of the investments needed for the transition to climate neutrality will need to be financed by private actors and will therefore have to be financially attractive. **An appropriate carbon price will be key to making this possible and should be the main fiscal instrument.**[40] However, it will not be enough to meet the climate targets on its own, since there are some instances where it will not be effective. This could be due to factors such as information deficits and asymmetries, disparities between long-term macroeconomic benefits and the short-term payback expectations of businesses and households, or because it does not provide a sufficient incentive for private actors to invest in infrastructure and R&D.[41] It will therefore need to be **combined with other, sector-specific measures**, first and foremost the removal of the subsidies that are still being granted to fossil fuels.[42] It will also be necessary to implement regulatory and

39 The role of centralised and decentralised assets and actors in the energy system is discussed in detail in acatech/Leopoldina/Akademienunion 2020-2.
40 See also acatech/Leopoldina/Akademienunion 2020-1; acatech/Leopoldina/Akademienunion 2017-1 Chapter 3.
41 acatech/Leopoldina/Akademienunion 2017-1, p. 55 f.
42 Current subsidies in Germany include special treatment for the lignite industry, allocation of free carbon allowances, and energy tax exemptions for diesel and kerosene and for a range of energy uses. The Federal Environment Agency publishes a regular summary of these and other environmentally harmful subsidies in Germany, see UBA 2021.

funding measures, amend planning and licensing procedures and create instruments to ensure that the necessary investments can be financed.

Carbon pricing has already been introduced in many of Germany's energy-consuming sectors. Energy-intensive industries and the energy industry itself are included in the EU Emissions Trading System (EU ETS), while fuels are covered by the national Fuel Emissions Trading Act (German: Brennstoffemissionshandelsgesetz – BEHG). There are also plans to introduce an EU emissions trading system for the heating and transport sectors from 2025, as part of the Fit for 55 package. The carbon price will need to be set at a sufficiently high level for this measure to provide an effective incentive for investment in low-carbon technologies, something that has not always happened in the past.

One of the challenges for carbon pricing is to create a single, harmonised system, since this provides an incentive for the efficient rollout of the most cost-effective option for preventing emissions in each sector. On the other hand, at least in the short to medium term, there is a case for establishing different pricing systems for different sectors. This would ensure that the transition is implemented within the necessary timeframe in every sector despite different price sensitivities and would also take distributional effects into account. For instance, it is essential not to overlook the importance of global competitiveness in the industrial sector.

In the building and transport sectors, the distributional effect of carbon pricing is an important factor that can positively influence acceptance of planned and implemented measures. For instance, well-designed repayments of carbon pricing revenue can enable social equity.

Another problem is that grandfather clauses and the importance of reliable forward planning make it desirable for carbon prices to start off at a moderate level before subsequently rising at a predetermined rate. However, low-carbon technologies are usually much more expensive at the beginning of the transformation and only get cheaper once they become more widely adopted. Additional funding could help to promote learning effects for these technologies. Minimum prices and price corridors can also provide confidence for investors.

PA 3.2 Reform levies, reallocation charges and taxes

In the heating sector, electricity is currently subject to more taxes, levies and reallocation charges than fossil fuels like natural gas and oil. However, rising carbon prices under the Fuel Emissions Trading Act are creating a more level playing field. In the transport sector, diesel and petrol are already more heavily taxed than electricity. Differences in the level of taxation affect the relative prices of the different energy carriers and thus also influence consumer choices. Consequently, it is important to harness this driver in a way that supports the transformation pathway. More specifically:

- The rapid diffusion of direct and indirect electrification technologies, especially heat pumps, electric vehicles and electrolysers, should be promoted by ensuring that taxes, levies and reallocation charges on electricity are kept as low as possible relative to fossil alternatives.

- Rapid growth in renewable energy generation will also require incentives to promote electricity demand flexibility, for example in the electric mobility and heating sectors. Varying the price of electricity depending on when it is consumed could be an effective means of incentivising greater demand flexibility in order to support system stability.

- Given the limited availability of land and resources for generating energy, incentives to minimise energy demand are also particularly important in a climate-neutral energy system.

These requirements can be met by reforming the relevant levies and reallocation charges. In the short term, a further **reduction in the levies, reallocation charges and taxes on electricity** may be necessary in order to make sector coupling technologies more financially attractive. For instance, tax on electricity could be reduced to a minimum level while other energy taxes are increased by a similar amount. In the longer term, taxation could be based on the energy carrier's energy content, rather than just on CO_2 emissions. As CO_2 emissions fall, this would help to limit negative impacts on energy efficiency and also prevent government revenue from dropping too sharply.

PA 3.3 Use non-market measures to accelerate the phase-out of fossil energy

In many cases, consumer choices are not made on purely financial grounds. For instance, the previous experience and recommendations of the available installers can have a major influence on a customer's choice of new heating system. Factors such as perceived range, prestige, (perceived) safety and driving experience are all important when buying a new car. Availability is also a key factor in purchasing decisions. For example, if there is a much larger range of internal combustion engine vehicles or the local installer only supplies gas boilers, customers are far likelier to choose these options. Moreover, failure to accurately estimate future running costs could cause people to continue using oil heaters or even install new ones because they have not reckoned with future rises in the price of heating oil. In some cases, there is also a shortage of energy consultants, while those that are available may not always be adequately trained.

Consequently, in order to prevent new fossil technology installations, it can be helpful to implement other measures in addition to increasing their cost. Examples include **training campaigns** for (energy) consultants, lower fleet-wide emission targets for motor vehicles, **access restrictions** for conventional vehicles or for very large vehicles in certain areas such as town centres, or **phase-out deadlines for certain technologies** such as the internal combustion engine or fossil fuel heating systems.

Policy area 4:
Upgrade the key network infrastructure as soon as possible

As well as renewable electricity generation capacity, the key infrastructure required for the transition to climate neutrality also includes various network infrastructures. Since these have very long lifespans and long planning periods, it is vital for their expansion to be addressed proactively and coordinated at European level.

PA 4.1 Integrated infrastructure planning with a system development plan

Increased sector coupling will call for **closer coordination of the expansion and upgrading of the electricity and hydrogen networks and the conversion of gas networks to hydrogen**. In recognition of this fact, a discussion has already begun about establishing a structured process for drawing up a system development strategy that would inform the formulation of network development plans. There are different opinions about the goal of this system development plan. Initially, it was discussed mainly as a means of improving coordination of the network development plans and the relevant scenario frameworks. However, a system development strategy could also pursue the wider goal of addressing and structuring other energy transition coordination processes.

The rationale for a broader system development strategy is the understanding that, because energy infrastructure is a natural monopoly with a long technical lifespan, reliable forward planning is of particular significance to the public interest. For instance, if electricity grid upgrades carried out today take the potential requirements of much higher heat pump and electric vehicle numbers into account, this will prevent the need for costly digging works in years to come. The current regulatory framework's very strong focus on the prevention of misinvestments leaves little room for manoeuvre. However, given the scale of the transformation, it is vital to take an approach that accounts for future uncertainties. Consequently, a system development strategy should clarify in a policy process which future requirements the relevant infrastructure should be designed to meet. This includes making decisions about when precautions should be taken against certain risks. This would allow infrastructure operators to invest in certain areas specified in the system development strategy even though their investments might not be optimal in every conceivable future scenario. The system development strategy would also send a signal to actors in other areas of the energy transition and would support reliable forward planning.

PA 4.2 Plan decommissioning of gas distribution grid and mitigate social impacts

The development of sector coupling means that a decentralised gas supply will be far less important in a climate-neutral energy system.[43] As a result, a substantial part of the gas distribution grid will no longer be needed. It will be necessary to draw up plans for the gradual decommissioning of these parts of the network, reflecting the progressive conversion of the heating supply in individual residential areas. This will include mitigation of potentially high costs for the last remaining users of the network.

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43 Natural gas will no longer be used in a climate-neutral energy system. The question of whether part of the decentralised natural gas supply should be replaced by a decentralised hydrogen supply is much debated in the meta-analysis studies. In any case, it is clear that the percentage of hydrogen systems will be low compared to direct electric alternatives and heating networks.

PA 4.3 Promote European grid infrastructure integration

Close cooperation on infrastructure will also be required at European level. On the power side, large interconnector capacities will be necessary in order to enable regional balancing of intermittent renewable energy and flexibility exchange. This can enable access to cost-effective opportunities for the expansion of renewables and the provision of system services. Particularly close coordination and cooperation will be required to ensure efficient upgrading of the grid in order to connect to offshore wind installations, especially in the North and Baltic Seas.

European coordination and cooperation is also necessary for other types of infrastructure, especially for hydrogen and CO_2 grids and storage infrastructure and also for infrastructure in the mobility sector. It will be key to ensuring that potential export nations can access demand for hydrogen or prospective CO_2 storage facilities and users, thereby keeping the cost of the European energy transition as low as possible. Ideally, integrated planning of these different infrastructures should also be carried out at European level.

Policy area 5: Establish transparent and consistent guidelines for the deployment of electrification, hydrogen, PtX and biomass

In many cases, climate-neutral energy carriers such as renewable electricity, green hydrogen and its derivatives and biomass can be used as alternatives for the same applications. However, **competition between these energy carriers results in uncertainty for those wishing to invest** in one or other of these technologies, thereby creating a barrier to their market rollout. Although there is still some uncertainty in certain areas of application, a consensus already exists with regard to the no-regret options for hydrogen use and market-ready technologies for direct electrification in the relevant application sectors. The next few years will be critical for meeting the 2030 targets and setting the overall course for achieving climate neutrality by 2045. Guidelines for the use of hydrogen and direct electrification in the relevant no-regret applications must be established as soon as possible and the priority uses of limited biomass resources must also be identified.

PA 5.1 Promote market diffusion of direct electric technologies

Since direct electric technologies such as battery electric vehicles and heat pumps have low conversion losses, they should be prioritised wherever they are available and economically viable. The meta-analysis of energy system studies and the working group's own simulations using the REMod model clearly indicate that the rapid market diffusion of these technologies is imperative if the 2030 targets are to be met efficiently. This remains true even if it is assumed that there will be a significant reduction in final energy demand.

In order to promote the market diffusion of direct electric applications, it will firstly be necessary to push ahead with the reform of electricity reallocation charges and levies (see policy area 3.2). Given its role as the most important energy carrier in the future energy system, the aim should be to make electricity as cheap as possible compared to other energy carriers. A variety of sector- and application-specific measures will also be required to support direct electrification (see heating, transport and industry policy areas).

Measures to promote direct electrification should also address opportunities to increase load flexibility and create a framework that incentivises flexible electricity consumption. Substantial flexibility potential can be leveraged in this way, especially in conjunction with thermal energy storage systems (for heating systems and process heat) and electrical energy storage systems (e.g. electric vehicle batteries).

PA 5.2 Analyse and establish priorities for biomass use

Biomass is a renewable resource with a wide range of applications both in the energy sector and as a raw material and building material. However, the cultivation of biomass crops for energy applications requires large areas of land, can damage soil and waterbodies, can harm biodiversity and competes with food crop cultivation.[44] As a result, (almost) all the scenario studies treat biomass as a limited resource and assume that most of its potential is already being exploited today. This points to the need for a comprehensive biomass strategy in order to ensure that only **sustainably produced biomass** is used for energy applications and that biomass is employed in ways that deliver **the greatest possible benefits for the overall system**.

Sustainability criteria for biomass must be established as the basis of any bioenergy strategy, with a focus on harnessing the **untapped potential of residual and waste materials**. It is important to recognise that residual and waste materials often perform less well in energy applications than the oil-bearing, starchy energy crops used today. The production of biofuels from residual and waste materials is particularly reliant on special techniques that are still at the development stage.[45] The cultivation of biomass crops for energy applications is often harmful to the environment and can exacerbate land shortages. Consequently, only very limited use should be made of this option, primarily in order to generate net-negative emissions in conjunction with carbon capture and storage (BECCS). Bioenergy use should always be weighed up against alternative sources of renewable energy that may be ecologically preferable to

44 acatech/Leopoldina/Akademienunion 2019.
45 Ibid.

the cultivation of energy crops. Peatland rewetting[46] combined with solar PV is one example. These opportunities and alternative land uses must be carefully weighed up in order to prioritise the solution with the greatest overall environmental benefits.

The existing scenario studies do not provide a clear picture of which biomass applications deliver the greatest system benefits. Some studies favour the use of biomass in **industry** on the grounds that industrial systems can, in time, be converted to BECCS. Other studies favour the use of biofuels for **shipping, aviation** and to some extent also heavy goods vehicles. One point on which a consensus does exist is that the current situation where the Renewable Energy Sources Act promotes biomass use in biogas plants for non-demand-based electricity generation makes little sense in the context of the overall system. The use of biomass to provide low-temperature heat, which is particularly prevalent in the building sector, should also be the exception in years to come. However, biomass can have highly beneficial effects as a **raw material** in the building sector, for instance as a replacement for high-emission building materials. Accordingly, the biomass strategy should take an integrated approach to the use of biomass as a raw material and biomass **cascading** (i.e. its use first as a raw material and then for energy applications).

The conclusion from the scenario studies is that, over the coming years, biomass use should shift away from the energy sector, primarily towards its use as a raw material (depending on the type of biomass) and secondly towards applications in industry and some parts of the transport sector. This will not necessarily happen if it is simply left up to market forces. Consequently, a bioenergy strategy should be drawn up based on a comprehensive analysis of how biomass can be used to deliver the greatest system benefits. The analysis should also address the question of competition with hydrogen and synfuels. The strategy should set clear **priorities**, for example by establishing minimum and maximum quotas for different applications. The analysis should also be informed by the strategy for achieving negative emissions (see Chapter 7), since this will have a major influence on whether and how widely BECCS needs to be used. Further research into the production of biofuels from residual and waste materials could also be addressed in the bioenergy strategy through targeted research funding.

46 Peatland rewetting can halt the decomposition of peat bodies caused by drainage and the high CO_2 emissions associated with this phenomenon. However, because peat grows slowly, it will only lock away insignificant amounts of additional CO_2 over the timescale relevant to the climate targets. Consequently, peatland rewetting is not expected to make a meaningful contribution to negative emissions. See also Erlach et al. 2022.

Policy area 6: Strengthen energy transition skills among industry professionals and provide free information

People need reliable information in order to make climate-friendly decisions about matters such as replacing a heating system, modernising a building or choosing a mode of transport. Installers and other industry professionals such as energy consultants can have a major influence, especially on decisions about building modernisations and heating systems. If the energy transition is to succeed, the people making the decisions must have the right information and be aware of all the options before making their investment. A larger pool of well-trained industry professionals and general information campaigns can help to make sure this happens.

PA 6.1 Provide better and more attractive training for industry professionals

Industry professionals have a major influence on private purchasing decisions. However, many heating system installers, for example, favour the technologies they are familiar with regardless of the building in question and advise their customers accordingly. Even energy consultants often use outdated information. Although training and professional development for energy consultants and installers does already include some content on new heating technologies, more needs to be done in this area. For instance, training and professional development courses could use the latest scenario study findings to more effectively communicate the requirements that future building envelopes and heating systems will need to meet to achieve the climate targets. In this context, they should emphasize and discuss options that go beyond the current statutory requirements.

In the building sector, people often prefer new buildings built with high-emission, energy-intensive materials. In order to address both land shortages and the high-emission, energy-intensive nature of many building materials, greater emphasis should be placed on **increasing the density and more flexible use of existing building stock** and on the use of **alternative, recycled and renewable building materials**. Inadequate training and professional development provision means that there are significant knowledge gaps in these areas, both among planning professionals (architects, licensing authorities) and installers (tradespeople, technicians).

There is also an acute shortage of skilled professionals for the mobility transition. After decades of focusing on car-centric mobility, urban and transport planners must now prioritise **the compact city** and **active mobility**. Training and professional development is necessary in this area to ensure that the public authorities have the basic knowledge needed to implement the new requirements for solutions such as bicycle-friendly mobility. This will mean moving away from the goal of optimising traffic flow and focusing instead on making towns and cities more pleasant places to be and on promoting active mobility. In addition to improving its technical knowledge about electric mobility, the private sector will also need to get better at providing **mobility advice** that includes all the available options, from motorised private transport to public transport, sharing models and cycling.[47]

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47 The topic of employment and training in the mobility sector has been addressed in detail by the National Platform Future of Mobility (NPM), see NPM 2021-1 and NPM 2020-2.

In order to recruit enough skilled workers, it will also be necessary to make **careers in the trades and technical professions** more attractive in general. This has implications for apprenticeships and for technical study courses, which have suffered a particularly sharp drop in student numbers according to the German industry association for mechanical and plant engineering VDMA. A major training campaign is needed to address the significant emerging shortage of skilled workers able to install the different technologies required by the energy transition.

PA 6.2 Information campaigns for interested members of the public

Consumers need easily accessible information to help them make climate-friendlier choices. The general principles of the necessary transformation should be communicated through a variety of different channels. Accessible, detailed information is also necessary, for example about the levelised cost of heat of different heating technologies and about the available energy retrofit options. Advice and information about sufficiency measures should also be provided. This should include easily accessible information about mobility services and housing quality advisory services that facilitate house swapping or provide advice about converting, adding storeys to or sharing properties and about temporary uses.

PA 6.3 Promote open science, interdisciplinarity and transdisciplinarity in energy transition research

The technical and economic modelling of potential energy transition pathways makes a valuable contribution to energy policy and the public debate. In order to ensure that the proposed solutions cover the full range of possible options, it is important for a wide range of actors from different academic disciplines to participate in the development of scenarios and models and in the interpretation of their findings.

Open science involves making all results, data, models and underlying research accessible to everyone, and is key to promoting cooperation and participation among researchers in the development and analysis of transformation pathways. Including open science principles in the eligibility criteria for research grants promotes more efficient use of research funding, since it prevents work from being duplicated and supports open research collaboration.

In addition, research questions and findings should be made as widely accessible as possible to the public through a variety of science communication formats catering to the varying levels of prior knowledge and information requirements of different social groups.

Policy area 7: Continuously monitor policy effectiveness

The large number of policy areas and necessary measures indicate the scale of the challenge facing government and the public administration if climate neutrality is to be achieved. To meet this challenge successfully and within the required timeframe, the relevant tasks will need to be shared among multiple actors and institutions. It is clear from the scenario studies that the **transformation must be driven forward rapidly and concurrently in every sector**. This means that every sector will need instruments for managing and monitoring the necessary measures. Early indicators can provide valuable support in this regard.

PA 7.1 Use early indicators to track progress on transition targets and enshrine them in climate law

Early indicators are a new governance instrument for the transition to climate neutrality. They can be developed and attached to targets and pathways for key actions that already enjoy widespread public and political acceptance. In this context, early indicators are defined as indicators that signal important steps towards climate neutrality before emissions have actually been reduced. These indicators are not conceived as short-term targets to complement longer-term targets – they are an instrument for monitoring whether long-term targets are on course to be achieved.

Early indicators have previously played an important role in the coordination of policy measures in Germany and at European level. Similar indicators could be developed and used more widely to track progress on the key transition targets. Examples of possible early indicators include the annual number of building energy retrofits, the proportion of raw materials produced climate-neutrally and recycled into high-quality products, public transport's share of total transport use or electric vehicles' share of the private car market.

It is important to strike the right balance when **selecting indicators** and to ensure that the number of early indicators is not too high. On the one hand, the chosen indicators should be significant and widely recognised in order to be relevant to policymakers, so that the responsible ministries make achieving the targets a top priority. On the other hand, the most important policy areas for the transition should all be captured and tracked by the early indicators to prevent the emergence of disincentives. Early indicators could contribute in the following ways:

- A targeted discussion of the transition's overall goals should be encouraged when choosing the indicators and formulating the targets. This can help to legitimise and implement individual measures that may often be controversial.

- Early indicators provide individual departments with transparency on progress towards meeting the targets and can help to manage the relevant measures.

- Tracking progress transparently and discussing potential reasons for any shortfalls provides a fair basis for "evaluating" the work of the relevant ministries.

In general terms, this approach can help to ensure that the main policy options for achieving climate neutrality are implemented in parallel, without overburdening individual institutions. It also provides a transparent basis for refining individual indicators and targets to reflect social priorities, technological advances and geopolitical developments. This could be done by a climate task force or similar body. The German Council of Experts on Climate Change also describes early "ex ante" indicators as a valuable instrument for monitoring the energy transition and cites similar concepts that have already been implemented in France, Sweden, the Netherlands and the United Kingdom.[48]

PA 7.2 Refine existing indicators, introduce new early indicators

Indicator monitoring in Germany is already carried out under the German Sustainable Development Strategy (DNS)[49] and at EU level (EU SDG indicator set[50]). Since both these sets of indicators are intended to measure progress towards the Sustainable Development Goals, they have only limited value as early indicators of progress in the policy areas proposed in this position paper. Progress in energy policy is also measured retrospectively by a suite of indicators in the annual monitoring reports of the Federal Ministry for Economic Affairs and Climate Action (BMWK) (the 2021 report, for instance, evaluated progress in 2018-19). Using the example of the **industrial sector**, Table 11 lists the existing indicators from the DNS, the EU SDG indicator set and the BMWK (formerly BMWi) monitoring report[51] that can also be used for the policy areas discussed above. It also contains examples of additional early indicators that could be used to replace or supplement these indicators. The availability of sufficient data to calculate the indicators is an important criterion for their specific design. As well as indicators based on the status quo, indicators of the rate of change can also be helpful.

48 ERK 2022, p. 207 ff.
49 Statistisches Bundesamt 2021.
50 Eurostat 2022.
51 BMWI 2021-2.

Policy area	Existing indicators (DNS or EU)	Proposed early indicators
Policy measures to promote climate-neutral processes and products	Market share of products with government eco-label (%) (Statistisches Bundesamt 2021) Electricity's share of final energy consumption in industry (%) (BMWi 2021-1)	Climate-neutral industrial processes as a percentage of total production for selected energy-intensive materials (Velten 2021).
Strengthen carbon pricing effectiveness and investment security		Cost ratio of low-carbon processes to conventional processes (Velten 2021) Proportion of industrial CO_2 emissions subject to taxation (%), by price interval (Velten 2021)
Creation of a circular economy	Percentage of total material consumed that is recovered and reused in the economy (Eurostat 2022)	Percentage of reused or recycled materials by material group (based on Velten 2021)
Material efficiency and material substitution	Raw materials (minerals, metal ores, biomass, fossil fuels) used for domestic product and service consumption sourced domestically and abroad (Eurostat 2022)	Non-renewable materials in products in relation to the lifespan of individual product types (OECD 2023)
Develop necessary infrastructure	-	Number of industrial locations with access to hydrogen production and storage (based on Velten 2021) Length/transport capacity of the hydrogen network/import capacity (Velten 2021)

Table 12: Possible early indicators for tracking progress on climate measures in the different industrial sector policy areas.

Existing indicators can also be used as early indicators for the policy areas in the **transport and building sectors** and supplemented by additional early indicators. The BMWK monitoring report[52] already includes indicators of reductions in final energy demand in the transport sector. These include:

- Change in total volume of passenger and freight traffic,
- Public transport's share of passenger traffic,
- Rail freight's share of total freight transport,
- Number of 3-wheel-plus electric vehicles.

52 BMWI 2021-2.

These indicators can be used as early indicators of falling consumption in the mobility sector. They could be supplemented by additional indicators of **infrastructure development in the mobility sector**, for example:

- railway track per capita or annual rail capacity [53],
- per capita cycle path distance[54],
- number of electric vehicle charging stations [55].

For the building sector, the German Sustainable Development Strategy (DNS) uses settlement density and the absolute increase in sealed land as indicators of sustainable land use (under SDG 11), although these indicators combine land used for residential purposes and for transport. Average per capita living space would be a better early indicator of falling consumption in the building sector achieved through flexible use of existing building stock and by limiting the number of new builds.

One potential early indicator of an increase in building modernisations would be the number of modernised buildings.[56] This could be further broken down into extensive, moderate and minor[57] retrofits. Changes in heating technologies could be measured by an indicator for the "percentage of buildings with heating systems that use renewable energy and electricity" (broken down into residential and non-residential buildings and rented or owner-occupied properties). While the BMWK monitoring report only considers the percentage of different heating systems for new builds, an effective early indicator would also need to include existing building stock. This would require regular data collection.

53 Based on DIW 2021.
54 Based on Duwe 2021.
55 Duwe 2021.
56 as in BMWI 2021-2.
57 DIW 2021.

4 Policy measures for reducing consumption

On the supply side, the goal of climate neutrality will require the energy system to transition to electrification and the exclusive use of renewable energy (consistency). However, it will also be necessary to significantly reduce energy consumption through demand-side measures. While an **ambitious increase in energy efficiency** will be needed across all sectors (efficiency), there is a danger that efficiency gains could be partly counteracted by additional demand. Consequently, an **absolute reduction in energy demand** (sufficiency strategies) must be pursued if the climate targets are to be met. In this context, reducing demand means a reduction in consumption and production levels that results in lower energy and resource consumption. While long product lifespans are fundamentally desirable, it may make sense to replace some products before the end of their life with products that offer clear environmental advantages during use. Examples include replacing fossil fuel heating systems with heat pumps, a massive increase in wind and solar capacity, or even the replacement of individual appliances such as refrigerators. When making a decision, it is vital to consider the energy and resources used to make the product. The decision-making process is complicated by the fact that Germany currently only publishes a production-based emissions balance – a consumption-based emissions balance is not available. This makes it difficult to take the emissions associated with a product's manufacture into account.

A reduction in demand can be promoted by rethinking existing concepts and introducing new ones, primarily in the mobility and housing sectors but also in the consumer and manufacturing sectors. Depending on the elasticity of demand, rising energy prices alone can be enough to reduce energy demand. However, there is a danger that this could have a negative impact on quality of life among low-income groups if they are unable to access attractive climate-friendly alternatives. It is therefore important for sufficiency strategies to focus on enabling climate-friendly behaviour without compromising quality of life, rather than asking people to make sacrifices in order to tackle climate change. It is also apparent that many measures can have positive side effects over and above demand reduction.[58] In view of the necessarily very ambitious targets for the technological transformation of the energy supply, **the concurrent pursuit of sufficiency and efficiency strategies can help to reduce the pathway risks of the transition to climate neutrality**.

It is important to recognise the potential conflict between a reduction in absolute energy consumption and sustained economic growth, especially if sustainable consumption causes demand for goods and products to fall. The discussion about which

58 For an overview, see Creutzig et al. 2022.

kind of growth is desirable and necessary is thus an important part of the debates on climate and environmental protection and social justice.[59]

Sufficiency strategies aimed at reducing absolute energy consumption are a key component of climate neutrality transformation pathways. These strategies also address other ecological indicators such as land and resource consumption and can help to reduce pathway risks, for example with regard to the availability of low-emission energy imports.[60] At the same time, sufficiency strategies require active policy measures that also address the associated social processes (see policy area 2). Moreover, it is important to stress that an active sufficiency policy does not make action in the other areas of the energy transition any less urgent – technological change and efficiency gains are also essential if the climate targets are to be met.

Policy area 8: Strengthen scientific research on the integration of strategies to reduce consumption

Scientific research provides valuable input on energy transition strategies and challenges. Scenario studies that identify and analyse pathways for the transition to a climate-neutral energy system often focus on their technological implementation and the associated policy, economic and social implications. This includes aspects such as the expansion and system integration of renewable energy, improving energy efficiency in the heating sector by switching to different technologies and energy carriers, or the development and implementation of new processes in industry. Even though they have been extensively researched, strategies for reducing energy consumption through behavioural change and societal processes have not hitherto been fully included in these transformation studies. While international studies in particular contain numerous such scenarios,[61] sufficiency strategies only play a peripheral role in the "major" national energy system transformation studies. The inclusion of these strategies should be advocated in policy advice and promoted through concomitant research. This will allow **the potential and limitations of demand reduction to be quantified**, interactions with and impacts on the technological dimension of the energy transition to be analysed, and policy options to be formulated. The corresponding **timescales** should also be investigated, since the time required for different measures to take effect may vary and some long-term effects (for instance in settlement structure policy) will need to be addressed by appropriate policies from an early stage. The scientific investigation of demand reduction potential requires both **empirical studies** and **detailed demand modelling of the transport, building and industrial sectors**. The modelling should address the energy services level – as well as final energy demand, it should also model indicators such as passenger kilometres, living area, heating and cooling temperatures and consumption and production levels. This makes it possible to investigate the drivers of energy

59 See e.g. D'Alessandro et al. 2020 or Vogel et al. 2021. For a more general introduction (in German), see Schmelzer/Vetter 2019.

60 For a discussion of the relationship between final energy consumption and energy import levels in climate-neutral German energy system scenarios, see Wiese et al. 2022.

61 See e.g. Grubler et al. 2018, Costa et al. 2021, Eerma et al. 2022.

consumption and estimate the impacts of different measures designed to reduce demand for energy services and thus also final energy demand.

Policy area 9: Reimagine mobility

The shift from conventional internal combustion engines to more energy-efficient electric vehicles and the efficiency gains delivered by technological advances will be key to reducing energy consumption in the transport sector. However, the energy savings achieved through more efficient technology have not so far translated into an absolute reduction in emissions, since they have been accompanied by a continuous increase in passenger and freight transport use and in average vehicle size and weight. Efficiency gains will thus not be enough on their own to meet the ambitious climate targets for this sector – it will also be necessary to reduce traffic volumes and switch to lower-emission alternatives. Mobility isn't usually an end in itself – it is a means of accessing workplaces, social activities, shops, etc.[62] Accordingly, the transition to sustainable transport cannot rely on a purely technological approach that merely seeks to replace conventional forms of mobility with more efficient, low-emission drive systems. Instead, mobility should be understood in terms of its function as a means of accessing particular destinations. This highlights its **close connection with areas such as urban planning and settlement structure policy**. A new **understanding of mobility** that puts people and their needs at the centre can make a significant contribution to reducing energy consumption. In addition to tackling climate change, it also offers co-benefits such as reduced land use and health benefits due to lower levels of traffic noise and fewer road accidents. This section focuses on an integrated approach to traffic reduction and modal shift (sufficiency strategies). Technological solutions (efficiency and consistency strategies) are discussed under policy area 15.

Policy measures will be required to support and in some cases enable the shift from motorised private transport to a mix of public transport, cycling, walking and vehicle sharing. This is particularly true of the infrastructure changes needed to facilitate climate-friendlier modes of transport. It will be vital to address the different challenges faced by urban and rural areas, the needs of different social groups (e.g. people with disabilities, older people and families) and the interactions with urban and regional settlement structure policy.

PA 9.1 Strengthening (urban and rural) public transport

To enable a shift away from motorised private transport, it will be necessary to expand and improve local, regional and long-distance public transport so that it provides an attractive alternative. It will be especially important to increase the **frequency** of public transport services and the number of **locations served**. Rural areas in particular will need additional regional bus and rail services on busier routes (e.g. popular commuter routes) and extra stops. For less busy routes and times of day, traditional public transport services can be supplemented by **on-demand or ridesharing services (such as share taxis and ridepooling) and sharing services** (carsharing, bicycle hire). The different modes of transport can connect to

62 Beckmann et al. 2022.

"mobility hubs" as part of intermodal transport chains.[63] Their use can be facilitated by ensuring easy access to conventional and web-based tickets and journey planning tools. Mobility services in general should be considered a public service and should not be privatised in the form of motorised private transport. Until new systems become established, these alternatives should be subsidised, since it is often not possible for private companies to operate them profitably, especially outside of the most popular routes and times in urban areas. At the same time, incentives to use motorised private transport such as company cars could be replaced by solutions such as giving employees a "mobility budget" that can be used for any mode of transport.[64]

PA 9.2 Redistribute urban traffic space for the benefit of active transport modes and local public transport

Redistributing road space in urban areas for the benefit of cycling, walking, public transport and micromobility can make car use less attractive and encourage people to switch to climate-friendly modes of transport. This can be achieved by turning parking spaces and car lanes into cycle lanes, green spaces or public transport lanes. Instead of increasing the overall amount of traffic space, the existing space should be utilised more efficiently and traffic volumes reduced. In this context, reducing energy consumption has the co-benefits of making towns and cities more pleasant places to be, strengthening their climate fitness and reducing traffic noise and pollution. Physically separating cycle lanes from car lanes, providing ample bicycle stands and creating extensive cycle path and footpath networks are particularly important measures for promoting active mobility. Certain European cities such as Barcelona ("superblocks") and Paris (reduction of parking spaces, etc.) have already adopted this approach to urban planning. Some German towns and cities have also implemented measures to reorganise traffic space, successfully reducing passenger car traffic in entire districts within a few months.[65] Other options for reducing motorised private transport in urban areas include financial incentives such as congestion charging supported by parking management measures and cheap local public transport. Digital parking guidance systems and park & ride systems can also help with urban commuter traffic.[66] Here too, an integrated approach is key – as well as reducing motorised private transport, it is also vital to address social challenges and in particular to ensure that mobility services guarantee access to urban destinations.

The **overall aims of road traffic regulations** will need to be realigned so that local authorities can reorganise transport infrastructure as described above. At present, road traffic regulations are geared towards optimising car traffic flows and are thus a barrier to local authorities making the necessary infrastructure changes.[67] Federal government policies could regulate the amount of space that local authorities allocate to different modes of transport, provide them with financial and planning support and help them to address skills shortages.

63 See Lemmer 2019.
64 NPM 2021-2.
65 For examples, see Agora Verkehrswende 2022.
66 Ibid.
67 Frehn et al. 2022.

PA 9.3 Reduce traffic

Sustainable mobility will require an integrated transport and settlement structure policy that enables compact cities and regions. In rural areas, it will be especially important to provide more local services to meet people's everyday needs. In some cases, this will require targeted funding. Removing incentives to travel longer distances can also help to reduce urban sprawl. The opportunities for more home working and teleworking enabled by digitalisation can also reduce travel distances. However, it will be important to address the potential side effects such as increased living space demand or social impacts like blurring of the boundaries between work and private life, unpaid overtime, unequal telework opportunities and potentially even an increase in commuting distances/urban sprawl. Moreover, efforts to reduce traffic should not be confined to commuting or travel for basic necessities – they should also address access to leisure activities and general holiday traffic.

In urban areas, the 15-minute city [68], is an innovative urban planning approach that seeks to minimise the distance people need to travel. Mixed-use neighbourhoods devote a minimum amount of space to housing, shopping, work, healthcare, education and leisure. All of these functions can be accessed by local residents on foot or by bicycle in under 15 minutes. Paris is already pursuing this approach with the aim of reducing car traffic by fifty percent and making the city a more pleasant place to be. Some of the specific measures adopted in Paris include turning car lanes and areas used for parking into green spaces, creating more cycle lanes and footpaths, using school buildings and playgrounds for leisure, sport and cultural activities outside of school hours, the introduction of a "mobile town hall" that visits the city's different districts, and the adoption of an urban planning approach that sites facilities typically visited one after the other in the same location. The number of cars in the city can be reduced by park & ride facilities and connected regional train services for people commuting from outside the city centre.

PA 9.4 Shift to rail freight and reduce freight volumes through economic regionalisation

Economic regionalisation reduces overall transport distances and freight traffic. It is necessary to establish the feasibility, costs and potential co-benefits (e.g. greater security of supply) of regionalisation for different categories of goods. Labels for regionally or locally produced or repaired products (including locally grown food) can provide greater transparency for consumers.[69] A reduction in product demand would also help to reduce freight traffic. A shift from road to rail freight (promoted by financial incentives, for example) can reduce final energy demand in the freight sector. However, the less extensive nature of the rail network means that road transport links will still be required for the last mile.

68 Allam et al. 2020.
69 This measure is proposed in the National Energy and Climate Plan of Belgium, for example (NECP Belgien 2019, p. 127).

PA 9.5 Shift to rail for long-distance travel

Shifting to rail for long-distance travel can also help to reduce transport sector emissions. Measures such as motorway tolls can encourage people to travel by rail instead of by car, although the rail infrastructure will need to be developed accordingly. It will be especially important to make rail travel more attractive than short-haul flights. This can be achieved by improving long-distance public transport services and through measures such as a plane ticket tax and appropriate taxation of aviation fuel. The shift to rail for long-distance travel can be promoted by increasing the number of international rail services and night trains and making them easier to book.

Policy area 10: Focus on housing quality, land use and climate adaptation

The building sector currently accounts for around forty percent of final energy consumption. Residential buildings are responsible for approximately two thirds of this figure, while non-residential buildings account for the remaining third. The main challenge at the systemic level is the decarbonisation of heating systems, around eighty percent of which are currently powered by fossil fuels. To do this, it will be vital to significantly increase the number of heat pumps, while heating networks and, where necessary, the use of climate-neutral fuels will also play an important role. In addition to the decarbonisation of heating systems, the rate and extent of building modernisations will also be key to achieving climate neutrality in the building sector. Private households' energy consumption is closely linked to per capita living space. However, achieving changes in per capita living space through policy measures is much more difficult and takes longer. The energy transition's impacts in the housing sector also include possible financial implications for residents and issues relating to quality of life, resource and land use and climate adaptation. It is therefore important to consider the transformation of the building sector in a wider context – the relevant social justice, resilience and land and resource use aspects should be urgently included in the discussion. Embodied emissions generated throughout the life cycle of building materials should also be taken into account. As improvements in energy efficiency cause energy consumption to fall during the occupancy phase, a growing percentage of greenhouse gas emissions will be linked to the production, maintenance and end-of-life stages of building construction.[70]

PA 10.1 Restrict increases in living space and use existing building stock more flexibly

Reversing the trend towards higher per capita living space is a key social enabler of reduced energy consumption in the building sector. At approximately 47 square metres, per capita living space has more than doubled since the 1960s. This partly counteracts efficiency gains, results in the development of more undeveloped land and contributes to the housing shortage in towns and cities. Consequently, the focus needs to shift from living space quantity to living space quality and optimal living space utilisation. This includes using existing building stock more flexibly in accordance with people's different circumstances and basic needs.

70 dena 2021-2.

Possible approaches include senior-friendly retrofits of existing properties, structurally dividing detached or semi-detached houses into multiple homes[71] and multigenerational housing projects or intergenerational house swaps. Policymakers could create incentives to structurally divide houses through programmes offering financial and planning support.[72] Trends towards communal living projects, communal spaces (such as guest apartments in apartment buildings and shared outdoor spaces) and co-working spaces can be harnessed and strengthened through advice and funding measures.[73] More generally, the trend towards higher per capita living space can be counteracted by promoting apartment buildings with communal rooms and gardens, for example.

In order to limit the amount of land used for housing, **minimising the number of vacant properties** should be prioritised over new builds in rural areas, too.[74] In urban areas, the removal of barriers for converting utility areas to living space could further reduce demand for new builds. Optimised sharing and utilisation of existing buildings should also be prioritised over new builds to help meet targets for limiting soil sealing. It will be necessary to investigate which conditions and incentives could make an effective contribution to this goal at the municipal level. It can take time to change established processes and practices. Consequently, the abovementioned measures for restricting living space and making better use of existing buildings are only likely to have a widespread impact in the medium to long term. This makes it all the more important to take the relevant policy decisions as soon as possible in order to drive a transformation of the building sector that goes beyond simply implementing efficiency measures and using different energy carriers.

PA 10.2 Promote climate adaptation

To reduce energy demand, it will be necessary to achieve a rapid and widespread increase in the energy efficiency of existing buildings (see policy area 14: Switch to a climate-neutral heating supply). Alongside improvements in energy efficiency, climate adaptation measures should also be an important factor in building modernisations and urban planning. In towns and cities, the urban heat island effect can seriously impact quality of life and affect the health of vulnerable people. Building planning and utilisation should therefore address heat protection measures from the outset. This will also help to reduce future energy demand for cooling systems. As well as window areas and solar protection, this also applies to building design in general (for example increasing thermal mass by using heavyweight interior building materials) and night ventilation.[75] As well as supporting climate adaptation, green spaces and trees quickly improve quality of life in towns and cities, reducing the incentives for urban sprawl. With space at a premium in urban areas, the conversion of traffic space into green spaces has particular potential as a solution that promotes active mobility and creates a more pleasant urban environment.

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71 Pioneering projects such as "aus alt mach 2 – und mehr" (convert 1 old home into 2 – or more) in Bodnegg (Baden-Württemberg) demonstrate the potential of these approaches.

72 Kenkmann et al. 2019.

73 Kenkmann et al. 2019 and Wuppertal-Institut 2021.

74 (Energy) retrofits of existing buildings are often an environmentally-friendlier solution than demolishing and rebuilding, not least due to the high additional material requirements for new builds (see e.g. Steger et al. 2022).

75 Offermann et al. 2022.

Policy area 11:
Reduce energy demand through sustainable consumption and production

Energy demand in the industrial sector can be reduced by switching to more efficient processes enabled by technological advances, and through direct electrification and recycling (see Chapter 6). Switching to climate-friendlier products and materials coupled with a general reduction in consumption can also make an important contribution. One way of reducing consumption is a stronger focus on being able to use products when you need them, rather than owning them. This will call for policy measures to promote sharing systems and longer product lifetimes. The consumption of durable, repairable, sustainably produced products should also be promoted through appropriate regulatory and information measures.

PA 11.1 Policy measures to promote consumption of climate-friendly products

Policy measures can help to increase demand for products made from alternative, recyclable and renewable materials that are less energy- and resource-intensive. To do this, it will be essential to provide consumers with **transparent information about products' climate footprint** so that they can take this into account when making their purchasing decision. Products should be required to carry simple, easily visible labelling that complies with fixed standards and is audited accordingly (see policy area 18.1: Mandatory product footprint labelling based on life cycle assessments). Ideally, these standards should be EU-wide. The transition to a circular economy can be promoted through financial incentives, for example taxes on non-recyclable products.[76]

The market penetration of climate-friendly products could also be accelerated by creating "green lead markets" through **quotas for low-emission materials and end products**. This approach could initially be introduced in public procurement. Criteria for classification as climate-friendly materials would need to be defined in advance and the quotas set at an appropriate level. In order to enable rapid implementation, the literature suggests beginning by focusing on individual materials in particularly high-emission end products (e.g. quotas for steel made by direct reduction by hydrogen in new cars) and then gradually increasing the quota for green materials.[77]. In the long term, the aim should be to classify materials based on their life cycle greenhouse gas emissions. Alternatively, quotas could be introduced directly for the climate-neutral production of certain materials (see policy area 16.3).

PA 11.2 Require and promote durability, repairability and reuse

Manufacturers should be required to guarantee products for a defined lifetime and provide the corresponding information, together with information about how to use and maintain the product. The requirements in the EU Ecodesign Directive stipulating that household appliances should be easy to disassemble using commercially available tools should be extended to other product categories. **Mandatory product repairability labelling** should also be introduced together with **mandatory access to spare parts and manuals for independent repair shops**. France introduced a statutory

76 See Irish National Energy and Climate Plan (Department of Communications, Climate Action & Environment 2020, p. 74).
77 dena 2021-1; Ariadne 2021; Agora Energiewende/Wuppertal Institut 2019.

repairability index along these lines in 2021.[78] Reducing V.A.T. on repair services or government financial assistance with repair costs could help to make repairs more affordable for consumers than buying new.[79] For instance, the "repair bonus" offered by the Thuringian Ministry for the Environment, Energy and Nature Conservation has proved very popular and could be extended to all of Germany's federal states.

Sharing schemes – e.g. for bicycles and cars, household appliances and clothes – help to increase product utilisation, create a market for durable products and ultimately reduce the need to make as many new products. They are particularly suitable for items that are only used occasionally (e.g. clothes for special occasions or power tools) or items that currently tend to be bought based on their maximum capacity (e.g. large cars bought with family holidays in mind).

Return systems are an established solution for reusing products, especially packaging, and should continue to be promoted. While the need for return systems in new areas such as the out-of-home eating sector became particularly apparent during the SARS-CoV-2 pandemic, there is potential to replace single-use items with reusable items in many other areas, too. It will be vital to fund the establishment of deposit return schemes for new reusable products. Reusable packaging quotas are one option for ensuring that the objective of reuse is actually met. The deposit return scheme for single-use beverage containers illustrates the need for continuous monitoring of these measures. Although the scheme has clearly failed to achieve its goal of increasing the percentage of reusable beverage containers, nothing has been done to address this failure. **Modular designs** can make it easier to adapt products with a very long lifetime – such as buildings – to changing needs and forms of use by modifying and upgrading them. This makes it possible to continue using the product instead of demolishing or scrapping it. R&D in this area should therefore be promoted. Other incentives for establishing this type of solution in the market could be provided when issuing building permits, by stipulating planning requirements that address uncertainties about future demand and allow for more flexible uses (for instance, the use of modular construction methods to facilitate partial conversion or demolition).

78 Initially applicable to smartphones, laptops, TVs, washing machines and lawnmowers, it was extended to include top-loading washing machines, dishwashers, vacuum cleaners and pressure washers in November 2022. Products are given a repairability score from 1 to 10 that consumers can see when buying new. The criteria that define repairability include availability of the information needed to repair the product, spare parts and tools, ease of disassembly and the price of spare parts. France plans to add further criteria to the index in 2024, making it into a "durability index" (www.ecologie.gouv.fr/indice-reparabilite).

79 Circular Economy Initiative Deutschland et al. 2021.

5 Shaping the technological transition: driving the modernisation of the energy system and promoting innovation

Policy area 12: Transition to a one hundred percent renewable electricity supply as soon as possible

The electricity supply will need to be one hundred percent renewable by no later than 2040, at a time when demand will be rising due to the electrification of the transport, heating and industrial sectors. The current target is to almost completely decarbonise the electricity system by 2035. To do this, it will be necessary to expand renewables much faster and increase the flexibility of the electricity system in order to optimise their integration.

PA 12.1 Accelerate the expansion of renewables

All the scenario studies indicate the need to significantly accelerate the expansion of renewables in the electricity sector over the next few years. Although all the scenarios assume major advances in energy efficiency and some also assume high levels of green energy imports, wind and solar capacity will still need to increase by four to sixfold between now and 2045. The German government's current targets for 2030 are more or less in line with the upper range of figures in the scenarios. Even the scenarios with high sufficiency targets still require significantly faster expansion of renewables and substantial levels of climate-neutral energy imports.

In order to achieve the desired growth rate, it will be necessary to create **financial conditions** that attract investment in renewable energy. The ambitious targets mean that, in the long term, it will also be necessary to use less favourable locations. Furthermore, electricity prices are usually lower at times when a lot of renewable energy is being fed into the grid. The future electricity market design should reflect this by providing appropriate incentives for sector coupling. The sharp fall in the levelised cost of electricity, especially for wind and solar power, means that some installations can already pay back in the regular electricity market. In all likelihood, however, **financial support for renewable energy will remain necessary in the medium term** in order to ensure that a sufficient number of projects are completed. This could continue to be implemented through the Renewable Energy Sources Act tenders, although the volume of the tenders would need to be adjusted to reflect the current growth targets. The cost of the funding can be reduced through a funding system that provides a high level of security for the installations themselves and only transfers production-related risks to the installation operators. Additional incentives will need to be created for small investors, especially through fixed tariffs.

A rapid expansion of wind and solar power will also call for improvements to the **non-financial conditions**. It will be vital to ensure that **enough land is made available for wind and ground-mounted PV installations**. This can be facilitated by federal and state land allocation targets that also inform regional planning. Multiple space uses can be enabled and land use conflicts mitigated by making greater use of suitable roof space and promoting agrivoltaics and floating PV.

It will be vital to expedite planning and licensing processes. The establishment of clear, nationwide nature conservation criteria can make a valuable contribution to this, while systematic public participation within a transparent framework can unlock the public's creative potential in terms of getting people to experience and understand the energy transition as a worthwhile collective endeavour. This could also help to reduce the likelihood of lawsuits against planned projects. The financial participation of local authorities and residents can also strengthen acceptance.

A separate ESYS working group has published a detailed position paper setting out twelve policy options for accelerating the expansion of wind and solar power.[80]

PA 12.2 Adapt the electricity system to the requirements of renewable energy

In the past, the electricity system was designed so that controllable fossil fuel power plants could meet electricity demand at all times by adjusting their output to short-term requirements. In the future, on the other hand, electricity will largely be generated from intermittent renewable energy sources, especially wind and solar. It will therefore be necessary to increase the flexibility of the existing electricity system. The main factors that can contribute to flexibility are electricity demand, storage systems and electricity generators. It will also be especially important to **upgrade the electricity grid**, both within Germany and in conjunction with our European neighbours. The advantage of close European integration is that a much more stable supply of renewable energy can be achieved at all times when electricity is fed into the system from all over Europe than would be possible in a single country. In addition, it makes it possible to leverage the flexibility potential of other countries (see also policy area 4). Possible measures include the **digitalisation** of electricity systems[81] and modifications to the balancing energy market. Complicated laws regulating matters such as atypical grid usage should be reviewed and reformed as necessary.

Market signals should, as far as possible, promote flexible operation of sector coupling technologies such as heating networks and electrolysers in order to reduce the cannibalisation effect[82] of renewables. In addition, longer-term **changes to the electricity market design**, which may become necessary, should be analysed and widely discussed.

80 acatech/Leopoldina/Akademienunion 2022-2.
81 The requirements of digitalised energy systems, especially in terms of energy supply resilience, are described in acatech/Leopoldina/Akademienunion 2021.
82 Sensfuß et al. 2008.

Policy area 13:
Enable a rapid ramp-up of the hydrogen and synfuel markets in areas where they can deliver system benefits

A much faster ramp-up of the hydrogen market is essential in order to meet the 2030 industrial emission targets and enable immediate investment in this technology during the upcoming investment cycles. This process is currently being delayed by supply-side bottlenecks. In addition to providing targeted funding, it will be vital to create a stable regulatory framework for green hydrogen production. This framework should also ensure that at least large **electrolysers are located and operated** in a way that delivers system benefits. Both domestic green hydrogen production and the relevant import relationships and capacity will need to be developed and expanded as quickly as possible.[83]

PA 13.1 Coordinate instruments to close the financing gap for the hydrogen market ramp-up

Green hydrogen is not currently able to compete with grey hydrogen,[84] and it is not absolutely certain that, in the longer term, it will be able to compete with blue hydrogen either. Even if rising natural gas prices reduce the profitability gap in the medium term, the need for specific investments in electrolysis plants will remain a major barrier to the ramp-up of the hydrogen market.[85] This market ramp-up is key to achieving the economies of scale projected to significantly reduce the production costs of electrolysis plants.[86] Until it occurs, **supply-side and/or demand-side funding** will be required to close the financing gap.

In order to meet the scenarios' projected demand for hydrogen and achieve the climate targets, the ramp-up of the green hydrogen market will need to occur extremely quickly – at a similar or even faster rate than the market diffusion of solar PV technology in the 2000s.[87] Simply funding individual projects will not be enough. Instead, it will be necessary to go beyond the current instruments by creating a funding and licensing framework that offers long-term opportunities. This might include supply-side funding instruments such as reducing the cost of electricity used to produce green hydrogen through reallocation charges or levy exemptions (see policy area 3.2) and supporting investment through a funding guideline.

Unlike the solar PV market ramp-up, where the infrastructure and demand for the electricity generated already existed, it will be necessary to develop the infrastructure and grow demand for hydrogen concurrently with the ramp-up of its production. Supply-side funding instruments should therefore be complemented by demand-side instruments (see policy area 13.2) and targeted infrastructure development (see policy area 13.3). It is vital to ensure that supply-side, demand-side and infrastructure instruments are closely coordinated due to the strong interactions

83 Staiß et al. 2022.
84 Green hydrogen is hydrogen produced by electrolysis powered by renewable electricity. While grey and blue hydrogen are both produced from natural gas, the CO_2 emissions from the production of blue hydrogen are captured and stored underground (CCS).
85 Odenweller et al. 2022.
86 Hydrogen Council/Mc Kinsey & Company 2021.
87 Ariadne 2021-2.

between them. This coordination can help to prevent overfunding/underfunding and is also necessary to ensure that the instruments promote system benefits.

PA 13.2 Prioritise hydrogen use in the appropriate areas of application

Even if supply-side instruments are used to promote green hydrogen (see policy area 13.1) and the conditions to enable hydrogen and synfuel imports are created (policy area 13.4), it is still likely that green hydrogen will initially only be available in limited quantities. **Willingness to pay (WTP)** for this limited supply **varies** across the different demand sectors. Although WTP tends to be high in the transport sector, mature alternative technologies already exist, especially for cars and trucks. Conversely, although WTP tends to be lower in industry, this sector is faced with the urgent need to start transforming processes for which there are currently few if any alternatives to green hydrogen (for instance in the steel and chemical industries). Consequently, demand-side funding for the hydrogen market ramp-up should be geared towards **steering demand** in this direction and should initially concentrate on the identified no-regret options for hydrogen. Potential instruments for promoting demand include investment cost funding through the decarbonisation programme and Important Projects of Common European Interest (IPCEIs), and operational cost funding through climate agreements or direct funding instruments such as those offered by H2 Global. There are also some parts of the transport sector where the use of hydrogen or synfuels is a no-regret option, especially aviation and shipping. In these areas, ambitious hydrogen/synfuel quotas that are increased at a predictable rate can help to grow demand (see policy area 15.4).

PA 13.3 Coordinate the expansion of infrastructure and electrolysis plants

From a whole system perspective, it is particularly important to build the necessary new infrastructure for hydrogen as quickly as possible. Ideally, this should be done concurrently with the market ramp-up of hydrogen application and production technologies.

While the siting of large-scale electrolysers is not a major factor at the pilot project stage, it will become an increasingly important consideration in the future. In view of the German government coalition agreement's target of achieving ten gigawatts of electrolysis capacity in Germany by 2030, there is a widespread consensus that, at this scale, the siting of electrolysis plants should take account of potential power grid congestion. Ideally, electrolysers should be located in coastal areas with good wind power and cavern storage potential. This would mean that, in the short to medium term, they could mitigate any discrepancy between the rapid expansion of renewables and slower upgrading of the electricity grid, thereby reducing redispatch requirements. Several of the scenario studies identify electrolysers as an important enabler of flexibility in the future electricity system. Furthermore, a hydrogen transmission network that brings domestically produced and imported hydrogen to the principal consumption locations could significantly reduce the power grid load and provide access to the global market for climate-neutral fuels.

In the absence of a hydrogen transmission network, electrolysers in the industrial sector – where major investment in new technologies is planned for the next few years – will be built in the vicinity of industrial locations, provided that sufficient land is available. Especially in the industrial centres in southern Germany, this could increase the power grid load and lead to higher redispatch requirements. Under certain circumstances, this could even result in higher emissions, for example if coal-fired power plants are used to meet the redispatch requirements. It could also hinder the expansion of wind power in northern Germany and make significant wind curtailment necessary. Consequently, the rollout of electrolysers and the hydrogen infrastructure should occur almost concurrently. The rollout of the hydrogen network thus constitutes a chicken and egg problem: it needs large numbers of network users to be profitable, but unless a hydrogen network is already in place, many of the electrolyser locations that optimise electricity grid benefits are automatically unattractive. In order to resolve this problem, it will be necessary to close the **significant hydrogen infrastructure financing gap during the early stages** of its development.

Even if adequate financing can be secured for the hydrogen network, this does not automatically mean that electrolysers in locations that optimise electricity grid benefits will be financially attractive. Further policy measures are needed to ensure the attractiveness of suitable locations, for example through exemption from reallocation charges or introducing nodal and zonal pricing in the wholesale electricity market. The introduction of deep grid connection charges[88] is another possible means of ensuring that grid benefits are taken into account when choosing electrolyser sites. A range of different instruments and approaches could potentially be employed to influence the siting of electrolysers. A detailed analysis of the pros and cons of different options should be carried out so that a choice can be made and the relevant policy measures implemented as soon as possible.

As well as identifying electrolysers as an important means of providing flexibility in the electricity system, the studies also project high demand for **hydrogen storage facilities** in the long term. This is because the scenarios assume that hydrogen will be used in backup power plants to ensure a secure energy supply. The fact that large quantities of hydrogen can be stored in underground salt caverns means that it can be used to balance seasonal fluctuations in the energy supply system. Since green hydrogen production should ideally be aligned with renewables generation, storage facilities (in addition to the linepack flexibility[89] of hydrogen transmission pipelines) can also help to serve the more or less constant demand from industry despite fluctuations in renewable energy generation. Consequently, as well as the location of electrolysis plants, connections to storage facilities should also be considered when developing the hydrogen network.

PA 13.4 Prepare for hydrogen and synfuel imports

There is a strong consensus that, even in the long run, Germany will not be able to produce enough of its own hydrogen to fully meet demand. Hydrogen can be imported efficiently from other parts of Europe via pipelines. However, it is likely that hydrogen derivatives will also be imported from **outside of Europe** in the future. It is important to start taking the necessary steps to enable these future imports. Further preparations should also be made within Europe for the development of a European hydrogen transmission pipeline infrastructure, taking into account the changes in the use of natural gas pipelines that are currently expected in the medium term. In particular,

88 Ariadne 2022.

89 Linepack describes the total volume of natural gas or hydrogen that can be stored in the pipelines of the gas/hydrogen network. The volume stored within the network can be adjusted by raising or lowering the operating pressure.

LNG imports will require higher capacity utilisation of natural gas pipelines running from western to eastern Europe and southern to northern Europe. This will reduce the opportunities to convert these pipelines to hydrogen if demand for natural gas remains at its current levels.[90]

Preparations for future imports from outside of Europe are already underway within the energy partnerships and through H2Global.[91] It is vital to consider the **sustainability** of these imports. This applies to the carbon footprint of electricity-powered electrolysis (the EU's forthcoming Delegated Act on synthetic fuels could provide a basis for this) and to other criteria such as minimising the environmental impacts of toxic ammonia. **Import country diversification** will also be important in order to maintain future security of supply. It will be necessary to engage in a broad public and policy debate to determine the weight attached to value-based criteria (such as democracy, press freedom and judicial independence), geopolitical factors and supplier country/supply chain resilience.

Policy area 14:
Switch to a climate-neutral heating supply

PA 14.1 Increase modernisation rate

The low flow temperatures that enable efficient heat pump operation and the integration of waste heat and renewable energy are most easily achieved in modernised buildings, while higher modernisation rates also help to reduce final energy demand. Consequently, the cost-optimised scenarios in simulations regularly identify the need for much higher modernisation rates than are currently being achieved. The high investment costs associated with modernisation mean that funding will continue to be necessary. The **landlord/tenant dilemma** is also a factor in this context, while the reluctance of many older homeowners to carry out costly modernisation measures presents a further challenge. The requirements for loans and "redemption grants" could also be simplified, for example with regard to the thermal bridge calculation that is sometimes necessary.

PA 14.2 Improve the framework for increasing the number of centralised and decentralised heat pumps and for the use of geothermal and solar heating

Whether in individual buildings, heating networks or industry, the switch to heat pumps will be key to providing heat in a climate-neutral energy system – at least for low-temperature heat. Depending on local potential, both renewable energy sources such as geothermal and solar thermal energy and waste heat should be used as low-temperature heat sources.

Although heat pumps can already operate cost-effectively in some buildings, it is still common for other systems to be installed instead. Continuation of the current funding for heat pumps, possibly coupled with a ban on fossil fuel boilers, can help to accelerate the transition to climate-neutral heating solutions. Training and professional development of more energy consultants and installers is also key to ensuring that

90 acatech/Leopoldina/Akademienunion 2022-1.
91 H2 Global Foundation, https://www.h2-global.de/

homeowners receive the right advice and are able to install the desired systems. In addition, it will be necessary to implement solutions to the landlord/tenant dilemma. The adequacy of the German government's recently adopted solution for splitting the carbon price between landlords and tenants will need to be promptly evaluated. Integrated, proactive grid planning should be carried out to prevent electricity distribution grid congestion caused by the simultaneous growth in the number of heat pumps and electric vehicles.

Currently few and far between in Germany, **large centralised heat pumps** will need to supply a significant proportion of district heating in a climate-neutral energy system. In addition to funding pilot projects to optimise the technology, it will therefore be necessary to create incentives for the widespread deployment of large heat pumps in industry and for district heating systems. The partially completed reform of taxes, levies and reallocation charges is an important step in this direction. Specific investment or operating cost subsidies will also be required during the initial ramp-up phase. These are now provided through the Federal Funding for Efficient Heating Networks (BEW) scheme.

Geothermal energy will also have an important part to play in achieving a climate-neutral heating supply. In combination with heat pumps, deep (1,000 to 5,000 metres), shallow and medium-depth (50 to 1,000 metres) geothermal has the potential to meet most future demand for low-temperature heat as well as providing a significant proportion of the necessary industrial process heat for temperatures up to 200 degrees Celsius.

PA 14.3 Expansion, decarbonisation and flexible operation of heating networks

In addition to the rollout of decentralised heat pumps, it will also be necessary to expand heating networks, especially to enable a climate-neutral heating supply in densely populated areas. Moreover, existing heating networks will need to be converted to low-temperature systems in order to enable efficient use of waste heat, renewable energy and heat pumps. Funding support for the expansion and conversion of heating networks should be continued. Other possible measures include compulsory connection of waste heat sources or third party access to heating networks, a proposal that already forms part of the Fit for 55 package. Heating networks will also benefit from the municipal heating planning recommended below.

Heating networks can also be an important enabler of more flexible electricity demand, thereby supporting the integration of intermittent renewables into the electricity system. When installing new heating networks or converting existing ones, it will therefore be important to ensure that they are capable of flexible operation in line with electricity availability. This could be achieved by incorporating large-scale heat storage systems into the networks, for example.

PA 14.4 Mandatory municipal heating planning

There are no one-size-fits-all blueprints for decarbonising heating in the building sector. The solutions will comprise a mix of measures tailored to local conditions such as population density, settlement patterns, renewable energy potential, etc. Nevertheless, it will be important to avoid unnecessarily creating or expanding parallel infrastructures that compete with each other. Municipal heating planning will therefore be key to the development of an effective and efficient long-term heating supply strategy. The German government's coalition agreement includes a commitment to introduce mandatory municipal heating planning as already implemented in Baden-Württemberg and Schleswig-Holstein. This commitment should be acted on as soon as possible.

Policy area 15: Drive the technological transition to a climate-neutral transport sector

The modal shift from private cars to eco-mobility (cycling, walking, public transport and rail) will be key to achieving climate-neutral mobility. This modal shift will require changes to (transport) infrastructure. This has already been addressed under policy area 9 "Reimagine mobility". Modal shift will need to be accompanied by a switch from conventional to climate-friendly drive systems for road and rail vehicles and in the shipping and aviation sectors. This policy area discusses the expansion and conversion of (energy) infrastructure (for example charging infrastructure) that will be required to support this technological transition.

PA 15.1 Remove the barriers preventing people from switching to battery electric cars

The total cost of battery electric cars is already lower than diesel or petrol cars[92] – the main barriers preventing people from switching to this technology are the high initial outlay and the perception that there are not enough charging points. The more limited range of battery electric vehicles is also off-putting for some people. During the initial market ramp-up phase, the cashback scheme for people purchasing battery electric vehicles helped to increase their visibility and enable economies of scale in their production.[93] However, with the scheme now due to end, future policy measures should focus on removing the barriers described above.

As far as the investment costs are concerned, Agora 2021 suggests that road tax could be reformed to provide a strong incentive to purchase battery electric vehicles. One potential model is the French bonus-malus system, which imposes a high, one-off registration tax on vehicles with high absolute emissions. Customer acceptance can also be increased through information and communication about the cost of battery electric vehicles and their suitability for everyday use.

The **expansion of the charging infrastructure** is critical. It is necessary to distinguish between private (usually in private households) and semi-public (usually in the workplace) charging points and public charging points. The funding required for the public charging infrastructure depends on two key factors: the profitability of public charging points and the percentage of all charging points that are public.

92 BDI 2021.
93 dena 2021-1.

The key to a public charging point's profitability is how frequently it is used. In order to resolve the chicken and egg problem where purchasing decisions are influenced by infrastructure availability and vice versa, the German government's coalition agreement states that the expansion of the public charging infrastructure should "anticipate demand".[94] This means that the charging points will probably not be profitable during the initial market ramp-up phase and will therefore require government subsidies. Charging points located on public streets are projected to remain unprofitable in years to come. Instead, it has been suggested that the expansion of the charging network should focus on public amenities (e.g. cultural and sporting facilities, shopping centres) and fast charging points on motorways and busy roads.[95]

A study by the National Platform Future of Mobility (NPM) highlights the importance of the ratio between public and non-public (private and semi-public) charging points.[96] An increase in the proportion of non-public charging points would allow the percentage of public charging points to be reduced. In some scenarios, their number could even be significantly lower than the target in the German government's coalition agreement of one million public charging points by 2030.[97] Consequently, there should be regular monitoring of non-public charging points and of technological advances, for example in fast charging. This should be used as a basis for regular critical reviews of the public charging point target in order to ensure that public charging points are not overfunded.

The expansion of the charging infrastructure also poses electricity distribution grid challenges. This important factor should be addressed early and proactively in grid upgrade plans (see policy area 4.1). Flexible power utilisation in the transport sector enabled by managed charging and vehicle-to-grid solutions[98] can help to integrate intermittent renewable energy into the grid. This will call for standardised charging interfaces and protocols, as well as price incentives for flexible charging (for example electricity tariffs that vary depending on availability).

In view of the commitment of both the EU and industry to a strategy of extensive electrification of the European passenger car fleet, investment in the charging infrastructure is now a no-regret strategy. Moreover, increasing the number of fast charging points on the main traffic routes can also help to address range anxiety.

94 SPD, BÜNDNIS 90/DIE GRÜNEN UND FDP 2021.

95 However, a study by the National Platform Future of Mobility (NPM) shows that public charging points in some locations can become profitable by as soon as 2025 (NPM 2020-1). The NPM also recommends increasing public charging point capacity utilisation through additional measures such as a reservation function on charging points or increasing parking fees after a vehicle has been charged.

96 NPM 2020-1.

97 Private and semi-public charging points are far more cost-effective than public charging points and should therefore benefit from continued support. At the same time, enough public charging points must be provided for car users who do not have a parking space of their own (for example in densely populated urban areas), and public charging points must also be available in sparsely populated regions.

98 This involves feeding the energy stored in vehicle batteries back into the grid to help supply electricity at times of peak demand. In other words, vehicle batteries are used as temporary storage devices for the power grid.

PA 15.2 Establish a strategy for HGVs

Various options for decarbonising HGVs are currently competing with each other, for example battery electric vehicles, overhead line trucks and fuel cell vehicles. However, all of these options present different infrastructure expansion challenges, some of which will require high levels of investment. As a result, there is still a lot of uncertainty about fuel cell vehicles' share of the future HGV market, for example. This means that investing in the hydrogen station network outside of the major pan-European motorways remains a high-risk venture that is not currently attractive to investors.

A strategy is therefore needed to create attractive conditions for investors. In principle, direct electric technologies should be prioritised due to their high energy efficiency (see policy area 5.1). However, all the different technologies have pros and cons that need to be weighed up against each other. Given the pan-European nature of long-distance haulage, close European coordination is essential.

Measures to promote the decarbonisation of HGVs should also take into account the pressing need to **switch a significant percentage of goods transport to rail freight** (see policy area 9.4). All the scenarios in the meta-analysis assume an increase in the proportion of goods transported by rail by 2045/50. The dena 2021 and Agora 2021 studies assume an ambitious increase of 25 percent, while the increase in the UBA 2019 study is as high as 35 percent.

PA 15.3 Prioritise investment in expanding the rail network

Over the next few years, it will be vital to prioritise investment in expanding the rail network. By 2045, rail passenger numbers increase by 80 percent in the dena 2021 study and as much as 160 percent in the Agora 2021 study. This increase in passenger numbers can only be achieved through a significant rise in rail service availability. Investment in expanding railway lines[99] will need to be accompanied by an increase in capacity achieved in particular through widespread digitalisation of the European rail network.

At present, 61 percent of the rail network is electrified.[100] Further electrification of as much as possible of the network coupled with a switch to climate-neutral drive systems such as fuel cell trains on the remaining lines is thus also a no-regret option.

PA 15.4 Pursue ambitious quotas and drive R&D in the aviation and shipping sectors

Climate-neutral aviation fuels such as synthetic kerosene will play an important role in the aviation sector from the 2030s on. Many of the studies identify ambitious, steadily increasing minimum quotas as a key instrument for ensuring an adequate market rollout of these fuels by this date. More and more studies now include international flights alongside domestic flights in their calculations. They stress that European airlines must not be put at a competitive disadvantage and that, in the long term, non-European airlines should also be covered by appropriate mechanisms.[101] **Synfuel quotas for domestic and international shipping** have so far been largely

99 The extremely long planning and implementation timeframes for rail network construction projects are currently hindering the desired changes and should be reduced as much as possible (see dena 2021-1).

100 BMDV 2021.

101 dena 2021-1.

overlooked in the public debate. Similar rules to the aviation industry could be introduced, with the quotas being increased progressively.

In both areas, there is also an urgent **need for research into the development of alternative drive systems**. While there are already a handful of pilot projects trialling the use of ammonia or methanol as a shipping fuel, for example, these solutions must be brought to market faster. In view of their high energy efficiency, it will also be important to continue researching direct electric drive systems, especially for domestic shipping and short-haul flights (see policy area 5.1). The high specific energy consumption of short-haul flights makes it vital to prioritise a reduction in demand and a switch to alternative forms of transport that consume less energy, such as night trains and high-speed trains (see policy area 9.5).

There is a consensus among the meta-analysis scenarios that Germany's synfuel demand will be met mainly by imports. It is therefore vital to build the relevant energy partnerships and import infrastructure as soon as possible and avoid unilateral dependencies (see policy area 13.4).

6 Strategies for climate-neutral industry: transforming processes and saving resources

There are several factors that make the decarbonisation of industry particularly challenging. Around one third of industrial greenhouse gas emissions relate to **process emissions** from chemical reactions and raw materials. These emissions are either unavoidable or can only be avoided by switching to completely different raw materials or production processes. Examples include the replacement of blast furnaces with direct reduction of iron ore by hydrogen in steel production, or the use of alternative binders in cement production. The decarbonisation of industry is further complicated by the fact that many industrial enterprises **compete in global markets**. It is therefore always important to consider whether national climate instruments could damage the competitiveness of the affected companies and how this can be counteracted without diluting the climate benefits or causing production to be moved abroad. This means that European solutions are preferable to national measures. Another feature peculiar to the industrial sector is the **long lifetime of its production facilities**.[102] This makes it vital to take the relevant policy decisions as soon as possible in order to prevent lock-in to processes with high greenhouse gas emissions. A key goal for climate policy measures in industry should therefore be to **enable reliable forward planning and create investment security** for the technologies that the transformation scenarios identify as being necessary in the immediate future.

In addition to reducing product demand (see policy area 11), three further policy areas will be key if industry is to make the necessary contribution to climate neutrality: the establishment of climate-neutral processes, the creation of a circular economy and the realisation of potential for material efficiency and substitution. Furthermore, additional policy areas arise from the need to take advantage of forthcoming windows of opportunity by creating the conditions to ensure that upcoming investments opt for low-emission technologies to replace old systems.

Policy area 16: Climate-neutral processes

A significant proportion of industrial greenhouse gas emissions arise from production processes, especially the use of fossil fuels to generate process heat. Since improving the efficiency of these processes is often not enough to support the transition to climate

102 In principle, production facilities with long lifetimes are more sustainable. However, problems arise if it is difficult or impossible to convert them to new processes. This could mean that they are locked in to long-term emissions ("committed emissions", Tong et al. 2019). The chemical industry is discussing modular production strategies that allow facilities to adapt flexibly to new requirements (such as new or modified products and fluctuations in demand) (see e.g. Dechema 2017). These strategies could also support the switch to climate-neutral processes.

neutrality, it will sometimes be necessary to switch to completely new processes. In steel production, for example, direct reduction with subsequent processing in electric arc furnaces is currently the most promising option for replacing high-emission blast furnaces. In addition to the energy carriers, the raw materials used also play an important role. Where possible, fossil feedstocks should be replaced by biogenic alternatives or by feedstocks made using green hydrogen. Process emissions must also be prevented, for example in the cement industry, by employing alternative raw materials (primarily alternative binders in this particular context). However, it will not always be technically possible to fully replace certain materials. In these instances, the residual emissions will need to be captured via carbon capture and storage systems or counterbalanced by negative emissions (see Chapter 8).

Emissions from industrial production are generated across different parts of the value chain and can be broken down into different intensity types: emission intensity (emissions per unit of energy used), energy intensity (energy used per unit of material), material intensity (material used per product unit) and product-service intensity (number of products used to provide a service). These are multiplied by each other and by demand for the service in question. Figure 11 illustrates the different intensity types. The main options for reducing industrial emissions are improving the energy efficiency of production through optimised processes and increased material recycling, improving material efficiency in production (for example reducing wastage, reusing materials) and improving material efficiency in product design (for example longer product lifetimes, lightweight design). Increased emission efficiency can be achieved by using renewable energy, for example, and is primarily an energy sector question (see Chapter 5). Improving product-service efficiency (achieved through solutions like carsharing or higher building occupancy) and reducing demand for services are also matters that lie outside the scope of industry (see Chapter 4).

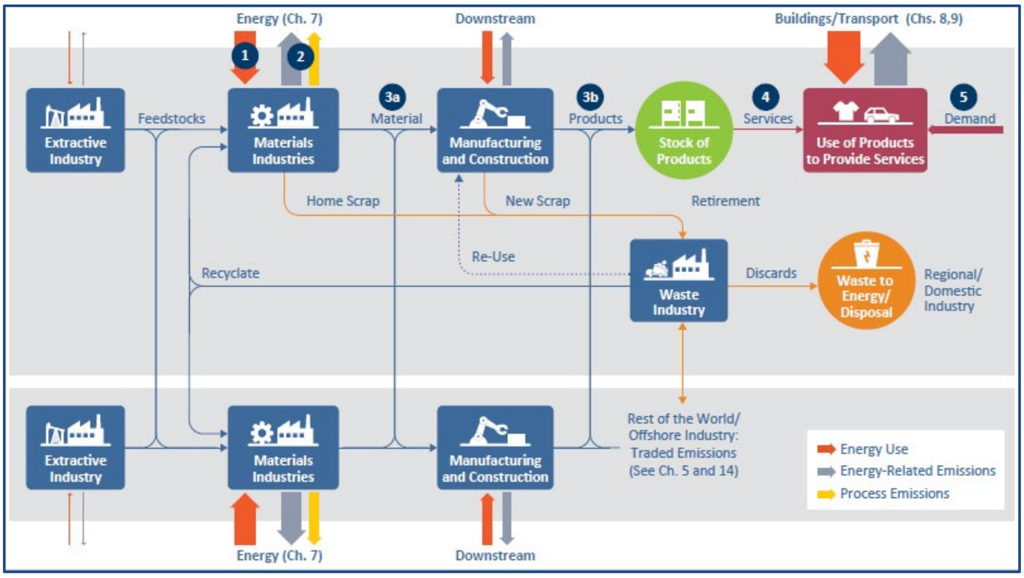

Figure 11: Industrial processes across value chains. The opportunities for reducing emissions occur at different points in the value chain.[103]

103 Adapted from Figure 10.2, Fischedick et al. 2014.

PA 16.1 Prioritise electrification of industry where possible

Overall, the meta-analysis scenarios show that direct electrification is also an efficient and important decarbonisation strategy for the industrial sector, especially for generating process heat. For example, electric steam generation using heat pumps and electrode boilers has already attained a high Technology Readiness Level. However, the same cannot yet be said of some other technologies such as electric industrial furnaces for metal production. Where mature technologies are available, it is important to make them economically attractive by ensuring that electricity is cheaper than fossil fuels. In addition to carbon pricing, this can also be done through the other price components of the electricity supplied to industrial customers. It will be particularly important to promote the use of electricity in a way that delivers system benefits, since – in principle – electrified processes have significant load flexibility potential. Dedicated markets could be created for industrial customers to provide load flexibility. Alternatively, they could be offered grid tariff discounts.

PA 16.2 Create incentives to switch from grey to green hydrogen

For production processes where hydrogen is already used as a feedstock, for example in methanol and ammonia synthesis, switching from grey[104] to green hydrogen has the potential to reduce emissions in the short to medium term. For example, the climate-neutral methanol needed to switch high-value chemical (HVC) production to the **methanol-to-olefin route** can be made with hydrogen produced by electrolysis using renewable electricity. The replacement of steam reforming by electrolysis is not yet competitive because the levelised cost of green hydrogen is currently still high. However, its use could be promoted through Carbon Contracts for Difference (CCfDs). It will also be necessary to determine the future shares of domestically produced and imported commodity chemicals.

PA 16.3 Set targets for the percentage of climate-neutral production materials

The introduction of fixed quotas is one possible way to promote the progressive replacement of conventional materials with climate-neutral alternatives. Quotas could initially be introduced for the most energy-intensive materials such as steel and cement, and for the biggest markets (for example the construction and automotive industries, household appliances and wind turbines). They could then be extended to other areas. However, the introduction of quotas for climate-neutral materials could distort competition and cause production to be relocated elsewhere. Consequently, a more workable solution would be for Germany, or better still the European Union, to establish a **target trajectory for progressively increasing the percentage of climate-neutral materials in primary production** and use appropriate instruments such as CCfDs to support compliance.

The producers of the relevant materials should also be required to produce plans setting out how they intend to switch to climate-neutral production processes. This requirement could initially apply to listed companies before gradually being extended to other businesses. It could also be a condition for the (continued) allocation of free carbon allowances and other types of support. In addition, setting a deadline after which only climate-neutrally produced basic materials can be sold in the EU could

104 Fuel Cells and Hydrogen Observatory 2020.

compel producers to make the switch or provide an incentive to counterbalance unavoidable emissions with negative emissions.

PA 16.4 Policy measures to make climate-friendly production technologies and processes the most attractive option for new investments

During the next decade, many industrial facilities will need to replace major assets such as blast furnaces in the steel industry. In view of the long lifespan of these assets, it is crucial to ensure that they are only replaced by systems that can already be operated climate-neutrally (for instance electric technologies, which will become climate-neutral when the electricity system no longer generates any greenhouse gas emissions), or systems that can be easily converted to climate-neutral operation. If the alternative climate-neutral processes are not competitive, they should be promoted, for example by increasing the investment support provided through existing structures such as the "Dekarbonisierung in der Industrie" (Decarbonisation in Industry) programme, declaration as an Important Project of Common European Interest (IPCEI) and the European Investment Fund. A regulatory alternative would be to prohibit new installations of certain production processes and technologies for which viable alternatives already exist. In addition to investment funding, support could also be provided during the operational phase by ensuring that there is a sufficient supply of green secondary energy carriers at affordable prices. One effective approach would be to reduce levies and surcharges on electricity as much as possible in order to incentivise direct electrification (see also policy area 3.1).

PA 16.5 Support research into and upscaling of climate-neutral technologies and processes with a low Technology Readiness Level

In order to achieve the transformation of industry within the necessary timeframe, several different climate-neutral technologies will need to be ready for market by between 2025 and 2030. This can be achieved through targeted support for research into and upscaling of innovative technologies. Hydrogen burners for providing **high-temperature process heat** and electric systems for providing heat at temperatures over 700 degrees Celsius are examples of technologies with a low Technology Readiness Level. However, these general-purpose technologies could be used in a wide range of different industries such as metalworking, primary aluminium production and the glass, cement and lime industries (or in other areas of application that use rotary kilns).[105] Targeted research and technology support in this area should focus on solutions that have a wide range of applications and thus high emission prevention potential.

Policy area 17: Creation of a circular economy

As well as switching to sustainable alternatives for all high-emission processes, it will be equally important to create **closed-loop material cycles** in order to reduce demand for primary production. Several different strategies can contribute to the establishment of a circular economy. The aim of this approach is to promote product durability, reusability and repairability and ensure that products can be easily disassembled into their component parts at end-of-life so that these can be reused to

105 European Commission 2022.

make new products. These objectives were already enshrined in the 1994 Waste Avoidance, Recycling and Disposal Act (now the Circular Economy Act, Kreislaufwirtschaftsgesetz). However, short-lived, disposable products are still widely used, and a high percentage of waste is still incinerated instead of being recycled into feedstock. The starting point for a circular economy strategy is to achieve behavioural changes such as reducing consumption and promoting reuse. This is discussed under policy area 11. Industry can enable these behavioural changes by making products that are durable and reusable. The secondary production of materials is also key.

PA 17.1 Establish statutory standards for the production of recyclable goods

Existing laws and regulations should be supplemented by standards requiring manufacturers to design products so that they can be easily recycled. One example of the current barriers to recycling is the plethora of different plastics and metal alloys. Restricting the number of plastic additives or only permitting a small number of standard alloys for particular specifications could help to reduce this diversity, allowing recycling processes to be more precisely tailored to the remaining materials. Recyclability could also be enhanced by providing digital information about products' composition and the materials used to make them. Potential recyclers could access this information in order to optimise material and component recycling.

PA 17.2 Improve recycling collection and logistics

Chemical recycling technologies for plastics have now attained a high Technology Readiness Level and are a better alternative than incineration. Processes such as gasification and pyrolysis convert plastic waste into raw materials for the chemical industry, where they are used instead of fossil feedstocks such as naphtha. Suitable collection and logistics systems are needed to support these technologies. These could be promoted through appropriate waste collection regulations (especially the "Grüner Punkt"/Green Dot). It will be important to ensure that waste and recycled materials are not transported over unnecessarily long distances – the collection and transport requirements should be in proportion to the amount of material recovered.

PA 17.3 Introduce quotas for secondary materials

Secondary materials could be included in the targets for the percentage of climate-neutral production materials proposed under policy area 16.4. The use of these materials would ensure an actual reduction in the consumption of primary materials. Quotas and target trajectories for the reuse of packaging materials do already exist. However, they can currently be complied with by downcycling or by exporting plastic waste. As a result, much less waste is actually recycled. Moreover, at present it is usually cheaper to use primary materials than recyclate, especially for plastics. Target trajectories supported by targeted funding can help to ensure that materials are actually recycled, wherever possible into equivalent products. Manufacturer take-back obligations are another instrument that could be used to promote material recyclability and recycling. This approach creates incentives for manufacturers to design products so that their materials can be recycled cheaply and, where possible, into products of equivalent value. A climate tax not linked to the CO_2 emissions from manufacturing a product could also be introduced for certain materials such as steel, plastic, aluminium and cement in finished products. This tax could be used to fund the promotion of climate-neutral materials and create incentives for resource efficiency.

Policy area 18:
Promote material efficiency and material substitution

There can be significant differences in the life cycle emissions of different materials and their production processes. For instance, the use of wood-based building components instead of conventional residential building methods and materials can reduce both the process emissions and energy consumption associated with the materials' production. At present, not enough weight is given to these embodied emissions (i.e. greenhouse gas emissions resulting from a material's production) when choosing materials, and there is also a lack of transparency about them. This could be addressed through mandatory labelling. Some current product standards also constitute a barrier to the use of climate-friendly materials.

PA 18.1 Mandatory product footprint labelling based on life cycle assessments

Mandatory carbon footprint labelling covering every stage of a product's life cycle should be introduced in order to promote the use of climate-friendly alternative materials in products. Calculating carbon footprints on the basis of fixed – ideally EU-wide – standards would make it possible for consumers to compare different products in the same category. This would allow them to take a product's climate-friendliness into account when making their purchasing decision (see policy area "Policy measures to promote consumption of climate-friendly products"). It is important to be aware of potential conflicts between the requirement for a highly accurate labelling system and the need for a system that can be widely implemented. Manufacturers could reduce their products' carbon footprint by using low-emission materials and feedstocks such as secondary steel, steel from direct reduction or recycled plastic. Procurement quotas or binding sustainable procurement rules for materials and finished products should be introduced in the public sector.

PA 18.2 Update building and product standards

Building and product standards and regulations should be continuously updated in order to facilitate material efficiency and substitution and the use of novel building materials. The use of climate-friendly building materials such as timber is currently hampered by building regulations, especially fire safety regulations. In some cases, this puts timber buildings at a significant disadvantage to buildings made from other materials. Other novel materials such as cement made with alternative binders have to go through complex licensing processes that can overly complicate and delay their use in construction projects. Licensing procedures should therefore be expedited so that climate-friendly materials can be used as soon as possible. Building materials' embodied emissions could also be factored into the licensing process and used as a criterion for issuing building permits.

Policy area 19: Strengthen carbon price effectiveness and investment security

One reason why embodied emissions are often not factored into production decisions is because the free carbon allowances allocated under the EU ETS mean that carbon pricing has had very little impact on production costs,[106] while most materials imported from outside the European Union are not subject to greenhouse gas pricing at all. It is important to ensure that carbon pricing is actually effective while also preventing offshoring. The price risks that can arise from the use of climate-neutral materials should be mitigated through Carbon Contracts for Difference. The current revision of the EU Emissions Trading System (EU ETS) already contains a number of important elements. In particular, it provides for the allocation of free allowances for low-emission, alternative processes and the introduction of a Carbon Border Adjustment Mechanism coupled with the phasing out of free allowances for the sectors covered by the mechanism.

PA 19.1 Introduce Carbon Contracts for Difference

Carbon Contracts for Difference (CCfDs) can incentivise investment in climate-neutral technologies by temporarily safeguarding investors against regulatory risks until the ETS provides sufficient incentives to invest. This instrument can help to ensure that reinvestments between 2020 and 2030 are only made in technologies that are already climate-neutral or have the potential to become climate-neutral either by using electricity or green hydrogen or because they can be easily converted. In return for reducing their CO_2 emissions, companies investing in low-carbon key technologies receive project-specific operating cost subsidies to help reduce their risks. The concrete level of the subsidies could be determined by auctions that would in principle be open to all companies. This instrument is due to be introduced in 2023. Carbon Contracts for Difference should be regarded as a temporary mechanism until the EU ETS provides sufficient incentives to invest. This will enable competition between individual assets, since the aim is not to fully switch to climate-neutral production processes during the transition period.

PA 19.2 Balance effective carbon pricing against the need to prevent carbon leakage

At the request of the European Council, the European Commission has included a Carbon Border Adjustment Mechanism (CBAM) in the revised version of the ETS Directive. A key goal of this mechanism is the prevention of incentives to offshore carbon-intensive production (especially the production of basic materials) and the associated emissions to non-EU countries without compromising the effectiveness of carbon pricing as an incentive to reduce emissions. Importers of basic materials like steel, cement and fertiliser will have to report the embedded emissions generated in other parts of the world and purchase carbon credits to cover them. The aim is to ensure equal treatment for products made in Europe and imports from outside of Europe. At the same time, free carbon allowances will be phased out. However, there was strong opposition from some member states to any significant reduction in the free

106 This effect arises from the combination of free allowances and the definition of the benchmarks (see Agora Industrie 2021, p. 35 f).

allowances, since the proposed mechanism cannot cover exports and their value chain, meaning that some carbon leakage risks remain.

The fact that reporting is restricted to certain materials (steel, cement and fertiliser) and value chains (only basic commodities) means that the biggest import streams subject to reporting would come from Ukraine, Russia and Turkey. Russia's invasion of Ukraine has changed the picture – in the future, the EU will be helping to rebuild Ukraine, whereas trade with Russia will be dominated by other considerations. This is another reason to refine the CBAM so that it provides an effective transformation instrument.

7 Carbon management: enabling the transition to net-negative emissions

To enable the transition to net-zero and eventually even net-negative GHG emissions, the relevant choices will need to be made as soon as possible – many of the necessary processes have not yet been trialled at scale and further research into their environmental impacts is also required. Having caused a significant proportion of historical emissions, the industrialised nations of Europe have a particular responsibility in this regard. Germany should therefore advocate the development of an **ambitious carbon dioxide removal strategy at EU level**.

The carbon dioxide removal strategy should form an integral part of an **overarching carbon management strategy** that also encompasses CCS for fossil CO_2 emissions that cannot be reduced sufficiently within the required timeframe, and CCU. This will make it possible to leverage synergies arising from overlaps between the three processes, especially in terms of geological storage and carbon capture technologies.

Figure 12 depicts a range of possible carbon pathways. The resulting carbon footprints are determined by the origin of the CO_2 (atmospheric, biogenic or fossil) and the length of time the carbon is stored for (no storage, storage in short-lived products, storage in long-lived products or geological storage). For example, while BECCS (Bioenergy with Carbon Capture and Storage) and BECCUS (Bioenergy with Carbon Capture, Utilisation and Storage) achieve net-negative emissions, in the case of BECCU (Bioenergy with Carbon Capture and Utilisation) the overall process is net carbon-neutral. On the other hand, if fossil CO_2 is used and stored in short-lived products (CCU, Carbon Capture and Utilisation), the overall process generates net emissions.

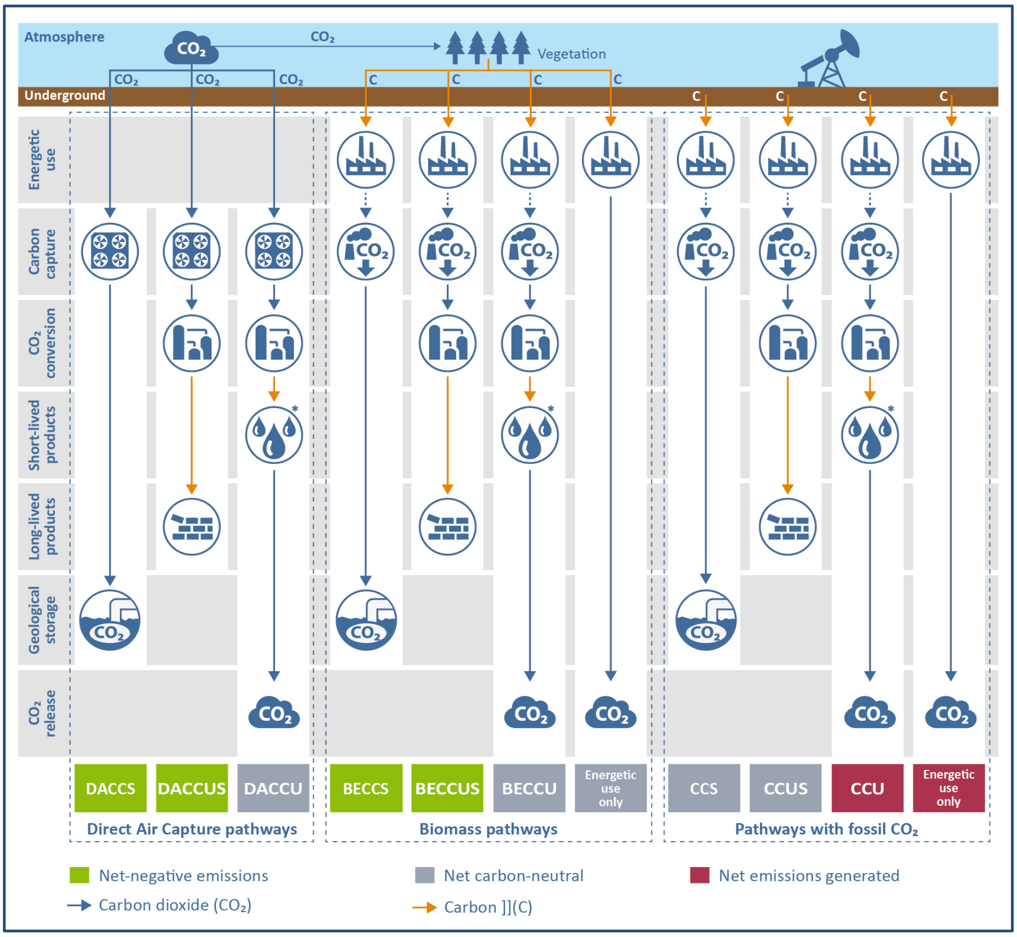

Figure 12: Selected carbon pathways. Authors' own illustration, IPCC[107] definitions of BECCUS, DACCUS and CCUS. *If a short-lived product (e.g. plastic) is incinerated at end-of-life and the resulting CO_2 captured, net-negative emissions can be achieved provided that the process uses biogenic (BECCU) or atmospheric (DACCU) CO_2. If fossil CO_2 is used (CCU), the process is net carbon-neutral.

Some members of the public are sceptical about CDR, CCS and CCU, while others know relatively little about these technologies and they are therefore not widely discussed. A (potentially Europe-wide) **public engagement process** is necessary in order to develop a strategy that enjoys widespread public support. In its coalition agreement, the German government undertakes to formulate a long-term strategy for dealing with the approximately five percent of unavoidable residual emissions[108] and refers to the need for technical negative emissions in this context. This **long-term strategy** could include the elements outlined below.

107 IPCC 2018.
108 SPD, BÜNDNIS 90/DIE GRÜNEN UND FDP 2021.

Policy area 20:
CDR – removing carbon from the atmosphere

PA 20.1 Establish goals and responsibilities

The prospect of offsetting emissions through carbon dioxide removal raises new questions relating to distributive justice. In a net climate-neutral Europe, which member states, sectors and companies should still be allowed to generate residual emissions? Who should counterbalance these emissions using CDR and who will pay for it?

It will be vital to ensure that the ambition of measures to reduce emissions is not diminished by the prospect of carbon dioxide removal at some point in the future. As well as shifting responsibility for tackling climate change onto future generations, this would be an extremely risky approach – more research is needed into the potential and side effects of CDR methods, and irreversible damage could be caused if the global temperature threshold is exceeded even temporarily. On the other hand, it would also be risky to neglect the further development of CDR methods due to concerns about competition with emission prevention measures. This would deprive society of a key tool for tackling climate change in years to come. In keeping with the precautionary principle, it is therefore essential to ambitiously pursue further research and development of CDR methods and to engage in a public and policy debate about their role in the wider climate strategy. The introduction of a **statutory target for the ratio of emission reduction to CDR** (for instance 95 percent reduction, 5 percent CDR) would ensure that the prevention of greenhouse gas emissions is prioritised.

Finding an appropriate, publicly acceptable balance between emission avoidance and CDR will call for a broad discussion involving stakeholders and the public about which **residual emissions** should continue to be allowed and in which sectors. It will be necessary to determine and transparently communicate the emission prevention options that currently exist or could be developed in different sectors and the associated costs and environmental and social impacts.

Another important question relates to the **regulatory integration of CDR in German and EU climate policy**. It may make sense to link technical processes such as DACCS and BECCS to the ETS but to include land-based processes such as afforestation and soil carbon sequestration in the LULUCF regulation.

In addition to the climate impacts, the **ecological and social implications of CDR measures** must also be taken into account. It will be necessary to consider the impacts of land-based measures (biomass production for BECCS, afforestation, soil carbon sequestration, enhanced weathering) on ecosystems. The establishment of criteria for CDR projects could be informed by past experience with the **regulation for bioenergy** under the Renewable Energy Directive (RED II).[109] It will also be necessary to address social distributional effects, for example potential rises in land prices and the price of land-intensive products if land-based CDR measures increase.

109 EU 2018.

PA 20.2 Establish clear accounting rules

Accurate accounting is indispensable for a proper assessment of CDR measures' climate impacts. Clear accounting rules are also a regulatory requirement for CDR incentive systems.

The **permanence of carbon storage and the risk of reversibility** are both key factors. Especially when carbon is stored in vegetation or the soil, there is no guarantee that it will remain locked away for hundreds or thousands of years. However, even if it is only stored for a few decades, this can still help to temporarily reduce the amount of carbon dioxide in the atmosphere until more permanent storage methods are available. The benefits are amplified if CDR measures also support other ecosystem services. Flexible concepts such as the **tonne-year** are a useful way of reflecting this. Tonne-year accounting compensates carbon storage on the basis of a predetermined sequestration period.[110] Further research is required to establish realistic estimates for the sequestration periods of different CDR methods.

In the long run, **accounting rules should be established at UN level**. The EU can take the first step by developing and testing solutions and standards that could subsequently be adopted globally. Germany should advocate this approach at EU level. The development of an accounting system could draw on past experience with the LULUCF Inventories and Forest Reference Levels. As part of the Fit for 55 package, the European Commission has already published proposals for a reform of the LULUCF regulation that will be highly relevant to any such accounting system.[111]

PA 20.3 Develop and test CDR methods and assess their risks

To ensure that sufficient quantities of carbon dioxide can be removed from the atmosphere in the space of a few decades, it will be necessary to refine and start using CDR methods as soon as possible.

There is still **a lot of uncertainty** about the individual CDR methods. The potential of CDR methods that increase the capacity of natural sinks (afforestation, soil carbon sequestration) is largely dependent on the future climate. Meanwhile, the potential of CDR methods that employ CCS or require expensive technology that is still under development is highly dependent on social and policy decisions. Assessments of the different methods should take the entire life cycle into account. For instance, high requirements for raw materials such as the steel and concrete used for DAC technology can limit a method's potential and increase greenhouse gas emissions if the materials used are not produced climate-neutrally.[112] A **diversified** approach with a **broad mix of CDR methods** can **minimise the overall risk**. Accordingly, **research funding should cover a wide range of different CDR methods**. Public acceptance is also likely to be greater if the different methods are not played off against each other. Instead, scenarios could be used to communicate how the different CDR technologies can complement each other in a transition pathway to a climate-neutral overall system and

110 Bier et al. 2020.

111 For example, the no-debit rule is due to be replaced with explicit targets for the member states in 2026. From this date, the current accounting rules will no longer apply. Instead, the emissions in the national inventories will be compared directly against the targets.

112 The same applies to all other technologies with high material requirements. However, if a technology's carbon footprint is only adverse during a transition period when the production of the materials needed to build the necessary systems still generates a lot of GHG emissions, it can nevertheless be worthwhile providing funding to support the technology's market rollout.

contribute to net-negative CO_2 emissions. It will be necessary to think beyond the 2045 deadline in this context, since the technology mix that enables GHG neutrality may not be sufficient to achieve the necessary level of net-negative emissions in the second half of the century. Scenarios that exclude CCS should be particularly carefully reviewed.

In order to respond to the uncertainties associated with the different technologies, it will be necessary to carry out **regular assessments of the potential and risks of the different CDR methods**, especially their impacts on ecosystems. **Learning, adaptive regulations** enable a swift response to new insights. The extensive past experience with the regulation of bioenergy in the German Renewable Energy Sources Act and the RED can help to ensure that the risks to ecosystems are properly addressed.

PA 20.4 Create incentives for the use of CDR

Many CDR methods will not initially be profitable under the current regulatory framework. Since carbon dioxide removal is a public good, its value is not reflected in the markets. This makes it a classic candidate for state intervention. Technology-neutral competition between the different methods would probably favour technologically mature or simple methods such as afforestation over newer, more complex methods like DACCS or enhanced weathering. However, the scenarios indicate that the potential of the cheapest methods will not be enough to meet the climate targets in the long run. Consequently, it will be necessary to explore the need for **temporary, technology-specific funding** for certain methods in order to enable learning effects. The phase model proposed in a 2021 study for the Wissenschaftsplattform Klimaschutz (see Figure 13) could provide a framework for short-, medium- and long-term measures to promote CDR.

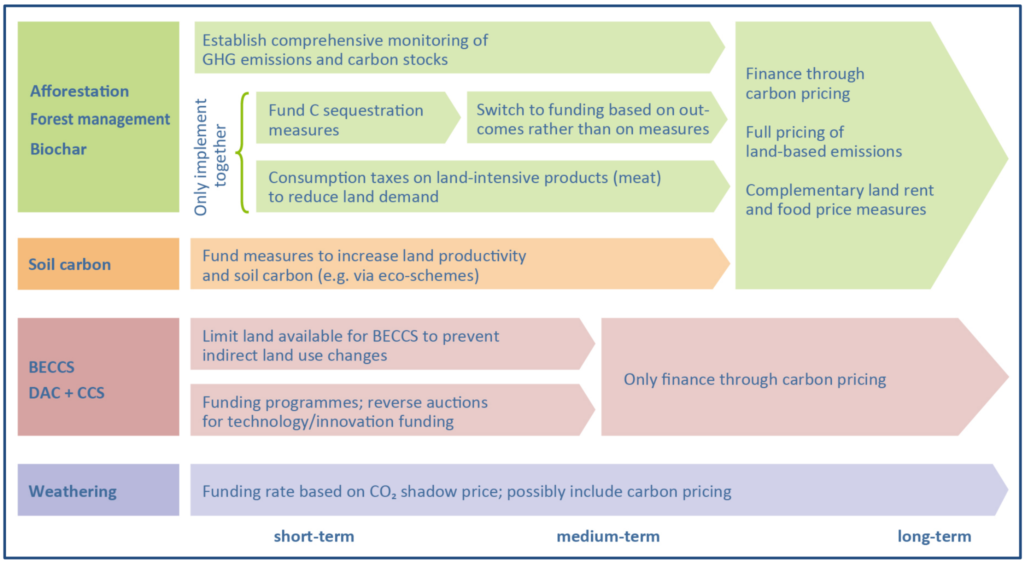

Figure 13: Phase model with potential policy instruments for the governance of different CDR methods, proposed by the Wissenschaftsplattform Klimaschutz[113]

113 Fuss et al. 2021, Fig. 8.

Policy area 21:
CCS – geological carbon storage

PA 21.1 Promote a public debate on CCS

A public debate on the acceptability of CCS is needed in order to build a **basic consensus on the role of CCS among government, science, industry and civil society**. This should initially address whether and how widely CCS should be used in Germany and the type and location of publicly acceptable storage facilities, for instance whether they should be in Germany or Europe and whether they should be onshore or offshore.

Until a few years ago, CCS was primarily seen as a solution for CO_2 emissions from coal-fired and gas-fired power plants. Today, on the other hand, it is mainly discussed in the following **areas of application**:

- CO_2 emissions from chemical processes that are essential for the production of certain products such as cement. Alternative strategies that could be used in conjunction with CCS include (i) reducing demand for the product, (ii) finding alternative, climate-friendlier ways of making the product (such as reducing the clinker factor in cement production) and (iii) finding a climate-friendlier replacement for the product (such as timber). These strategies should be weighed up against each other in terms of their cost, development level and feasibility. For example, it should be borne in mind that failure to use CCS for certain processes such as cement production would result in higher residual emissions that would then need to be counterbalanced by CDR.

- CO_2 from waste incineration (this should be accompanied by a discussion about the potential for waste prevention).

- CDR for emissions that are difficult to avoid in sectors such as farming. It will be necessary to discuss which residual emissions in which sectors should be allowed and for how long, as well as which measures for reducing emissions are acceptable. Once again, it will be necessary to determine whether emissions can be reduced through changes in demand, for example by switching to more plant-based diets.

- the long-term achievement of net-negative global emissions that will be necessary in order to keep to the 1.5 degree Celsius target (this will depend on how fast and extensively emissions should and can be reduced).[114]

114 Germany's concrete contribution to this global target has not yet been determined by policymakers.

Clear and binding statutory regulations can mitigate concerns about CCS. The following points are of particular importance:

- Clear rules on the permitted areas of application for CCS in order to ensure that it is only used where there is no alternative and not as a means of prolonging the use of coal, natural gas and oil as energy sources.

- It is necessary to establish a clear policy regarding the treatment of products made using CCS in other parts of the world (especially blue hydrogen).

For all potential storage locations, it will be necessary to ensure that the long-term stability of the carbon storage is guaranteed, the risks (groundwater contamination, earthquakes, threats to people and animals from leaks) are minimised and any issues are identified at an early stage through appropriate monitoring. Demonstration projects could provide valuable insights and serve as practical examples of how to address these issues.

PA 21.2 Develop a Europe-wide CO_2 storage and transport infrastructure

A cross-border CO_2 transport infrastructure would enable access to the extensive CO_2 storage sites in Norway, the Netherlands and the UK. Mostly located far from human habitation under the Norwegian and North Seas, these sites have huge potential. Germany should encourage the EU **to develop a European regulatory framework for CO_2 storage as soon as possible**. One possible measure would be to include CO_2 transport and storage infrastructure in the trans-European energy infrastructure rules (TEN-E regulation).

The development of the CO_2 transport infrastructure should begin as soon as possible. In its December 2021 Communication on Sustainable Carbon Cycles, the European Commission stated that it would study the cross-border CO_2 infrastructure deployment needs. This will call for **systematic, cross-border mapping** of the development over time of unavoidable CO_2 point sources (such as cement works), potential DAC sites and CO_2 storage sites.

Policy area 22:
CCU – climate-friendly carbon utilisation

Carbon is contained in many products such as plastics, medicines and fertiliser. While most of this carbon currently comes from oil and gas, sources such as biomass or CO_2 captured from the atmosphere will need to be harnessed in order to achieve climate-neutral production. If the CO_2 used is derived from fossil fuels or chemical processes such as cement production, the entire chain is not carbon-neutral, since the CO_2 is released into the atmosphere at the end of the product’s life. It is thus important to take a nuanced approach to Carbon Capture and Utilisation (CCU). CCU can help to tackle climate change, but under some circumstances it can also result in higher emissions – it all depends on the source of the CO_2 used, how long it is stored for, whether or not it replaces fossil-based products and the carbon footprint of the process chain.

PA 22.1 Create incentives for carbon dioxide removal

In the long term, incentives for measures to tackle climate change in the form of technology funding or favourable regulatory and economic conditions should only be made available for carbon dioxide removal or emission prevention, not for carbon utilisation per se. There is a danger that incentives for the utilisation of CO_2 from fossil sources could counteract climate measures by making the processes that emit this CO_2 more economically attractive. Consequently, regulatory and funding measures for CCU should be carefully reviewed in order to avoid this risk.

PA 22.2 Crediting long-term carbon sequestration based on how long it is locked away for

Nevertheless, there may be a case for initially also supporting CCU that uses fossil CO_2. This support would only be provided for a transition period to help bring the relevant CCU technologies to market within the very short required timeframe. The potential benefits of this approach would need to be carefully weighed up against the abovementioned risks – it will be vital to assess the effects on the system as a whole. As well as taking the entire life cycle of CCU products into account, it is also necessary to consider the available alternatives (for example timber instead of CCU building materials and biogenic raw materials for industry instead of power-to-chemicals). A tax on fossil carbon extraction is one possible measure to prevent the negative climate impacts of creating incentives to use fossil carbon for CCU.

If carbon is locked away for a long time in products like building materials that remain in use for several decades, this is essentially the same as a temporary CDR effect. This type of carbon dioxide removal could be counted in tonne-years (see policy area “Establish clear accounting rules”). Alternatively, its proportional contribution could be accounted for by a discount factor based on how long the carbon is stored for.

Conclusion

The consequences and risks of global warming threaten to jeopardise our prosperity and our very existence on this planet. Limiting extreme warming will require a far-reaching transformation that can only be accomplished through a combination of social, technological and economic solutions. In the space of less than three decades, it will be necessary to reverse the current trend of continuously rising global greenhouse gas emissions so that emissions can be reduced to net zero by the middle of this century. Germany has already reduced its national greenhouse gas emissions by around forty percent in the last three decades. However, it will need to significantly step up its efforts and also transform sectors and processes that are difficult to decarbonise if it is to meet its target of achieving climate neutrality by 2045. This is particularly true of the industrial, building and transport sectors. The necessary measures include a significant reduction in energy service consumption, highly efficient energy and raw material use and a rapid and widespread expansion of renewable energy. It will also be vital to integrate the demand sectors, energy infrastructure and supply of renewable energy through widespread implementation of sector coupling.

The 22 policy areas discussed in this paper outline the key potential solutions and address the challenges from a whole system perspective. They are based on a comprehensive meta-analysis of the current literature and the working group's own simulated scenarios. The identified policy areas indicate the need to approach the transformation of the energy system as a global, societal process and to implement the key technological, economic and infrastructure requirements as soon as possible. Addressing the socioeconomic aspects such as the development of innovative mobility concepts and the training of energy technology professionals is just as important as the efficient technological and economic implementation of sector coupling.

This systemic analysis highlights the extremely ambitious nature of the transformation. The achievable growth rates for renewable energy and other technologies will not be enough to bring climate neutrality within reach unless accompanied by sufficiency measures and major improvements in energy efficiency. Carbon management solutions will also be necessary to tackle emissions that are difficult to avoid.

However, the best measures for achieving the desired system transformation are not always obvious in every sector. This applies to questions such as how to increase building modernisation rates or accomplish the shift from private to public transport. Current scenario-based system analysis studies often make ambitious assumptions for these areas that will be extremely difficult to achieve in practice. There are also several unanswered questions with regard to integrated, cross-sectoral infrastructure planning. Moreover, it will be important to gain a better understanding of the energy transition's social dimension and ensure that future research addresses the distributional issues arising from climate and energy policy measures.

Targets have sometimes been missed in the past and some measures may not be sufficient to achieve the relevant goals. Incentives must therefore be created concurrently in every sector. Increased energy saving measures must not diminish efforts to expand renewables, for example. Likewise, while a public debate on carbon sinks and their planning will be essential, this should not detract from sufficiency, efficiency and technology rollout measures.

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The Academies' Project

In the Energy Systems of the Future initiative, acatech – National Academy of Science and Engineering, the German National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities provide input for a fact-based debate on the challenges and opportunities of the German energy transition. Around 160 experts collaborate in interdisciplinary working groups to develop policy options for the transition to a sustainable, secure and affordable energy supply.

The "Integrated Energy System" working group

Germany and Europe have adopted more ambitious climate targets, a global hydrogen economy is emerging, and the potential for removing CO_2 from the atmosphere (negative emissions) is being explored. How do these developments affect the energy transition? The "Integrated Energy System" working group examines potential pathways for achieving climate neutrality before 2050 under these changing conditions. Based on a comparison of current energy scenarios and its own simulations, the working group provides an overview of different pathways to climate neutrality and highlights the influence of key technological and economic parameters and social preferences on the future energy supply. Which greenhouse gas reduction pathways are required for the different sectors in order to meet the German and European climate targets? Which technologies and infrastructures must be available and by when? What role do changes in consumption behaviour or energy efficiency play? And which policy and regulatory measures are needed by when to achieve this transformation?

The working group's findings were published in two formats:

1. The **analysis** "Szenarien für ein klimaneutrales Deutschland. Technologieumbau, Verbrauchsreduktion und Kohlenstoffmanagement" (German only) presents the assumptions and findings of the working group's own simulations, an analysis of current energy scenarios in the literature and the working group's conclusions about potential pathways to climate neutrality.

2. The **position paper** *"Towards a Climate-neutral Germany: Policy Options for the Technological Transition, Reducing Consumption and Carbon Management"* provides a concise overview of the findings and presents a series of policy options.

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