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# Biomass: striking a balance between energy and climate policies

Strategies for sustainable bioenergy use

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# Biomass: striking a balance between energy and climate policies

Strategies for sustainable bioenergy use

# Preface

There is no longer any time to lose when it comes to climate protection. The coming years are vital to ensuring that the planet does not become further unbalanced. This is apparent from the IPCC Special Report published in 2018. If we perpetuate the current situation, global warming will probably exceed the 1.5 degree mark as soon as 2030.

The IPCC is calling for far-reaching changes in all areas of society in order to prevent this undesirable development. Bioenergy can, for example, assist with replacing fossil energy carriers. According to the IPCC, bioenergy with carbon dioxide capture and storage (BECCS) has the potential to remove carbon dioxide from the atmosphere. This will be necessary in the future, for instance, in order to offset unavoidable emissions from agriculture and industrial processes. The EU Commission also considers "negative emissions" to be essential in order to achieve the self-imposed target of ensuring greenhouse gas neutrality in Europe by 2050.

However, using biomass to produce energy is not in itself climate-friendly and involves risks for the environment and nature. As long ago as 2012, a Position Paper from the German National Academy of Sciences Leopoldina warned of the consequences of poorly thought-out bioenergy use. Initial proposals as to how bioenergy can be put to sustainable use in the energy system were outlined in the "Raw materials for the energy transition" Position Paper published in 2017 as part of the Academies' Project "Energy Systems of the Future" (ESYS).

In the present publication, the German Academies of Sciences continue this work and show how bioenergy can best contribute to the energy supply and climate protection. They are calling for the limited biomass potential to be put to system-beneficial use. Bioenergy is of greatest benefit to the energy system where it offsets the weaknesses of other renewables, for instance as a fuel in aviation or shipping. Environmental risks can be curbed primarily by putting residues and waste materials to use as energy.

Policy instruments such as comprehensive $CO_2$ pricing and certification systems should provide an incentive for further use of bioenergy. These will have the greatest effect if they are applied to all agricultural and forestry products. The ESYS working group, moreover, recommends that $CO_2$ removal technologies such as BECCS be considered as climate protection options.

We would like to express our sincere thanks to the scientists and reviewers for their commitment.

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# Contents

# Abbreviations and Units

| | |
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| BECCS | Bioenergy with Carbon Capture and Storage |
| CCS | Carbon ($CO_2$) Capture and Storage |
| CCU | Carbon ($CO_2$) Capture and Utilisation |
| CHP | Combined Heat and Power generation |
| CHP plant | Combined Heat and Power plant |
| $CO_2$ | Carbon dioxide |
| DAC | Direct Air Capture |
| EEG | German Renewable Energy Sources Act |
| GHG | Greenhouse Gas |
| ILUC | Indirect Land Use Change |
| IPCC | Intergovernmental Panel on Climate Change |
| RED | EU Renewable Energy Directive |

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| a | year |
| EJ | exajoule (1 EJ corresponds to 277.8 TWh) |
| $km^2$ | square kilometre |
| MW | megawatt |
| $MW_{el}$ | megawatt of electrical power |
| $MW_{th}$ | megawatt of thermal power |
| t | tonne |
| t/a | tonnes per year |
| TWh | terawatt-hour |

# Glossary

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| BECCS | Bioenergy with $CO_2$ capture and storage. This works by plants capturing $CO_2$ from the air by photosynthesis and using it to form energy-rich carbon compounds. If these are used to generate electricity or heat or to produce motor fuel, this $CO_2$ is released again, but it is not discharged back into the atmosphere and is instead captured and put into permanent underground storage. As a result, in net terms, $CO_2$ is removed from the atmosphere. |
| Biochar | Charcoal-like material produced by carbonising biomass which is incorporated into the soil. Carbonisation prevents decay so the carbon captured from the air in the form of $CO_2$ by the plants is therefore not released again as $CO_2$ (or at least only after a very long time). This method can therefore permanently remove $CO_2$ from the atmosphere. |
| Biogas | Energy-rich gas produced by microbial fermentation. The main components are methane and carbon dioxide. Biogas can be produced, for example, from maize silage, grass silage, animal slurry and food residues. In contrast, biomass which primarily consists of lignocellulose such as straw or wood, is unsuitable or less suitable for fermentation. Lignocellulose can be converted into a flammable gas by high-temperature gasification, but this is known as synthesis gas rather than biogas. |
| Biomass | Irrespective of the type of use, biomass is defined as "the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste"[a]. Bioenergy denotes biomass which is used as an energy carrier. In addition to the material streams put to use producing energy, biomass also includes those proportions which are used for producing food or materials. |
| Biomethane | Upgraded biogas largely consisting of methane. During upgrading, the $CO_2$ present in the biogas is captured. The gas is additionally dried, desulfurised and conditioned so that it meets the technical requirements to be fed into the natural gas grid. Biomethane can then be transported in the natural gas grid and used for various purposes instead of natural gas. |
| Cultivated biomass | Biomass grown on agricultural land. This includes, for example, not only cereals and grasses, but also short rotation coppicing of fast-growing tree species. |
| CCS | Carbon (dioxide) capture and storage. $CO_2$ from energy or industrial plants is captured and put into permanent underground storage. The storage sites that may primarily be considered include depleted oil and gas deposits and deep, saline aquifers. |

a) EU 2009.

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| $CO_2$ equivalent | Measure of a chemical compound's global warming potential. The $CO_2$ equivalent indicates how strongly one kilogram of a chemical compound contributes to the greenhouse effect in comparison with one kilogram of $CO_2$. Since gases break down in the atmosphere at different rates, the $CO_2$ equivalent can only be stated for a defined period. Often it is stated for 100 years after release of the gas. Nitrous oxide (N2O), for example, has a $CO_2$ equivalent of 265 based on a period of 100 years.[b)] In other words, the greenhouse gas effect of one kilogram of nitrous oxide corresponds to that of 265 kilograms of $CO_2$. Methane has a greenhouse gas equivalent of 28 based on a period of 100 years. |
| Deforestation | Land use change in which forest area is lost permanently or for an extended period, for example because it is converted into agricultural or pasture land. Forestry activities involving temporary clear-cutting of forested areas are not counted as deforestation if forest then regrows on the land. |
| Direct Air Capture (DAC) | $CO_2$ capture technology, in which $CO_2$ from the ambient air is captured in technical facilities by chemical processes such as absorption or adsorption. Once captured, it can then be compressed and stored underground (which is the case considered here) or used alternatively, for example, as a raw material for chemical products. |
| Electricity-based synthetic motor fuels | Electricity from wind power or photovoltaics is used as the energy source for producing such fuels. This works by splitting water into hydrogen and oxygen by electrolysis. Electricity is required for this energy-intensive process. In a further process step, the hydrogen is then further processed with $CO_2$ to form carbon-containing compounds such as methane or liquid fuels. |
| Forest wood | Forest wood is here defined as wood harvested in the forest excluding harvesting residues (forest wood residues). The balances stated here record forest wood residues with residues and waste materials. |
| Forest wood residues | Timber harvesting residues which mainly remain in the forest. Forest wood residues are any timber less than seven centimetres in diameter and raw wood which remains in the stand. It is thus made up of stemwood including bark, branches and twigs, harvesting residues, roots and stumps and any adhering needles and leaves.[c)] The figures for potential used in the study do not include roots and stumps. |
| Lignocellulose | The material forming the cell walls of woody plants. Wood and straw largely consist of lignocellulose. Today's usual methods for producing liquid fuels and biogas plants cannot process lignocellulose. |
| Negative emissions | $CO_2$ removal from the atmosphere, for example, by bioenergy with CCS or afforestation. Total emissions are net negative if, overall, more $CO_2$ is removed from the atmosphere than is emitted (thus resulting in lower $CO_2$ content in the atmosphere). |

b) IPCC 2014.
c) Brosowski et al. 2015.

# Summary

Today, bioenergy covers around one tenth of Germany's energy demand. This means it currently provides a greater proportion of the country's energy needs than do wind power, solar energy, hydroelectric power and geothermal energy combined. Its advantages are that biomass energy carriers are readily storable and can be put to flexible use not only for generating electricity and heat but also as transport fuels.

However, the quantity of biomass that humans can utilize with an acceptable impact on the environment is limited. The increasing global population means that **demand for biomass** for producing food, for manufacturing products and for supplying energy will probably continue to rise, and thus so too will competition for land. Extending or intensifying land use would have a considerable impact: greenhouse gas emissions might rise, biodiversity would be jeopardised and soil and water quality might be impaired. In addition, complex repercussions on global carbon sinks in forests, plants and soil must also be taken into account. However, some of these are almost unquantifiable, and various approaches for estimating them are the subject of scientific controversy. The extent to which using agricultural biomass and forest wood will be capable of contributing to climate protection in the future is therefore unclear.

Since **agricultural commodities and wood** are traded internationally, a scientifically well-founded estimate of the volumes of bioenergy that can be sustainably used can only be made on a global level. Bioenergy use in Germany and global land use are inseparably linked. When devising a bioenergy strategy, account must therefore be taken of the impact outside Germany of bioenergy use in the Federal Republic. This applies all the more given that Germany consumes more biomass than it produces and, for calculation purposes, can therefore be considered to make use of land area outside Germany.

Estimates of sustainably usable global bioenergy potential range from around 50 exajoules annually, or roughly the current level of bioenergy use, up to several hundred exajoules. The forecasts are greatly influenced, among other things, by the extent to which it proves possible to increase agricultural yields in the future. The restrictions on land use necessary to maintain ecosystems and biodiversity also play a major role. Moreover, there is a high level of uncertainty as to the availability of unused degraded agricultural and pasture land that could be used for the environmentally friendly production of bioenergy. Future diets also have an immense impact on the amount of land required for food production. It would be most likely for there to be scope for making greater use of agricultural biomass to produce energy if global meat consumption could be significantly reduced. It has for instance been calculated that, given a purely plant-based diet, the world could feed approximately twice as many people from the same land area as today. Cutting food waste is another lever for reducing the area of land required for food production.

Overall, it is clear that using forest wood and agricultural commodities for energy involves considerable environmental and social risks. These risks can only be minimised if sustainability requirements for all forms of land use and all agricultural and forestry products are implemented worldwide. In a climate protection context, it is particularly important to curb global deforestation. Until this is achieved, there should be no further increase in the use of bioenergy from forest wood and agricultural commodities.

## Prioritise use of residues and waste materials

The priority should instead be to make use of **residues and waste materials** for energy, as the risks to ecosystems and food security are significantly lower than in the case of forest wood and agricultural biomass. Since it is generally uneconomic to transport residues and waste materials over relatively long distances, there is hardly any international trade in them. In contrast with forestry and agricultural biomass, the potential for Germany can be quantified for these materials. Around half the overall bioenergy used in Germany is already obtained from residues and waste materials (approximately 150 terawatt-hours per year). In addition, there is still unused potential from forest wood residues, cereal straw and animal excrement of 108 to 189 terawatt-hours annually. Overall, some 7 to 9 per cent of Germany's current primary energy demand could thus be met just with residues and waste materials. If primary energy consumption can be reduced from today's level of some 3,800 terawatt-hours to 2,000 terawatt-hours annually by 2050, which is the goal set by the Federal Government's Energy Plan, residues and waste materials could meet as much as 13 to 17 per cent of primary energy demand.

However, various factors, including their higher pollutant content, usually make waste materials costlier and more complicated to process than forest wood and conventional energy crops. Bioenergy plant technology has to be adapted to these feedstocks. A low-pollutant, recycling-friendly design of bio-based materials such as wood products can also help to facilitate subsequent energy use.

A further challenge facing the production of liquid motor fuels is that a large proportion of the residues and waste materials consists of **lignocellulose**, which forms the cell walls of woody plants. Processing this material requires chemical processes utterly different from those used, for instance, to produce biodiesel from oilseed rape or bioethanol from maize. Some processes, such as a synthesis gas biorefinery, are currently still in development. In particular, optimising plant design to ensure functional and economically viable overall plant operation is a vital factor here. It is not yet possible to predict the timing of a successful commercial introduction. Wet fermentable waste, in contrast, can be converted into biogas through microbial processes.

## Consider bioenergy with $CO_2$ capture as a technological option

If the global climate protection targets set out in the Paris Agreement are to be achieved, on the basis of current knowledge, the $CO_2$ content of the atmosphere must be reduced in the second half of this century at the latest, i.e. more $CO_2$ will have to be removed from the atmosphere than is still being emitted. One technology which makes this possible is bioenergy with carbon (dioxide) capture and storage (**BECCS**). This works by plants capturing $CO_2$ from the air and using it to form energy-rich carbon compounds. If these are used to generate electricity or heat or to produce motor fuel, the $CO_2$ is released again, but it is not discharged back into the atmosphere, instead being captured and put into permanent underground storage.

In addition to BECCS, there are further options for removing $CO_2$ from the atmosphere. These include large-scale afforestation of unused areas, production and storage of "biochar" (a carbon compound similar to charcoal with long-term stability) in agricultural soils and using chemicals to absorb $CO_2$ from the air and then store the $CO_2$ underground (Direct Air Capture, DAC). The potential, environmental impact and cost associated with most **$CO_2$ removal technologies** and how long each is capable of storing the carbon cannot be clearly predicted. In all likelihood, a mix of different technologies will have to be used in order to be able to meet total $CO_2$ removal requirements. The role played by BECCS is uncertain. Many IPCC scenarios include a massive use of BECCS with up to 300 exajoules of bioenergy per year (some five times current levels of bioenergy use). BECCS should therefore be considered as one of the technological options in the debate around the future paths of development in bioenergy.

Whether bioenergy is to be used in future with or without CCS will have a major influence on the further development of bioenergy use, since not all bioenergy technologies are equally well suited to $CO_2$ capture. Since $CO_2$ capture and connection to the necessary transport infrastructure is worthwhile only for relatively large plants, biomass streams might have to be diverted from the current decentralised pattern of use to larger, more centralised plants.

## Coherent climate protection policy

A **bioenergy policy** which provides strong incentives for the use of biomass to produce energy must ensure that the increased demand for bioenergy has no negative social and environmental impacts and actually makes the desired contribution to climate protection.

Which resources are used and what impact they have on land use systems is pivotal to the environmental risks involved, social acceptance and the greenhouse gas balance. **Indirect Land Use Changes (ILUCs)** are a particular challenge in this respect. Such changes occur if the cultivation of bioenergy crops results, due to an associated increase in biomass prices, in an expansion in cultivated areas in other regions, often in countries outside Europe. It is not feasible to put a statistically or empirically well-founded figure on indirect land use changes. While approaches to quantifying and certifying the risk of ILUCs have already been developed, they have not yet been demonstrated to be robust, effective and generally implementable in certification systems. For this reason, reliably preventing ILUCs using a German or European bioenergy policy is largely impossible.

In Germany, the use of biomass for energy has so far largely been governed by the energy sector's body of legislation. However, this does not sufficiently take into account effects outside the energy system. Energy and land use systems must be viewed as an integrated whole in order to record these effects and to provide an incentive for bioenergy use which also takes proper account of environmental and social requirements. In the light of the probable rise in the use of residues and waste materials, the interface between the energy and waste management sectors will also become increasingly important. Greater coordination of the various funding and governance mechanisms in energy, agriculture, forestry and environmental policy is therefore indispensable.

One effective instrument for regulating the greenhouse gas emissions from bioenergy over the entire life cycle would be a **uniform and sufficiently high $CO_2$ price**. In any event, the greenhouse gases arising from land use, especially nitrous oxide, must be taken into account because they are the greatest source of emissions in agriculturally-cultivated biomass. In the long term, all greenhouse gases should ideally be priced in every sector of the economy, thus also including food and feedstuff production. This would result in overall climate-friendly land and energy use and would make further deforestation economically less attractive. As a result, greenhouse gas emissions from indirect land use changes could also be reliably regulated.

For the foreseeable future, it would seem to be difficult to implement a global $CO_2$ price for all greenhouse gas emissions within the framework of an international agreement. Ever more countries and regions have, however, begun to introduce emissions trading systems or $CO_2$ taxes which already cover around 20 per cent of worldwide greenhouse gas emissions. Various steps can be taken to bridge the gap until a global agreement on $CO_2$ pricing is reached. In the case of domestically produced biomass, statutory provisions at the national or EU level can ensure that bioenergy is produced sustainably and makes a specific contribution to abating emissions. Possible policy instruments for imported biomass are certification, a border tax adjustment or the integration of greenhouse gas emissions present in imports into the European Emissions Trading System.

Biofuels imported into the EU are already being **certified**. Only biofuels proven to achieve a defined minimum greenhouse gas savings over fossil fuels can count towards the biofuel quota. Under the current new version of the EU Renewable Energies Directive, the sustainability requirements which previously applied only to liquid fuels have been extended to biogas and solid energy carriers. In addition to greenhouse gas emissions, a certification system can also include social and environmental sustainability criteria. It could also be used for this purpose as a supplement to a $CO_2$ price.

The greenhouse gas emissions of imports could be subject to a **border tax adjustment** in order to ensure that domestic and imported biomass are treated equally, and that reasonable account is taken of greenhouse gas emissions generated during production outside Germany. Because of the European internal market, the border tax adjustment would have to be introduced by the European Union. Alternatively, the greenhouse gas emissions present in imports could be **integrated into the European Emissions Trading System**. In this case, importers would have to purchase emissions rights for the greenhouse gas emissions arising outside of Germany during the production and processing of the biomass. The magnitude of the “imported” greenhouse gas (GHG) emissions could be demonstrated by certification, as in the case of the border tax adjustment.

Greenhouse gas emissions from ILUCs cannot be prevented using these instruments if they are only applied to biomass for energy production. All biomass imports, including foods and feedstuffs, would have to be subject to the same criteria to solve this problem.

The described instruments provide a selection of well-developed, largely market-based methods for regulating greenhouse gas emissions. However, promoting the environmentally and economically sound sourcing of raw materials means that impacts on water quality, nutrient cycles and biodiversity must also be taken into account. Incorporating these **ecosystem services** into funding and incentive models is far more difficult than for greenhouse gas emissions. Although theoretical approaches for evaluating ecosystem services do exist, there is virtually no experience in implementing them in practical policy instruments. Further research is required.

## System-beneficial use of biomass

What limited biomass potential there is should in the future be used in such a way that it makes the most valuable contribution possible to the energy transition. The **interplay between bioenergy and other renewable energy sources** must be optimised accordingly. Bioenergy should primarily assume those functions in the energy system which cannot be performed by other renewable energy sources or only at very high cost. The most important future fields of use are currently considered to be the provision of industrial heat and of fuels for transport applications which are difficult to electrify. Combined heat and power (CHP) generation from bioenergy will probably be carried out flexibly in the future in order to compensate the fluctuating feed-in from wind and solar power systems. CHP plants can be combined with thermal storage to increase flexibility. Bioenergy can also help to bridge extended periods with little wind and sun. For heating purposes, bioenergy will probably primarily be used in difficult-to-insulate buildings not well suited to heat pumps.

The sectors in which bioenergy will primarily be used in the future will essentially be defined by three factors:

Firstly, by whether carbon dioxide capture and storage **(CCS) will be accepted as part of the climate protection strategy** – a central prerequisite for the use of BECCS. This is above all a decision for society to make that will have far-reaching consequences for the energy system and land use. If the decision is *against*, not only BECCS, but also direct air capture will not be usable as a $CO_2$ removal technology that involves little demand for land. It will then be necessary to check whether and how climate protection targets can still be achieved without these technologies. If the decision is *in favour* of using CCS, infrastructure for $CO_2$ transport and storage would have to be put in place and BECCS plant engineering developed in the near future. This is because if BECCS is to make a contribution to climate protection on the order of magnitude required in global climate protection scenarios in the second half of this century, the first large-scale industrial plants would have to come on stream as soon as within the next ten to twenty years. Industrial process heat generation using biomass is a suitable application for trialling BECCS. The debate in society about whether and for what purposes CCS should be used should therefore take place as quickly as possible.

Secondly, the future use of bioenergy depends on if and when liquid **transport fuels made from lignocellulose** will be commercially launched. These could make a valuable contribution to the energy system because they offer an alternative to fossil fuels, for example, in aviation and shipping. Moreover, during biofuel production, some of the carbon present in the biomass can be captured as $CO_2$ and stored underground.

If hydrogen is produced instead of carbon-containing motor fuels, as much as the entirety of the carbon present in the biomass can be captured. Producing fuels from lignocellulose is, however, very technically complex and costly. Further development is required to make them applicable for commercial launch. Like BECCS, fuel production from lignocellulose can only be carried out viably in large plants. This technology too would therefore mean a partial move away from small-scale bioenergy use as is currently dominant and preferred by society and strengthen the trend towards industrial bioenergy production.

Thirdly, a further **expansion of combined heat and power (CHP) infrastructure** will decide the extent to which bioenergy will in the future be able to contribute to electricity and heat generation. Flexible biomass CHP technologies are already technologically well developed. Relatively large plants for supplying industrial plants or urban areas could in the long term also be combined with CCS. CHP plants furthermore permit efficient, decentralised bioenergy use. If they are to play a major role in the energy system, there would have to be systematic support for the necessary investment in expanding heating networks.

Of the development pathways present, the CHP approach is possibly the simplest to implement both technically and socially. However, abandoning BECCS and transport from lignocellulose would also miss opportunities to use bioenergy to contribute to the transition of the energy system and achieve long-term climate protection targets, not least precisely in those areas where there are few prospects for alternative solutions.

In the case of lignocellulose, the biomass supply and use concepts are very different in the presented development pathways: decentralised CHP plants could largely be supplied from today's existing decentralised supply structures. Biorefineries or BECCS plants, on the other hand, require industrial bioenergy production and supra-regional supply chains. This would fundamentally change the structure of the stakeholders, as a result of which relatively significant impact on and resistance from society is to be anticipated.

In the case of biogas produced from wet, fermentable waste, in contrast, a smooth and progressive transition from today's decentralised use in combined heat and power plants to new applications can be achieved comparatively simply. The biogas can be upgraded to biomethane and fed into the natural gas grid. This technology is commercially mature and already in use today. Like natural gas, biomethane can be flexibly used for electricity and heat generation and as motor fuel. A national biomethane strategy could stimulate biomethane production and use and form an important building block in an overarching bioenergy strategy. Since the $CO_2$ present in biogas must in any event be captured during upgrading, it would be appropriate to investigate options for combining the process with CCS. However, the volume of $CO_2$ captured per plant is relatively low, and thus would entail costly $CO_2$ pipeline infrastructure. The extent to which this might be economically viable, logistically feasible and accepted by the population would have to be investigated.

## Creating system knowledge

A comprehensive bioenergy strategy should ensure that bioenergy provides the best possible long-term support for the energy transition and achieves climate protection targets without harmful effects on soils, water resources and biodiversity while ensuring acceptance by society. This entails a better understanding of the **interactions between the energy system and land use**. Integrated models of energy and land use systems could help to indicate development pathways by which climate protection targets can be achieved in various ways. In future, BECCS technologies and alternative $CO_2$ removal technologies (e.g. afforestation) should also be taken into account.

There is, moreover, an urgent need for a **social and political debate** around the opportunities and risks of the various technologies. This applies in particular to CCS and the various $CO_2$ removal technologies which are currently the focus of much controversy. A **platform** for discussing transformation pathways could ensure that development pathways are being thoroughly evaluated from different viewpoints.

The results of the discussion platform could be used as the basis for establishing a systematic **monitoring system** with the aim of evaluating all the contributions to the system made by bioenergy against suitable indicators. If such an evaluation system, periodically extended and interpreted by experts, were regularly applied to different development pathways, it could help to direct the further development of bioenergy in a system-beneficial direction. This could reduce constant changes of course in bioenergy policy and increase planning certainty for stakeholders.

# 1 Introduction

Biomass[1] already provides a greater proportion of Germany's energy needs than do all other renewable energy sources put together. Overall, biomass accounts for some 60 per cent of electricity, heat and fuel production from renewable sources, amounting to approximately one tenth of Germany's final energy consumption.[2]

What role will bioenergy play in the energy system of the future? Which sectors is it well suited to supplying, and how can it be used in practical terms? Bioenergy has major potential to contribute to an energy supply which will in future be based to a great extent on renewable energy sources. It can be readily stored over long periods and thus help to bridge extended spells with little wind and sun. It has many and varied uses: bioenergy can be used for predictable power generation, as a transport fuel, for heat generation and as a source of carbon in industry.

However, if sustainability criteria are ignored, using bioenergy can have a negative impact on the environment. Biomass is the food base for all heterotrophic organisms (animals, fungi, microorganisms). Biomass also contributes to carbon sink formation in the form of living biomass (e.g. trees) and as soil carbon arising from the degradation of plant-based biomass in the soil. Removal of biomass by humans always involves an intervention in ecosystems and their carbon balance. For example, if forests are cleared in order to cultivate energy crops, bioenergy use makes little or no long-term contribution to climate protection. Biodiversity, soil quality and water resources can also be harmed by energy crop cultivation, as they too can be affected by other forms of intensive agriculture.[3] Biomass is, moreover, in demand, not only being used for supplying energy, but also in the food and feedstuffs industry and for manufacturing products. Ongoing growth in the global population means that demand for biomass and thus also competition for land will continue to increase. Since both foodstuffs and bioenergy carriers are traded internationally, the environmental and social impacts of bioenergy use outside Germany must also be taken into consideration.

Estimates of the actual global potential for sustainable bioenergy use diverge greatly, ranging from some 50 exajoules annually, roughly corresponding to today's bioenergy use, up to several hundred exajoules per year.[4] According to most studies, however, global (and national) potential is limited. Bioenergy should therefore assume those functions in the energy system that cannot be performed by other renewable energies or only at very high cost. It is, however, not straightforwardly possible to establish

1 Irrespective of the type of use, biomass is defined as "the biodegradable fraction of products, waste and residues of biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste". (EU 2009) Bioenergy denotes biomass which is used as an energy carrier.

2 BMWI 2017-1.

3 Water usage and the impact of intensive agriculture on soils are discussed in Leopoldina 2013.

4 An evaluation of various estimates of potential can be found in Klepper/Thrän 2019, section 2.

which functions these might be over the coming years and decades. The outcome is heavily dependent on ongoing developments in individual technologies that compete with bioenergy in certain fields. At present, these are, for instance, storage technologies, direct electrification technologies and processes for producing electricity-based synthetic combustion and motor fuels (power-to-X technologies). If it is to make the greatest possible contribution both to supplying energy and to protecting the climate, bioenergy will in future have to be used in a way which is particularly beneficial to the changing energy system. A national bioenergy strategy must therefore address not only embedding bioenergy in Germany's energy transition but also global climate protection targets.

This study essentially focuses on bioenergy sources already in use – plant-based biomass from agriculture and forestry together with residues and waste materials. The range of issues addressed here is complemented by other publications from the German Academies of Sciences on bioenergy and the bio-based economy which shed light, among other things, on the future possibility of using microorganisms to obtain energy. These include the 2013 Leopoldina Position Paper "Bioenergy – Chances and Limits" which, in addition to conventional energy crops, also discusses from a scientific standpoint using algae for energy use and the biological production of hydrogen by genetically-modified microorganisms.[5] The 2018 German Academies of Sciences Position Paper "Artificial Photosynthesis. State of Research, Scientific-Technological Challenges and Perspectives" provides a detailed description of various processes for obtaining chemical energy carriers and valuable products from sunlight, water and carbon dioxide.[6] This may involve biological or technological processes (such as Power-to-X) as well as hybrid biological-technological systems. In the long term, these processes may come to compete directly with biomass-based processes.

## 1.1 Bioenergy in Germany's energy transition

Today, Germany uses nearly two thirds of its bioenergy to generate heat, while 22 per cent is used for generating power. Transport fuels from biomass, despite often being the focus of debate in society, at 14 per cent account for the smallest proportion of bioenergy used.[7]

5 Leopoldina 2013.
6 acatech/Leopoldina/Akademienunion 2018-3.
7 BMWI 2017-1.

Energy scenarios indicate that the nature of bioenergy use will change fundamentally in the years up to 2050.[8] Important future fields of use are currently considered to be

- provision of industrial heat,
- provision of fuels for transport applications that are difficult to electrify,
- compensating fluctuations in wind and solar electricity and
- heating buildings that cannot be adequately insulated and are not well suited to heat pumps[9].

The provision of industrial process heat might in the future become a major application for bioenergy. This is because heat pumps, which make very efficient use of electricity for heating buildings, cannot be used for providing heat above 200 degrees Celsius. Biomass, in contrast, can straightforwardly be used as a combustion fuel even at temperatures of several hundred degrees. Process heat in industry currently accounts for one fifth of Germany's final energy consumption with a large proportion of this demand being met by natural gas. It can in the future be replaced gradually by biogas and/or synthetic methane without entailing any consequent changes to the industrial processes. Alternatively, wood could also be used as a fuel in industry, but that would require more major changes to the industrial processes.

In addition, biomass can replace fossil resources as a carbon source in the manufacture of products and materials, but this falls within the realm of material use which this Position Paper does not address in detail.

Another major field of use in the future might be transport applications in which purely electrical powertrains are difficult to implement, for example in shipping, aviation or heavy goods vehicles. Even if electricity-based synthetic liquid fuels for powering ships and aircraft are likely to become ever more important in the future, biofuels are an inexpensive alternative. Combining the production of electricity-based hydrogen with biofuel production is also a possibility. Hydrogen from electrolysis plants could, for instance, be blended with synthesis gas obtained from biomass in order to optimise the ratio of hydrogen to carbon for motor fuel production. As a result, virtually all the carbon present in biomass can be converted into fuel, thus doubling fuel yield.

In future, the purpose of bioenergy plants will probably no longer be to generate as much electricity as possible, but instead to be a flexible resource for levelling out fluctuations in wind and photovoltaic power generation. In heating applications, bioenergy will primarily be used in buildings which cannot be thoroughly insulated and where heat pumps alone cannot be efficiently used.

8 For example acatech/Leopoldina/Akademienunion 2018-1; BMWI 2017-2.

9 Conversion to heat pumps may, for example, be inadmissible due to architectural heritage protection requirements because radiators cannot be replaced with panel heaters without a change in appearance. Conversion to heat pumps in the general building stock may come up against the limits of possible investment, the feasibility of passing on costs (limit to maximum permitted increase in basic rent excluding heating) and of the acceptability of refurbishment (removal of radiators and installation of underfloor heating mean that a tenant has to move out).

Various studies attempt to categorise the use of bioenergy.[10] Depending on the assumptions made by the scientists, the optimum breakdown of bioenergy into different applications differs greatly between energy scenarios.11 The authors of most studies are in agreement, however, that bioenergy is an important energy carrier for achieving climate protection targets.

## 1.2 Bioenergy in global climate protection

In the long term, i.e. beyond 2050, bioenergy might play an additional role in the energy system that has not yet been taken into account in the national energy scenarios. Global climate protection scenarios show that it will only be possible to limit global warming to 1.5 or 2 degrees Celsius by 2100 if $CO_2$ is removed from the atmosphere over the coming decades.[12] This is because even if the world's energy supplies are completely converted to renewable sources, there will still be greenhouse gases from agriculture and some sectors of industry which will be very difficult to avoid. $CO_2$ removed from the atmosphere could compensate for these greenhouse gases. The climate protection scenarios analysed in the Intergovernmental Panel on Climate Change (IPCC) assessment reports mainly use bioenergy with carbon dioxide capture and storage (BECCS) for this reason. This works through plants capturing $CO_2$ from the air by photosynthesis and using it to form energy-rich carbon compounds. If these are used to generate electricity or heat or to produce motor fuel, this $CO_2$ is released again, but it is not discharged back into

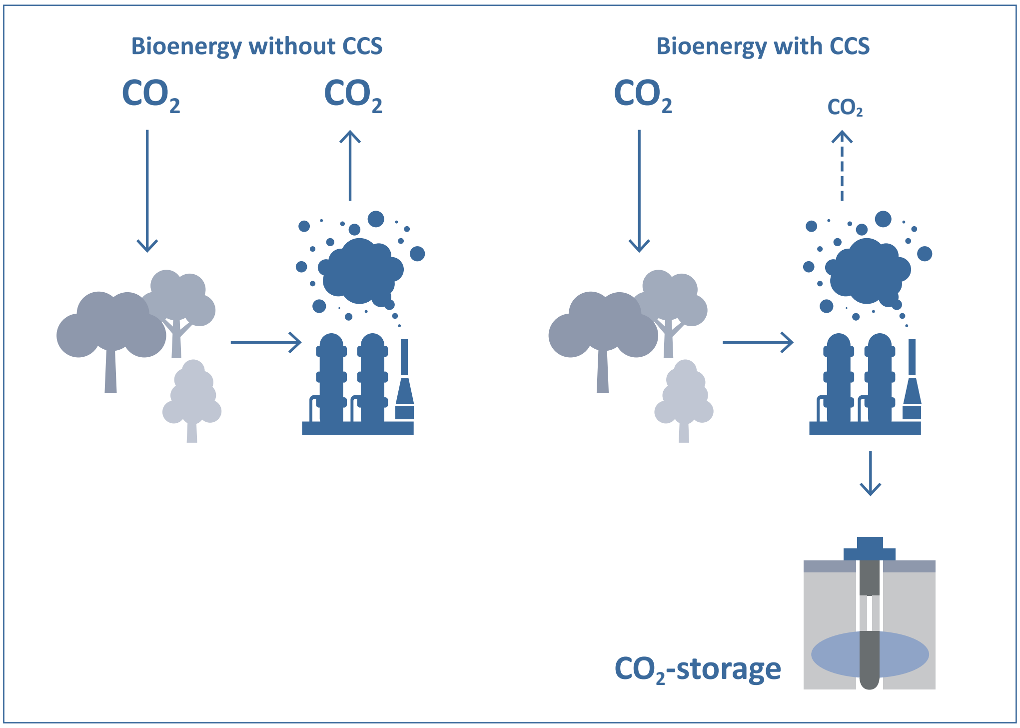


**Figure 1: Workings and carbon flows in bioenergy with and without CCS. Emissions from land use are not shown.**

10 A study into integrated energy systems, set up as part of the ESYS project, is using modelling *inter alia* to investigate the optimum use of bioenergy. The modelled, optimum cost scenarios for 2050 make industrial use of a large proportion of bioenergy. Further proportions are used for producing biofuels and for electricity and district heating in combined heat and power plants (acatech/Leopoldina/Akademienunion 2018-1).

11 Szarka et al. 2017.

12 UNEP 2017; easac 2018; IPCC 2018.

the atmosphere and is instead captured and put into permanent underground storage (Figure 1). The overall result is a reduction in the $CO_2$ content of the atmosphere and "negative emissions" are obtained. BECCS thus performs two functions: firstly providing energy and secondly reducing the content of $CO_2$ in the atmosphere.

Mainstream scientific institutions such as the IPCC have been talking for many years about the need for negative emissions and the potential of BECCS,[13] but it is a topic which has hardly featured in social and political discussion.

If this technology is to make a contribution to climate protection even approaching the order of magnitude set out in the scenarios, the first commercial plants will have to come into operation within the next ten to twenty years. When it comes to deciding for or against BECCS, it will also be necessary to take into account the potential, costs and risks of possible alternatives, such as large-scale afforestation.

## 1.3 Towards a long-term bioenergy strategy for Germany

Not only is bioenergy expected to be beneficial to the climate and to ensure a more sustainable energy supply, but society has other, sometimes inconsistent, expectations of the use of biomass in the energy system. For instance, there is public debate around the impact of energy crop cultivation on the landscape (unattractive maize monocultures) and on biodiversity in agricultural land. New sources of income for farmers, whose focus may move to the production of energy resources and the resultant wealth creation in rural areas are another main theme in the debate. Whether BECCS will be used in future depends to a great extent on society's acceptance of underground $CO_2$ storage, which has so far been very controversial in Germany. Considerable attention is also being paid to the question of whether bioenergy use should remain decentralised as in the past. While this would be preferred by the public, it is not really compatible with technically complex processes such as BECCS and fuel production, which will probably mainly be carried out in large plants to ensure economies of scale.

Climate protection and energy scenarios show technically how the energy supply can be made environmentally compatible and what role bioenergy can play in achieving this. These models cannot, however, take sufficient account of the differing ideas supported by various groups of stakeholders. However, the fact that new technologies can only gain a proper foothold if they are supported or at least tolerated by society results in uncertainty, which can put a brake on technological development and investment. A long-term bioenergy strategy must therefore take numerous technological, environmental, economic and social criteria into account. A debate within society is thus required.

This Position Paper initially addresses the question of how much bioenergy should be used for the German energy transition. Since biomass for energy, like biomass for other purposes such as food, feedstuffs or construction timber, is traded on a large scale internationally, the global impact of such trade must also be investigated. The second question to be discussed is how bioenergy can contribute to removing $CO_2$ from the atmosphere in the second half of this century. This topic, which has previously

13 For example Azar et al. 2006 and IPCC 2014.

received very little attention in the debate around bioenergy, is addressed in detail. Not only BECCS, but also further $CO_2$ removal technologies which can additionally or alternatively be used for compensating unavoidable greenhouse gas emissions will be examined.

The question will then be addressed as to what factors will have to be taken into account when transforming today's bioenergy use into future systems. This will be done by presenting a catalogue of criteria drawn up by an interdisciplinary group of experts under the auspices of the Academies' Project 'Energy Systems of the Future'. Two development pathways, one for biogas and one for wood and other lignocellulose, will be evaluated against the 29 criteria. These include technical criteria such as technological maturity and efficiency, system-related criteria characterising integration into the energy system and economic criteria such as energy production costs and the potential for regional wealth creation and employment. In addition to greenhouse gas emissions, environmental criteria including further emissions, land use and impact on biodiversity will also be taken into account. Social criteria include issues of equitable distribution, perceived autonomy, risk perception and possible harm to health (e.g. by fine particulates). The possibility of $CO_2$ capture from each development pathway will additionally be taken into account and investigated. Evaluation against the defined criteria shows the advantages and drawbacks of the various development pathways and reveals possible obstacles to implementation.

The next step involves using the results as the basis for identifying courses of action for ensuring a sustainable bioenergy strategy.[14] Priority areas here are a coherent climate protection policy and the interplay between energy, agricultural, resource and environmental policies. Proposals are also made as to how today's bioenergy use can be transformed stepwise until 2050 to meet the needs of the changing energy system, and how the debate in society can be appropriately shaped to this end.

14 The analyses and options presented relate to bioenergy use with modern technologies in Germany. Worldwide, a large proportion of bioenergy is used for cooking and heating in traditional fireplaces, which is harmful to both the environment and health (Thrän 2015).

# 2 How much biomass should be used for energy?

Germany imports and exports various biomass products, such as cereals for food and feedstuff production, meat and dairy products, wood and biofuels. International markets therefore inseparably link bioenergy use in Germany with global land use. Overall, the Federal Republic of Germany consumes more biomass than it produces and, for calculation purposes, can therefore be considered to make use of land area outside Germany.[15] Against this background, it makes no sense to define national bioenergy potential. A scientifically well-founded estimate of the volumes of bioenergy that can sustainably be used can only be made on a global level.

Only for residues and waste materials can potential be determined for Germany because, especially if they have high water content and low energy density, it is uneconomic to transport them over long distances. As a result, in contrast with other biomass, there is hardly any international trade in them. At present, at 0.54 exajoules (150 terawatt-hours) annually, residues and waste materials account for approximately half the total bioenergy used in Germany. Residues and waste materials yet to be used have a potential of approximately 0.39 to 0.68 exajoules (108 to 189 terawatt-hours) per year.[16] These are primarily forest wood residues[17], cereal straw and animal excrement[18]. Cereal straw has as yet barely been used as an energy source in Germany, but it could become more significant in the future.[19]

In Denmark, cereal straw has been used as an energy source for generating electricity and heat since the 1990s. In Germany, greater use of cereal straw has in particular been hindered in part by stricter emissions limits and requirements when using straw in comparison with wood and more costly plant engineering.[20]

Some 7 to 9 per cent of Germany's current primary energy requirement could be met with just residues and waste materials. If primary energy consumption can be reduced to 7.2 exajoules (2000 terawatt-hours) annually by 2050, which is the goal set

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15 Estimates of such "virtual land imports" sometimes differ considerably depending on the underlying data and calculation methodology. Lugschitz et al. 2012 conclude that Germany makes use of approximately four times its own agricultural area (77 million hectares) outside Germany. WWF 2011 estimates the demand for land generated by agricultural imports across the entire EU to be 30 million hectares, 6.4 million hectares of which are accounted for by Germany.

16 Brosowski et al. 2016.

17 Forest wood residues are, in general, any timber less than seven centimetres in diameter and raw wood which remains in the stand. It is thus made up of stemwood, including bark, branches and twigs, harvesting residues, roots and stumps and any adhering needles and leaves. The potential for forest wood residues here includes all harvesting residues from wood extraction, but disregards roots and stumps (Brosowski et al. 2015).

18 Definition of animal excrement: liquid and solid dung from animal husbandry (Brosowski et al. 2015).

19 Weiser et al. 2014.

20 Weiser et al. 2014; DBFZ 2012.

by the Federal Government's Energy Plan[21], residues and waste materials could meet as much as 13 to 17 per cent of primary energy requirements.[22]

The extent to which bioenergy from energy crops or forests can be used over and above this depends on the impact such use has on land use systems and on the global carbon balance. The most important interrelationships are explained below.

## 2.1 Global bioenergy potential

There is broad consensus that food production and material use have a higher priority than the production of bioenergy, and that areas of particularly high environmental value should be excluded from use.[23] In addition, deforestation must be ruled out since the $CO_2$ stored in forests would otherwise be released, thus having a harmful impact on the climate. Estimating future bioenergy potential therefore means that assumptions must be made as to how much land area will be required in the future for producing foods and products and which zones are reserved for protecting ecosystems.

Figure 2 provides an overview of land use and global biomass streams utilised by humans. The data shown date back to 2000, since no more recent consistent biomass and land balance data are available. The entire volume of harvested biomass has risen since 2000, but the overall picture, in particular with regard to land use and the orders of magnitude, as well as the interrelationships of the flows, should still be substantially valid.

Three quarters of global land area (apart from Greenland and Antarctica) is already being used by humans.[24] Unused land consists, on the one hand, of unproductive soils such as deserts, and on the other, of the last untouched primeval forests. Additional land area therefore cannot and should not be cultivated for bioenergy production. It thus follows that any expansion in land area for bioenergy production is only possible if in future a smaller area is required for other types of use or if combined use (e.g. simultaneous food and energy production) is possible.

Humans harvest a total of 233 exajoules of biomass annually. Half of this quantity is crop plants from arable land, one third is plants grazed by livestock and up to 16 per cent is harvested timber. More than half of the total quantity of biomass used is utilized as feed for livestock. In addition to grazed pastureland plants not directly edible by humans, some 50 per cent of the global cereal harvest is fed to livestock. Of 135 exajoules of biomass used as feed each year, only 5 exajoules (4 per cent) enter the human diet in the form of animal products, and the remainder are consumed by the animals or end up as a waste product.

21 UBA 2018.

22 The primary energy input required per kilowatt-hour of final energy will drop distinctly in a future energy system in which wind and solar systems are the dominant energy carriers. This is firstly because electricity from wind and solar systems is entered into the balance as primary energy. Primary and final energy therefore differ only slightly in their conduction losses. In contrast, when power is generated in combustion power plants, conversion losses mean that two to three kilowatt-hours of primary energy (combustion fuel) are required per kilowatt-hour of final energy (electricity). Secondly, technologies which use electricity (e.g. electric vehicles and heat pumps) are more efficient than technologies which use combustion or motor fuels (Ausfelder et al. 2017).

23 For instance, the German Bioeconomy Council recommends that biomass from agricultural land should primarily contribute to food security (Bioökonomierat 2012).

24 Erb et al. 2016.

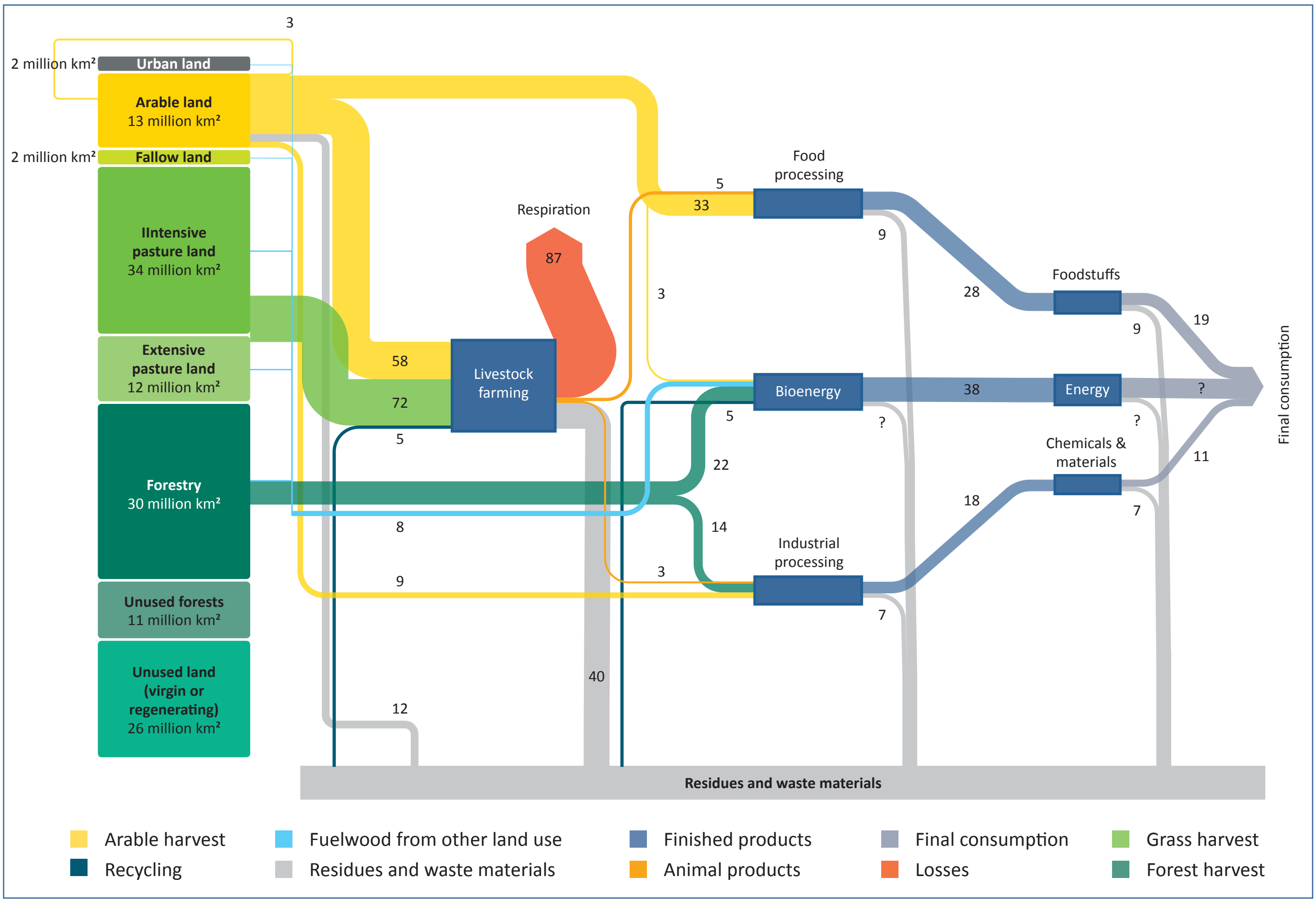


**Figure 2: Flow diagram of global harvested biomass flows in exajoules/year for 2000[25]:** the left-hand column illustrates the use of global land area.

It is clear from these figures that future dietary habits will have a huge influence on the demand for land for food production. It has, for instance, been calculated that, given a purely plant-based diet, the world could feed approximately twice as many people from the same land area as today.[26] This would free up areas which could be used for bioenergy production or other purposes. In the light of population growth and rising demand for animal foodstuffs in populous countries such as India and China, the Food and Agriculture Organization of the United Nations (FAO), however, is working on the assumption that global agricultural production will have to increase by 60 per cent over 2005 levels by 2050.[27]

It is likewise apparent from Figure 2 that less than half of the biomass harvested (84 exajoules per year) arrives with humans in the form of foodstuffs, energy carriers, chemicals and materials. At least as much biomass ends up as residues and waste materials which arise during harvesting and further processing.[28] A small proportion of this is used for energy, while some performs important functions in agriculture, for example by contributing to humification. Considerable quantities of foodstuffs are, furthermore,

25 Based on Smith et al. 2014 and data from Erb et al. 2007, Schneider et al. 2009, FAO 2010, Wirsenius 2003, Sims et al. 2006, Krausmann et al. 2008, FAOSTAT 2012 and Kummu et al. 2012.

26 Erb et al. 2016.

27 These estimates are based on a forward projection of current trends and may therefore differ greatly from reality (Alexandratos/Bruinsma 2012).

28 Residues arising for energy use have not hitherto been quantified, so a question mark hangs over them.

discarded by consumers, approximately 70 to 90 kilograms per capita annually in Germany.[29] Reducing food waste is therefore an important lever for reducing land-use pressure.[30] Considerable volumes of plant and timber harvesting residues remain in the field or on the forest floor where they help, among other things, to fertilise the soil and maintain biodiversity (e.g. saproxylic beetles). If they were removed from the ecosystem to produce energy, it would have to be ensured that the nutrients (nitrogen, phosphorus[31], potassium) were recovered and returned to the ecosystems, because making up for nutrient losses with chemical fertilisers would increase costs and have a negative impact on the environment.[32]

Since 2000, global bioenergy production has risen from 38 to approximately 50 to 60 exajoules per year. The majority (87 per cent) of this originates from wood, which is predominantly used in developing countries as firewood and charcoal in traditional fireplaces. These are usually very inefficient (up to 90 per cent of the energy in an open fire is wasted) and, moreover, extremely harmful to health due to high levels of smoke in living areas.[33] At 7 to 8 per cent, energy field crops play more of a subordinate role.[34]

Table 1 provides an overview of estimates of global bioenergy potential to 2050 and the most significant influencing variables. This overview draws a distinction between cultivated biomass[35] from arable and pasture land, biomass from forests and residues and waste materials. Arable and pasture land can be used to grow not only conventional energy crops such as maize, sugar cane and oilseed rape, but also grasses such as elephant grass (miscanthus) and fast-growing species of energy wood. Grasses and energy wood plantations are preferable from an environmental standpoint since they require less fertiliser and also grow on poorer soils (for instance on degraded land). The divergences between different estimates for agricultural biomass potential are substantially greater than they are for forest wood and residues and waste materials. This is due to the greater levels of uncertainty with regard not only to future increases in yield, but also to future requirements for biomass for food and feedstuff production (depending on dietary habits and population trends).

The production of biofuels from algae remains a hot topic for research and development and is also being driven forward by business. At present, however, the focus is moving away from energy use and more towards material use of algae. This is because production capacity for algal biomass currently remains too low, resulting in relatively high production costs which make it necessary to produce higher priced products to ensure economic viability.[36] In addition, the energy requirements for culturing and

29 Kranert et al. 2012, p. 16.

30 Muller et al. 2017.

31 Phosphorus supplies are not unlimited and it is classified by the EU as one of the twenty critical raw materials. Continuous monitoring of deposits and recovery of phosphate from clarifier sludge could help to secure supplies (acatech/Leopoldina/Akademienunion 2018-2).

32 OECD/IEA 2017; WBA 2017.

33 REN21 2016.

34 WBA 2017.

35 Cultivated biomass is defined as plants which are agriculturally cultivated for energy use.

36 The production costs for algal biomass are estimated at 480 to 20,100 euros per tonne of dry solids (based on Sun et al. 2011, Norsker et al. 2011, Benemann 2013 and unpublished calculations made by DBFZ in 2011). They are thus distinctly above the level of producer prices for internationally traded raw materials such as oilseeds (oilseed rape) of around 329 euros per tonne of dry solids or wheat of around 169 euros per tonne of dry solids (Thrän/Pfeiffer 2015).

processing in algal production plants using current technology are so high that the energy balance would appear to be unfavourable for producing energy.[37]

| | Estimate of global potential to 2050 (exajoules/year) | Major influencing factors |
|---|---|---|
| Cultivated biomass from arable and pasture land | 30 to in excess of 1,000 (most more recent studies estimate sustainable potential to below 200 EJ) | • Forecast food requirements (population growth, type of diet)<br>• Forecast increases in yield for crop plants<br>• Lack of data certainty for pasture land |
| Forest (excluding timber residues) | up to 40[38] | • Unanswered questions regarding carbon balance<br>• Trends in demand for material use (e.g. construction timber)<br>• Success in stopping global deforestation (if global deforestation is stopped, wood supplies will decline in future) |
| Residues and waste materials | 40 to 140[39] | • Assumptions as to what proportion of agricultural residues should remain on the field to maintain soil quality and carbon sinks<br>• Assumptions regarding future agricultural production |

Table 1: Estimates of global bioenergy potential

**Potential from arable and pasture land**

Estimates diverge the most as far as estimates for the bioenergy potential of pasture and arable land are concerned. High estimates of several hundred exajoules per year are mainly based on the assumption that it will be possible to achieve very major increases in agricultural yields (including for livestock). In some cases, yields are assumed which are almost four times present average above-ground biomass production.[40] These increases in yield are, however, in future at best possible by increased intensity of cultivation, irrigation and fertilisation. In particular in developing countries, this is difficult to achieve and can, moreover, have a negative effect on the environment and biodiversity.

There is also great data uncertainty in relation to land use. For instance, according to some studies, there are large areas of fallow land which could be used to cultivate energy crops. Other studies, however, assume that these areas are already used as pasture land and are therefore either not straightforwardly available or often not available at all.[41]

37 There are currently various processing factors in algal production which require energy optimisation (Rocca et al. 2015). These include pump capacity, harvesting and dewatering and selection of the nutrient medium from an energy standpoint (Slade/Bauen 2013).

38 40 EJ/a corresponds to current use. With regard to the significance of forests for biodiversity and the uncertainty regarding the carbon balance for the use of wood for energy (see section 2.2), it is questionable to which extent forest wood (excepting timber residues) can be used for energy sustainably.

39 12–39 EJ/a forest wood residues, 9–39 EJ/a animal excrement, 46–67 EJ/a agricultural residues (of which 19–40 EJ/a are required for animal feed and traditional use), 11–17 EJ/a refuse.

40 Possible increases in yield are the subject of much controversy (see also Klepper/Thrän 2019, section 2.2.1). While it has been possible since the 1960s to increase yields of individual plants by up to 80 per cent, the rate of increase has flattened off in recent years. In addition, there are physical upper limits to maximum possible production (Leopoldina 2013). Mueller et al. (2012) estimate that production of the most important agricultural crops could be increased by 45 to 70 per cent if the gap is closed between actual yields and the yields which might be achievable using current technology (varieties, cultivation methods etc.). The extent to which technically possible sustainable increases in yield can be implemented is, however, also always dependent on the political and social situation. It must also be borne in mind that agricultural intensification, in particular increased use of fertilisers, can cause higher greenhouse gas emissions and greater environmental impacts. Approaches such as precision farming can assist in making intensification more sustainable.

41 Erb et al. 2009.

Reliable estimates for long-term agricultural bioenergy potential are not possible due to data uncertainty and imponderables in terms of food requirements and increases in yield. Comparing various studies nevertheless suggests that making larger-scale use of agricultural biomass for energy will only be sustainably possible if a diet involving lower meat consumption is adopted in the future. Meat consumption in industrialised nations must fall and the trend towards increasing meat consumption in developing and emerging nations must be curbed if this is to happen. This would also open up greater latitude in land use, for example, for expanding organic farming.

**Potential from wood**

At approximately 40 exajoules per year, wood biomass (excluding woody residues and waste materials) accounts for the greatest proportion of today's bioenergy use.[42] The extent to which biomass from forests should be used to produce energy is, however, contentious,[43] because forests sequester large quantities of carbon. Intensifying use reduces carbon stocks, resulting in the release of additional $CO_2$ and greater climate change. In contrast, if timber harvesting from an intensively managed forest is reduced, carbon stocks in the forest can increase and $CO_2$ is then removed from the atmosphere. After several decades or centuries, however, unmanaged forests will reach a state of equilibrium in which, despite storing large quantities of carbon, they cease to be net absorbers of further $CO_2$, and growth is balanced by the rotting of dying plant material. Many managed forests are, however, far from this equilibrium state. If forest wood is used for producing long-lived products (e.g. for buildings), the carbon present in the wood is sequestered for the service life of the products which is thus one option over and above the storage capacity of the forest for the long-term removal of carbon from the atmosphere. Such carbon storage in products must be taken into account in the overall environmental balance. The impact of using wood to produce energy on the carbon balance of forests is the subject of controversy.[44] The crucial factor here is particularly the definition of system boundaries and observation periods which, however, always involve subjective value judgements (see section 2.2).

It is accordingly extremely difficult to put a figure on how much forest biomass can be sustainably used. In addition to the unresolved carbon balance issues, it must also be borne in mind that forests play a central role in maintaining biodiversity. Tropical rain forests are the most species-rich ecosystems on earth, but there are high levels of biodiversity even in Central Europe's forests.[45] In addition, forests store and purify rainwater and thus assist in securing drinking water supplies. The quantity of wood which can be used to produce energy is furthermore dependent on trends in requirements for material use (e.g. construction timber). Since wood can replace energy- and $CO_2$-intensive materials such as steel-reinforced concrete,[46] wood will increasingly be required to produce climate-friendly materials. Overall, it is therefore questionable whether increasing current bioenergy use from forest stands is sustainably possible.

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42 Bais et al. 2015.

43 Bentsen 2017.

44 One methodology for evaluating the conflicts of interest between wood use and increasing forest carbon stocks for various types of forest management is explained in Pingoud 2018 by reference to the example of forests in southern Finland.

45 UFZ 2015.

46 IPCC 2014, chapter 11.

**Residues and waste materials**

In contrast, waste from timber cutting and processing and waste wood offer reliable, sustainable potential. Using wood first as a material and only later to produce energy ("cascade use") reduces competition for its use and increases its added value.[47] However, timber residues are generally already very efficiently used, for instance, for producing particle board. Increasing demand for residues above existing levels of supply can ultimately lead to increased cutting.

In addition to timber residues, it is also possible to put agricultural residues (e.g. straw), animal excrement and household waste to use as energy sources. It should be considered that agricultural residues are to a certain extent already being used as animal feed or as a replacement for fuelwood. In addition, some of the harvesting residues must remain on the field in order to maintain soil fertility and carbon sinks. This kind of energy use can thus compete with previous types of use or help achieve other environmental goals. In addition, residues and waste materials (e.g. waste wood) can contain pollutants which must be removed during energy use so that they do not get into the environment. Despite these limitations, using residues and waste materials for energy is far less problematic from an environmental standpoint than using forest wood and energy field crops. Moreover, there is a high level of social acceptance in Germany for using residues and waste materials.[48] Overall, 5 to 20 per cent of global energy requirements could be covered with residues and waste materials.[49]

## 2.2 Greenhouse gas balance of bioenergy

Since the aim of using bioenergy is to avoid greenhouse gas emissions, this is an important evaluation criterion. Estimating the contribution made by bioenergy to climate protection entails recording as completely as possible the greenhouse gas balance over the entire life cycle. The greenhouse gases which arise from the provision and conversion of biomass must then be offset against the savings of fossil fuels which are replaced by bioenergy. Greenhouse gases are generated during agricultural management and during conversion into and the application of useful energy. Such 'process' emissions can be relatively readily recorded because direct measurements can be made for most relevant processes. International standards (ISO 14040/44) provide standardised life cycle assessment rules for determining the level of greenhouse gas emissions. One of the aims of these industry standards is to ensure comparability.

On the other hand, demand for bioenergy can result in changes in land use, for example, when cultivating energy crops or with increased extraction of wood from forests. This changes the quantity of carbon stored in vegetation and soil. Reducing carbon sinks leads to the release of greenhouse gases. Some of these effects cannot be measured, but only estimated on the basis of modelling, in which case the particular calculation methods used and assumptions made have a major impact on the results. This applies in particular to indirect land use changes (ILUCs). ISO 14040/44 does not take into account GHG emissions from ILUCs. The approach of using predictions for

47 UBA 2014.

48 Wüste 2012.

49 In 2016, global primary energy demand amounted to 560 exajoules, and by 2040, it could rise to some 700 exajoules per year if the climate protection measures announced by governments are implemented (IEA 2017, p. 79, New Policies Scenario).

the future based on assumptions, which is the approach used for ILUC modelling, has not previously been compatible with the nature of a standard.[50]

Various approaches for determining GHG emissions from ILUCs are the subject of some controversy. There should, however, be no yielding to the temptation to make a blanket assumption of zero emissions due to a lack of data, because this would virtually always be incorrect.[51] Despite the existing uncertainty, however, some sources of biomass can be considered to involve a low ILUC risk. This includes, inter alia, residues and waste materials and biomass grown on previously unused land (see also section 5.2.1).

#### Process emissions

The largest emissions source in the production of agriculturally-cultivated biomass is the use of nitrogen fertilisers,[52] since the application of such fertilisers results in part in emissions of nitrous oxide (N2O), a strong greenhouse gas. The level of nitrous oxide emissions varies greatly depending on plant species, site conditions and the quantity, type and timing of fertilisation.[53]

However, many common life cycle assessment models only have a very simplified view of nitrous oxide formation which assumes default emission factors for the proportion of nitrogen fertiliser that becomes nitrous oxide. As a result, in these models, nitrous oxide emissions always rise linearly with rising quantities of fertiliser. Recent studies indicate that the default values[54] recommended by the IPCC overestimate nitrous oxide emissions for oilseed rape.[55] A more precise recording of nitrous oxide emissions would therefore be desirable. As a first step, measurement programmes would be required in order to determine specific values for various crops and soil/climate areas.

The significant factors which come into play in the conversion of biomass into energy are primarily the provision of process energy using fossil energy carriers and the use of further auxiliary and working materials. In addition, certain processes can give rise to further direct emissions, for example, the greenhouse gas methane can escape during biogas production.

The statutory provisions of the EU Renewable Energy Directive (RED) have meant that the determination of process emissions, in particular for biofuels, has come to be of relevance in recent years. Numerous publications have appeared which contain calculations of the greenhouse gas emissions or savings involved in the provision of various biofuels. An evaluation of various international studies reveals the broad ranges set out in Table 2. The sometimes large ranges are attributable not only to differences in the raw materials and residues used, but also to the selected allocation methods and system boundaries and the assumptions made for biofuel concepts still in development.[56]

50 Finkbeiner 2014.
51 Plevin et al. 2010; Plevin et al. 2014.
52 Creutzig et al. 2015.
53 Creutzig et al. 2015, p. 925.
54 IPCC Tier 1 method (IPCC 2006).
55 Ruser et al. 2017.
56 Mueller-Langer et al. 2014.

| Biofuel | Kilogram $CO_2$ equivalents/GJ |
|---|---|
| Biomethane from residues and waste materials | 3–55 |
| Bioethanol from lignocellulose | 0–32 |
| Biodiesel from various oil crops | 8–78 |
| Fossil reference (mix of petrol and diesel) | 84 |

Table 2: GHG process emissions for various biofuels based on Mueller-Langer et al. 2014

#### Repercussions on carbon sinks in vegetation and soil

Combusting biomass initially gives rise to approximately as much $CO_2$ per unit of energy provided as does combusting coal. Obtaining energy from biomass is thus only $CO_2$ neutral if the emissions arising during combustion and the preceding harvest[57] and upgrading stages (today mainly using fossil energy carriers) are offset by plants and soils absorbing additional $CO_2$. This is only the case if the combusted plants are either those which have grown in addition to the plants which would have grown in the absence of bioenergy, or those which would otherwise have been quickly biodegraded, as a result of which the $CO_2$ would have been released without any energy gain.[58]

The quantity of carbon stored in vegetation and soil depends on the type of vegetation. In general, land used by humans stores less carbon than is stored in natural vegetation.[59] If demand for bioenergy results in the exploitation of previously unused land with natural vegetation, in particular virgin forests, there is therefore a risk that the stored quantity of carbon will be reduced and $CO_2$ released. Determining the influence of bioenergy use on the global carbon balance entails a reference scenario which describes how vegetation would have developed in the absence of bioenergy use. Calculating the greenhouse gas savings achieved by using bioenergy also entails a reference scenario which describes how the amount of energy would have been generated without bioenergy, i.e. which fossil energy carriers the bioenergy displaces. Selection of the reference scenarios can have a major influence on the results.

In the case of cultivated biomass, forest clearance can in particular greatly reduce the contribution to climate protection. A distinction is made here between direct and indirect land use changes. If a forest is cleared and the same area used for cultivated biomass, this a direct land use change. Greenhouse gas emissions due to such direct land use changes are measurable and already taken into account in the certification of biofuels (Renewable Energy Directive 2009/28/EC). Indirect land use changes (ILUC) describe market-based feedback effects which result in bioenergy cultivation on one area causing a land use change on another area. If, for example, an area of agricultural land on which crops for producing food and feedstuffs have previously been grown is used for growing bioenergy crops, this can result in forests being cleared at another location in order to develop new areas for the production of food and feedstuffs. These

57 An increased harvest can modify the soil water balance and consequently lead to emissions of the greenhouse gases methane and nitrous oxide (Bentsen 2017). Account must also be taken of effects on the carbon balance of the soil. For instance, an increase in the temperature of forest soil after clear-cutting can result in $CO_2$ emissions because of soil carbon breaking down more rapidly (Covington 1981; Hararuk et al. 2017).

58 According to the accounting rules of the United Nations Framework Convention on Climate Change (UNFCCC), separate accounts are kept for emissions from the energy system and from land use. For example, if a forest is cleared in order to produce bioenergy, the carbon degraded in the forest is counted as a $CO_2$ emission from the land use sector and not from the energy sector.

59 Recent research results show that, globally, the current vegetation, which largely consists of forests, pasture and agricultural land used by humans, stores only around half as much carbon as would be sequestered in natural vegetation untouched by humans. It can be calculated that, without land use, an additional 466 gigatonnes of carbon (corresponding to 1,700 gigatonnes of $CO_2$) could be sequestered under today's climatic conditions (Erb et al. 2018).

indirect land use changes are not verifiable because it is not possible to establish the extent to which, for example, deforestation was caused by the demand for bioenergy. Various approaches to determining GHG emissions from ILUCs have been the subject of much controversy among scientists since the end of the first decade of the current millennium.[60] As a consequence, indirect land use changes are the greatest problem in estimating greenhouse gas emissions for energy carriers obtained from agricultural biomass.

The slow growth cycles of trees must be taken into account when it comes to establishing the carbon balance for forest biomass. It may accordingly take several decades before released $CO_2$ has been sequestered again by the vegetation. Even if the same quantity of timber regrows as was extracted, it cannot therefore simply be assumed that the bioenergy obtained is $CO_2$ neutral. Instead, the greenhouse gas balance depends on the observation time frame.[61] Experts speak of a 'carbon debt' which must be paid back before bioenergy truly contributes to abating emissions by displacing fossil energy carriers. In particular with regard to short- and medium-term climate protection targets, for instance for 2030 or 2050, the 'carbon debt' can considerably reduce bioenergy's potential contribution to climate protection. Estimates of the carbon debt vary greatly depending not only on climatic conditions and the type of forest management, but also on the calculation methodology used.[62] The range extends from the position that the $CO_2$ payback time[63] for the use of bioenergy from forest biomass is in many cases negligible to doubts as to whether using forest products for producing energy makes any contribution at all to climate protection.[64] Using thinnings is generally regarded as less harmful than using entire stemwood compartments for making energy directly.[65]

To summarise, bioenergy offers considerable potential for making greenhouse gas emission savings in the following cases:

- If waste and residues are used which would otherwise decompose (possibly emitting methane) or be combusted without energy recovery.

- If wood is put to co-product and cascade use. Co-product use involves using high quality fractions (roundwood) for use as a material and using lower quality fractions (e.g. thinnings) to produce energy. Cascade use initially involves putting wood to use as a material and, at the end of the products' service life, using it to produce energy.

- If degraded agricultural land is used for growing bioenergy crops, in particular, if carbon is accumulated in the soil as a consequence (e.g. by perennial grasses or woody plants).

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60 Finkbeiner 2014; Wicke et al. 2014.

61 It must also be borne in mind that the ideal time for felling trees in forest management terms is precisely when they are growing strongly (at around seventy years in Central Europe). As it regrows, a new-growth forest absorbs less $CO_2$ in the initial years than the older forest would have absorbed (had wood not been extracted). After some decades, however, the older forest would approach saturation and then absorb only little, and in the long term, no additional $CO_2$ from the atmosphere. In contrast, the younger forest (after wood extraction) would continue to remove $CO_2$ from the atmosphere for significantly longer.

62 Bentsen 2017.

63 The $CO_2$ payback time is the time which is required for the carbon debt to be settled. It is only from this moment onwards that bioenergy, viewed over its entire lifetime, truly contributes to $CO_2$ savings.

64 Naudts et al. 2016; Bentsen 2017.

65 See for example Forest Research 2018.

- If, for example thanks to additional income, bioenergy production enables a cultivation management which achieves higher yields. Therefore biomass for energy is produced in addition to the previous land use.[66]

- If land and vegetation are managed in such a way that they absorb more $CO_2$ than they would absorb without bioenergy use (taking account of indirect land use effects). One example is cultivating fast-growing tree species such as poplars or willows (short rotation coppices) on pasture land.[67]

- If nitrogen fertiliser requirements are as low as possible.

- If there is an optimum ratio between nitrogen fertiliser inputs and biomass yields, and nitrous oxide emissions due to nitrogen losses are kept as low as possible.

The greenhouse gas savings which are actually achieved also depend on which fossil energy carriers the bioenergy replaces. If coal is replaced, the $CO_2$ savings are greater than if oil or natural gas are replaced.

The question, furthermore, arises as to whether a greater contribution to climate protection might be made by alternative forms of land use (e.g. afforestation) than by cultivating biomass for energy production. The contribution to climate protection made by replacing natural gas, oil and coal with biomass should therefore be set off against possible $CO_2$ uptake due to an increase in carbon stocks in vegetation. In many forests in OECD countries, for example, carbon stocks are much lower due to intensive forestry and earlier overexploitation than they would be in a natural, unmanaged forest.[68] These forests could therefore absorb large volumes of additional $CO_2$.[69] Instead of extracting wood for energy use, it could therefore also be left in the forest and so possibly make an equally large or even greater contribution to climate protection.

Integrated approaches to forest use in which forest biomass is put to use as both materials and energy are, however, capable of offering the greatest benefits. In this case, three mechanisms can contribute to reducing greenhouse gases: firstly, materials such as steel and concrete, the production of which causes very high greenhouse gas emissions, can be replaced by wood. Secondly, carbon can be stored for an extended period of time, for example, as construction timber in buildings. And thirdly, wood products at the end of their service life and secondary products from timber harvesting can be put to use as energy and replace fossil energy carriers.[70]

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66 It must, however, be verified on a case-by-case basis whether the increase in yield is genuinely achieved thanks to bioenergy production, or whether it would have occurred anyway due to general progress in agricultural practices. This can be demonstrated, for example, by comparing the increases in yield which are achieved with bioenergy production with average historical increases in yield (Ecofys 2016).

67 Haberl et al. 2012.

68 This does not always apply, however. It has, for instance, been shown that a Siberian coniferous forest stores less carbon on average than a commercial forest (Korpel 1995, p. 295).

69 Creutzig et al. 2015, p. 928.

70 IPCC 2014, chapter 11; Schulze et al. 2019.

## 2.3 Conclusion

The bioenergy potential from residues and waste materials can be relatively reliably estimated and involves only slight risks to ecosystems and food security. Exploiting previously unused potential could therefore allow Germany to meet some 10 to 15 per cent of its future primary energy requirements.

In contrast, when it comes to the use of agricultural commodities and forest wood (other than forest wood residues), the potential for sustainable use is very uncertain since complex effects on global land use systems have to be taken into account. However, some of these are largely unquantifiable since some indirect effects cannot be measured but only estimated on the basis of modelling, in which case the particular calculation methods used and assumptions made have a major impact on the results. Various approaches for determining GHG emissions from ILUCs and the carbon debt are the subject of some controversy. The contribution to climate protection of making energy from agricultural biomass and forest wood is therefore unclear.

Given the uncertainties and environmental risks associated with using cultivated biomass, greater efforts should instead be made to use bioenergy based on residues and waste materials. Latitude for making greater use of agricultural biomass for energy can only be expected if global meat consumption is significantly reduced. Substantially increasing the use of forest wood for supplying energy could reduce carbon sinks in forests and jeopardise important functions of forest ecosystems. In terms of the environmental impacts, it therefore makes little sense to do so.

If bioenergy use is to be sustainable, the role of bioenergy in the energy and land use systems must be taken into account. Monitoring and controlling the use of biomass for energy is thus becoming a cross-sectoral issue which requires close alignment between climate, energy, agricultural and environmental policies. In the long term, it would therefore be desirable to have a toolkit which views climate and ecosystem protection and social aspects of food security as an integrated system. Only if environmental, social[71] and economic aspects are taken into account can bioenergy be used in an environmentally and socially responsible manner.

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71 Important social aspects which are debated in connection with bioenergy are land rights and access to foodstuffs.

# 3 What is the significance of long-term climate protection targets to the future of bioenergy?

Climate protection scenarios from global integrated assessment models[72] (IAM) reveal that in future technologies which can remove $CO_2$ from the atmosphere will probably be required. Achieving the 2°C target, and even more so the 1.5°C target, will be very difficult to virtually impossible without these technologies. If these technologies are to be available in sufficient quantity, they must be developed soon. On the one hand, this is because unavoidable emissions have to be offset, in particular, nitrous oxide ($N_2O$) and methane from agriculture and some process-related emissions from industry. On the other hand, the total remaining $CO_2$ budget for humanity will be exceeded in the first half of the century unless GHG emissions from the energy and transport sector are quickly reduced to a sufficient extent. These excess emissions will then also have to be removed from the atmosphere again.

$CO_2$ removal is not in any way able to replace the move away from fossil energy carriers and towards a reduction in energy consumption but merely to supplement it. Emissions of greenhouse gases must in any event be reduced far more quickly than has so far been the case. Taking a scenario for the 2°C target by way of example, Figure 3 shows how the entire global $CO_2$ budget can be met through an interplay between $CO_2$ avoidance and $CO_2$ removal.

In the example scenario shown in Figure 3, $CO_2$ avoidance technologies will bring about a turnaround in greenhouse gas emissions in around 2020: annual $CO_2$ emissions will decline rapidly from this point forward. $CO_2$ removal technologies will begin to be used in around 2030. Initially, however, annual $CO_2$ removal will still be below $CO_2$ emissions. While there will indeed be gross negative emissions, the net emissions, i.e. the difference between emissions and removal, will still be positive. However, these net emissions will drop more rapidly thanks to $CO_2$ removal. In the following decades, $CO_2$ removal technologies will become more and more widespread and the annual $CO_2$ removal volume (negative emissions) will rise. At the same time, greenhouse gas emissions from energy generation, industry and agriculture will continue to fall. The reductions will apply more to $CO_2$ than to the other greenhouse gases. In around 2090, greenhouse gas neutrality will finally be achieved, meaning that just as much $CO_2$ will be being removed from the atmosphere as is being emitted. At the end of the century, net negative emissions will then be achieved, i.e. more $CO_2$ will be removed from the atmosphere than is be being emitted. As a result, the $CO_2$ content in the atmosphere will decline again. Achieving the 1.5°C target would entail bringing forward the point in time at which greenhouse gas neutrality is achieved and relatively large volumes of net negative emissions would have to be achieved in the second half of the century.

72 IAM scenarios are computer simulations which model the interrelationships between socioeconomic development, developments in the energy system, emissions of greenhouse gases, their concentration in the atmosphere and the resultant temperature changes. IAMs contain at least one climate model and one economic model (e.g. a general equilibrium model) as submodels. Many IAMs are optimisation models which, within specified constraints, seek out the cost-optimal development pathway for achieving a given climate protection target. They view time frames of several decades, often up to 2100.

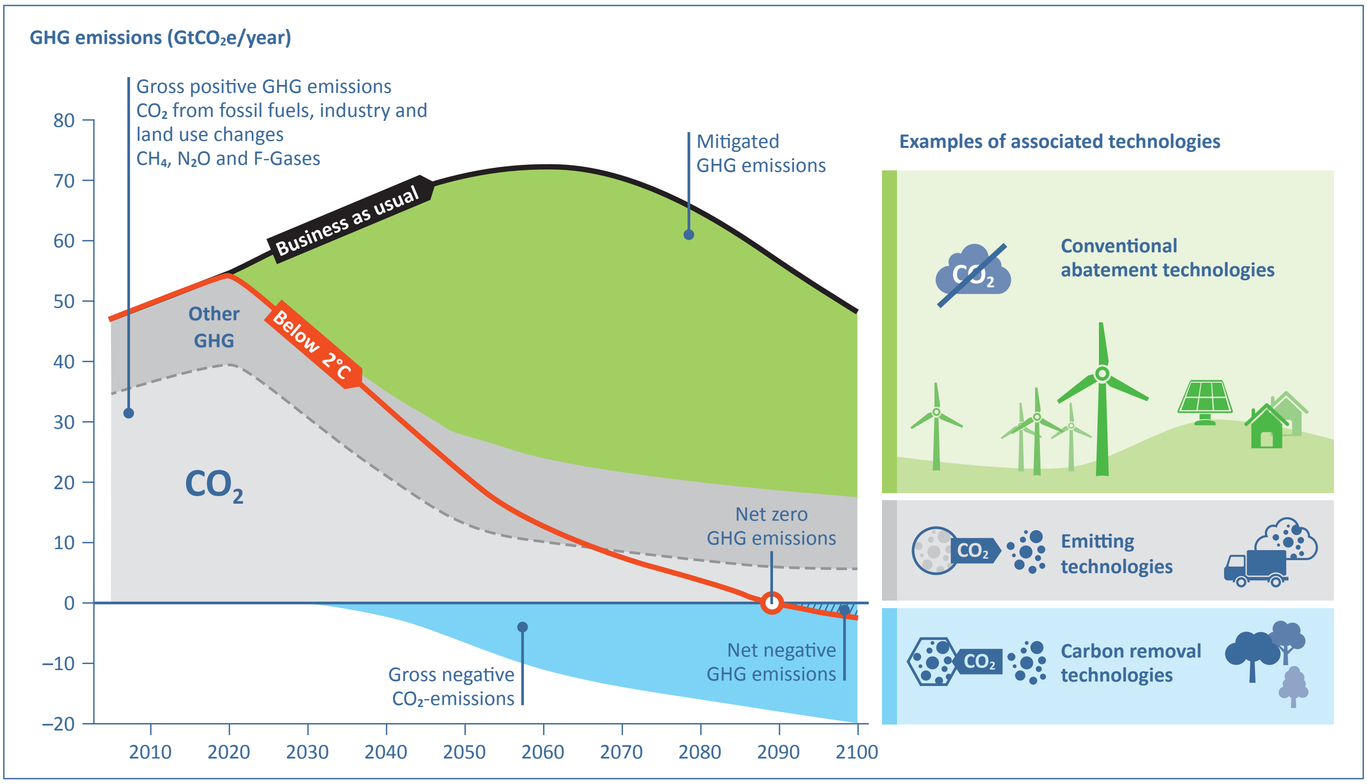


**Figure 3: $CO_2$ avoidance and negative emissions for achieving climate protection targets.** There is a probability of at least 66 per cent that this scenario will result in global warming being limited to below 2°C above pre-industrial temperature levels. Global $CO_2$ emissions will be reduced by approximately 90 per cent in comparison with today's values. Since the remaining greenhouse gases are difficult to avoid, they are offset by removing $CO_2$ from the atmosphere. At the end of the century, there will be net negative emissions, i.e. more $CO_2$ will be removed from the atmosphere than greenhouse gases are emitted. $CO_2$ removal technologies are, however, set to come into use as early as around 2030. (Diagram based on UNEP 2017).

Since it has not proved possible to achieve sufficient reductions in global emissions over the past twenty years, a major part of the global $CO_2$ budget has already been used. On the basis of current knowledge, $CO_2$ removal technologies would therefore appear to be indispensable in achieving climate protection targets. In not one climate protection scenario calculated thus far has it been possible to keep global warming to below 1.5°C by 2100 without $CO_2$ removal technologies.[73] While the need for $CO_2$ removal can indeed be greatly reduced if very optimistic assumptions are made about technological progress and climate-friendly consumer behaviour, it cannot be completely avoided.[74] In 99 of 116 climate protection scenarios analysed in the IPCC AR5 status report, net-negative emissions will be required in the second half of the century even to achieve the 2°C target.[75] The later the emissions peak and the slower the decline, the greater the need for negative emissions will be. In no case are the nationally determined contributions (NDCs) set out in the Paris Climate Agreement sufficient to achieve the 2°C target without net-negative emissions.

**How can Germany become greenhouse gas neutral?**

In the course of the negotiations on the governance regulation, in January 2018, the European Parliament called for net greenhouse gas emissions in the EU to be reduced

73 UNEP 2017, p. 60.

74 The analysis covered, among other things, the impact of a very rapid further development and reduction in cost of renewable energy sources, storage technologies and energy efficiency, wide-ranging changes in consumer behaviour (lower meat consumption, use of more environmentally friendly means of transport, less heating and air conditioning), intensification of livestock farming and cereal cultivation and the introduction of cultured meat as a foodstuff (Vuuren et al. 2018).

75 IPCC 2014, chapter 6, figure 6.31.

to zero by 2050 in line with the Paris Agreement, and for $CO_2$ to be captured from the atmosphere shortly afterwards in order to limit global warming to 1.5°C by 2100. The final version of the governance regulation stated that the EU was aiming to bring about a greenhouse gas neutral economy 'as soon as possible'. By April 2019, the Commission is due to put forward scenarios which analyse how to achieve greenhouse gas neutrality by 2050 and net-negative emissions afterwards.[76]

Optimistic scenarios for Germany forecast unavoidable emissions in an amount of at least 60 million tonnes of $CO_2$ equivalents per year for 2050 and beyond.[77] These are made up of approx. 14 million tonnes of $CO_2$ equivalents from industry (above all the cement and lime industry); 35 million tonnes of $CO_2$ equivalents from agriculture; 8 million tonnes of $CO_2$ equivalents from land use, land use changes and forestry; and 3 million tonnes $CO_2$ equivalents from waste and wastewater. These scenarios presuppose, for example, a complete changeover by the energy and transport sector to renewable energies and a halving of energy consumption in households, transport, industry and in commerce, trade and services relative to 2010. Further underlying assumptions include a 25 to 55 per cent reduction in meat consumption, a substantial expansion of electric steel production and a complete changeover by the chemical industry to renewable carbon sources[78] by 2050. Actual emissions might therefore prove to be higher.

If net greenhouse gas emissions are to be reduced to zero, emissions must be captured from the atmosphere in a volume at least as high as unavoidable emissions. If there are remaining emissions from other sectors, it is important to use $CO_2$ removal technologies to a still greater extent. While industry-related emissions can be abated using conventional carbon (dioxide) capture and storage (CCS) technology,[79] emissions from other sectors which do not occur in a locally concentrated form require technologies which are capable of absorbing $CO_2$ from the air. In comparison with the previous climate protection targets for the EU and Germany of cutting $CO_2$ emissions by 80 to 95 per cent relative to 1990, complete greenhouse gas neutrality may therefore require $CO_2$ removal technologies to be added to the toolkit.[80]

## 3.1 Comparison of various $CO_2$ removal options

Various methods can be considered for $CO_2$ removal; Table 3 provides an overview. In addition to the mode of operation and advantages and drawbacks of the various methods, the table also states how much land area or energy might, for example, be necessary for offsetting unavoidable emissions in Germany.[81]

76 Regulation (EU) 2018/1999.

77 For example the study 'Treibhausgasneutrales Deutschland im Jahr 2050' (UBA 2015).

78 In the short to medium term, it is primarily biomass and, in the long term, also $CO_2$ which are possible renewable carbon sources.

79 This involves capturing $CO_2$ from flue gases for example.

80 Various studies have concluded that in Germany, on the basis of current knowledge, some 60 million tonnes of $CO_2$ equivalents, for the most part from agriculture, are largely unavoidable (UBA 2015; BMWI 2017-2: report module 10.a). Abating greenhouse gases by more than 95 per cent relative to 1990 would thus require the use of $CO_2$ removal technologies.

81 The unavoidable emissions from UBA 2015 were used as the basis. For methods using CCS (BECCS and direct air capture), it was assumed that the 14 million tonnes of $CO_2$ from industry were directly captured at the source, and therefore only 46 million tonnes of $CO_2$ were needed to be absorbed from the air. For the other methods, it was assumed that there was no infrastructure for $CO_2$ transport and storage, and therefore the entire 60 million tonnes were removed from the atmosphere. The figures are associated with considerable uncertainty and are merely intended to illustrate the order of magnitude of the necessary measures.

| Method | CCS re-quired? | Competition for land | |
|---|---|---|---|
| **Afforestation/ reafforestation** | no | yes | **Mode of operation:**<br>Trees absorb $CO_2$ from the atmosphere and store the carbon in wood. Potential can be increased by harvesting wood and transforming it into long-lasting products.<br>**Advantages:**<br>Immediately feasible (however, depending on the climatic zone, ten years to several decades can elapse before newly planted trees absorb significant quantities of $CO_2$), relatively inexpensive.<br>**Drawbacks:**<br>Large areas of land required. The stored carbon can return to the atmosphere as $CO_2$ as a result of clearance, fire and pests. Albedo from forested areas can increase warming.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Approximately one quarter of Germany's agricultural land area would have to be planted with forests. |
| **Soil carbon sequestration** | no | no | **Mode of operation:**<br>Carbon is accumulated in the soil by specific forms of land management (e.g. specific crop rotations, ploughless tillage).<br>**Advantages:**<br>Immediately feasible, relatively inexpensive. Land can be put to simultaneous agricultural use. Water and nutrient storage capacity of the soil can be improved.<br>**Drawbacks:**<br>Potential uncertain. This is just a one-off effect and uptake is not continuous since the soil becomes saturated after a few years to several decades. In addition, any change in management can result in the stored carbon getting back into the atmosphere as $CO_2$.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Potential for Germany uncertain. |
| **Restoration of wetlands and marine habitats** | no | yes | **Mode of operation:**<br>Ecosystems such as wetlands or mangrove forests store huge volumes of carbon in vegetation and soil.<br>**Advantages:**<br>Can be started immediately, but carbon sequestration is a protracted process. Contributes to maintaining biodiversity and to water conservation.<br>**Drawbacks:**<br>Major potential for GHG avoidance but potential for any further $CO_2$ removal uncertain and rather low. In the short term, additional emissions of methane and nitrogen oxides could cause greater global warming. Areas which are currently used for producing food would have to be abandoned.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>The underlying calculation of unavoidable emissions has already assumed that 85 per cent of wetlands (> 1 million hectares) will be rewetted. Any further $CO_2$ uptake by peat formation uncertain and rather low (less than 5 per cent of unavoidable emissions). |
| **Biochar** | no | yes | **Mode of operation:**<br>Carbonised biomass (charcoal) is incorporated into the soil. Carbonisation prevents decay so the carbon is not released again as $CO_2$ (or only after a very long time).<br>**Advantages:**<br>Charcoal production produces energy, but less than in BECCS (merely enough to cover the process's own energy requirements). Improvement of water and nutrient storage capacity of the soil possible.<br>**Drawbacks:**<br>Negative effects on the soil possible if biochar poorly suited to soil. Need for research into long-term stability of biochar. Competition with BECCS for biomass.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Potential for Germany uncertain. |
| **Bioenergy with $CO_2$ capture and storage (BECCS, bio-CCS)** | yes | yes | **Mode of operation:**<br>Biomass is used for energy production (e.g. burnt in a power station) and the resultant $CO_2$ is captured and stored underground.<br>**Advantages:**<br>Energy is obtained. $CO_2$ is put into underground storage and kept out of the atmosphere for the long term.<br>**Drawbacks:**<br>The entire process chain has only been industrially trialled for ethanol production from maize (capture is also already carried out in biomethane production). Need for research and development for other ideas (e.g. biorefinery).<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Half to more than the entire quantity of bioenergy used would have to be equipped with CCS. |

| Method | CCS required? | Competition for land | |
|---|---|---|---|
| **Direct air capture** | yes | no | **Mode of operation:**<br>$CO_2$ is captured from the ambient air by technical installations using chemical processes (for example absorption), compressed and stored underground.<br>**Advantages:**<br>Virtually unlimited potential since no competition for land involved. $CO_2$ is put into underground storage and kept out of the atmosphere for the long term.<br>**Drawbacks:**<br>The low content of $CO_2$ in the air means that the plants have to filter very large volumes of air in an energy-intensive process entailing correspondingly high costs.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Energy requirement of over 100 terawatt-hours, which would additionally have to be provided from renewable sources (corresponding to over one sixth of present power consumption). The plants can, however, be operated flexibly, permitting the use of surplus power from wind and photovoltaics. |
| **Enhanced weathering** | no | no | **Mode of operation:**<br>Natural minerals react with $CO_2$ and sequester the carbon in the rocks (weathering). In nature, this process occurs very slowly. The reaction is accelerated by grinding the minerals finely and distributing them over a large area.<br>**Advantages:**<br>Land can be put to simultaneous agricultural use. The minerals can have a fertilising effect. The $CO_2$ is securely sequestered in the rocks and kept out of the atmosphere for the long term.<br>**Drawbacks:**<br>Possibly high energy requirements for extracting, grinding and applying the minerals; high costs. Major need for research.<br>**Prerequisites for offsetting unavoidable emissions in Germany:**<br>Some 200 million tonnes of rock would have to be extracted, ground and dispersed (roughly corresponding to the order of magnitude of Germany's entire coal extraction volume). |

**Table 3: Comparison of $CO_2$ removal technologies**[82]

The working group carried out an evaluation of the various $CO_2$ removal technologies on the basis of the current literature, stating details of global potential, land take, energy balance, costs, environmental impact, permanence of $CO_2$ sequestration and technological maturity. This evaluation is set out in detail in the analysis published in parallel to the present document.[83]

There is still a major need for research into the potential, environmental impact and costs of most $CO_2$ removal technologies. According to current assessments, methods directed towards increasing the carbon content in soil and vegetation are usually less costly than methods such as BECCS or direct air capture in which the $CO_2$ is captured using technical measures and stored underground. They are additionally perceived as being of lower risk because they are 'natural'. Social acceptance is therefore greater.[84] However, it is uncertain in these methods how long the carbon will remain stored and how large the potential for storing the necessary volumes in soil and vegetation is.[85]

In afforestation, biochar and BECCS, the $CO_2$ is absorbed from the atmosphere by photosynthesis i.e. the formation of biomass. All three methods therefore require very large areas of land for the cultivation of the plants.[86] They compete for this cultivated

82 A more comprehensive description of the various $CO_2$ removal technologies can be found, for example, in easac 2018.

83 Klepper/Thrän 2019, section 4.2.

84 Humboldt-Viadrina Governance Platform 2018.

85 UNEP 2017, chapter 7.

86 Global climate protection scenarios show that 5 to 7 million square kilometres of land could be planted with forest over the coming decades in order to remove 100 to 300 gigatonnes of $CO_2$ from the atmosphere (Fuss et al. 2018). This roughly corresponds to 10 to 15 per cent of the pasture land currently in use by humans.

land both among themselves and with agriculture and forestry. All three methods thus pose similar risks to food security and biodiversity.[87] Since Germany has virtually no unused land, these methods have limited potential. If additional residue and waste material potential is exploited, BECCS and biochar can make a contribution to $CO_2$ removal without requiring any land area.

Direct air capture and enhanced weathering are not dependent on agricultural land but are associated with great logistical complexity, high costs and large energy requirements. In all likelihood, a mix of $CO_2$ removal technologies will have to be used to offset the unavoidable emissions. This applies all the more if still further emissions have to be offset because emissions are not being reduced quickly enough and the total budget is being exceeded.

### Biochar: carbon sink and soil conditioner

The idea underlying the storage of carbon in the form of biochar is based on findings about historic Terra Preta soils in the Amazon region. These contain stable structures of anthropogenic origin which are derived from charcoal and contribute to the high fertility of Terra Preta soils. Intensive research is being conducted into how this concept could be applied on a large scale and transferred to different soils in other regions of the world. This is attractive for two reasons. Firstly, "coalification" of the biomass prevents or considerably delays its microbial degradation in the soil. The $CO_2$ taken up by the plants is thus locked up for the long term as carbon in the biochar and does not get back into the atmosphere. Secondly, incorporating the biochar into the soil can improve soil functions, in particular fertility. Agricultural yields could rise as a consequence. The positive effects on the soil can be optimised by supplementing the biochar, for example by composting, with easily metabolisable nutrient-rich, organic substances which can then be released back into the soil.

If this is to make a long-term contribution to climate protection, it is important for the carbon in the biochar to stay sequestered for many decades or centuries. Stable carbon compounds can be produced by charring (pyrolysing) biomass, i.e. by thermally decomposing it in an oxygen-free atmosphere. The material composition and physical characteristics of the resultant biochar greatly depend on the input starting material, and in particular, on the temperature and duration of treatment. The higher the production temperature, the more stable the biochars.[88] Under outdoor conditions, mean residence times of more than 100 to in excess of 1,000 years can be assumed. Around three quarters of the energy present in bioenergy remains in the biochar, the remainder in a flammable gas. The latter is needed in order to provide the energy required to produce biochar, so the process yields no additional energy. Biochar is thus not included among BECCS processes.

The commercial processes used to produce current global charcoal output of in excess of 40 million tonnes of charcoal per year range from simple heaps and kilns to retorts with more efficient process technology. Numerous processes for residual biomass and other biogenic feedstocks are currently in development. In addition to this use of biochar as a carbon sink and soil improver, other fields of use, such as the production of activated carbon or energy-rich pellets as combustion fuels, are also being researched. In addition to charring, other methods such as torrefaction, hydrothermal carbonisation or steam-assisted processes are being investigated for this purpose. Due to the lower process temperatures, not all of the methods are suitable for producing durable biochar. The numerous starting materials, production processes and conditioning options involved mean that systematic investigations are required to obtain a better understanding of the processes underlying the action of biochar in soils. In particular, there is a lack of long-term outdoor investigations. One potential risk is that organic pollutants will be formed during biochar production and will accompany the biochar into the soil.[89]

87 Afforestation can have a negative impact on biodiversity because open land is home to the greatest number of species in Germany (Schulze et al. 2015).

88 EBC 2012.

89 UBA 2016-1.

## 3.2 CCS technology: the basis of BECCS

CCS consists of the process steps $CO_2$ capture, transport and storage. The technical method used for $CO_2$ capture has to be adapted to the particular $CO_2$ source, in particular its $CO_2$ concentration. In the case of BECCS and unavoidable emissions from industry,[90] capture proceeds in the exhaust gas stream, while in direct air capture the $CO_2$ is absorbed from the air. Once the $CO_2$ is captured, it can be transported and stored in an identical manner regardless of the nature of the $CO_2$ source. There are currently 17 large-scale CCS projects worldwide.[91] Most of them are intended for enhanced oil recovery (EOR) or enhanced gas recovery (EGR). Only four of the large-scale CCS projects are solely intended for permanent geological $CO_2$ storage. Although some of the compressed $CO_2$ is re-extracted with the recovered oil or natural gas in EOR and EGR projects, these projects also typically result in net $CO_2$ storage. How permanent this storage is largely depends on whether the numerous wells required for extracting the oil or gas can be permanently sealed. From a geological standpoint, there is nothing to prevent permanent storage in EOR and EGR projects as well.

The $CO_2$ can be stored in depleted oil and gas deposits or in deep saline aquifers[92]. Table 4 provides an overview of the storage capacity. At the level of 60 million tonnes per year of unavoidable emissions estimated by the Federal Environment Agency, Germany has sufficient storage capacity to last for 150 to 250 years. Moreover, there is major storage potential beneath the North Sea and the Norwegian Sea, some of which could be used by Germany, subject to a legal framework enabling transboundary $CO_2$ transport.[93]

| | Billion tonnes |
|---|---|
| Depleted natural gas fields, German North Sea | 2.8 |
| Saline aquifers, Germany | 6–12 |
| Natural gas and oil deposits beneath the North Sea and the Norwegian Sea | 38 |
| Saline aquifers, Europe | 165 |

**Table 4: $CO_2$ storage capacity in Germany and Europe[94]**

Overall, experts are coming to the conclusion that CCS technology with pipeline transport and geological storage is ready for service today, and that sufficient storage capacity is available to store $CO_2$ in the amount of unavoidable emissions and beyond.[95] The greatest obstacle to the use of this technology in Germany is probably its low level of social acceptance. This may in part be because CCS technology has previously been discussed in connection with reducing emissions from coal-fired power stations and as an argument in favour of the further use of coal as an energy source.

90 acatech 2018 discusses the use of CCS in industry in detail.

91 Global CCS Institute 2017.

92 Body of rock with cavities holding groundwater.

93 Currently governed by the London Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.

94 Knopf et al. 2010; acatech 2018.

95 acatech 2018 provides a detailed description of CCS technology including storage capacity, risks, legal framework and acceptance factors.

## 3.3 Bioenergy with CCS

Various chemical processes are used for capturing $CO_2$ in bioenergy plants.[96] The lower the $CO_2$ concentration (e.g. in the flue gas from a combustion process), the higher is the energy demand for capture. To date, the world has only one large-scale BECCS plant, which is located in the USA and each year captures approximately one million tonnes of $CO_2$ during ethanol production from maize starch.[97]

Many climate protection scenarios, on the other hand, make massive use of BECCS, for instance to handle up to 300 exajoules of bioenergy per year solely in BECCS plants.[98] By way of comparison, approximately 59 exajoules of bioenergy are currently used worldwide. In order to establish the required capacity, these scenarios specify the large-scale use of BECCS from as early as between 2020 and 2030. In these scenarios, total bioenergy use of up to 400 exajoules amounts to two to four times the lowest estimates for sustainably-usable bioenergy potential as discussed in section 2. This could result in considerable conflict with the aims of conserving ecosystems, maintaining biodiversity and ensuring food security, unless it proves possible to achieve a significant increase in agricultural yields or to reduce the area of land required for producing feedstuffs by adopting a predominantly plant-based diet.

In many climate protection scenarios, BECCS is the only $CO_2$ removal technology considered. $CO_2$ could, however, in principle also be removed by other technologies set out in Table 3. Dispensing with BECCS would not necessarily result in lower requirements for bioenergy. Climate protection scenarios which dispense with BECCS accordingly use volumes of bioenergy which are of a similar, if not higher, level to those used in scenarios which include BECCS.[99] The availability of other $CO_2$ removal technologies, on the other hand, could reduce the need for BECCS and also for bioenergy overall. Issues around sustainably usable bioenergy potential, environmental impact and competition with food production must therefore be investigated independently of whether bioenergy will be used with or without CCS in the future.

The role $CO_2$ removal using BECCS will play may have a decisive impact on the nature of future bioenergy use. This is because a BECCS plant always provides two products: energy and negative emissions. Various bioenergy technologies differ in terms of the extent to which $CO_2$ capture can be applied.

Efficient $CO_2$ capture is only possible for large, stationary plants such as power stations, large CHP plants and industrial process heat generation. Likewise, in the production of hydrogen from biomass, all the carbon present in the biomass is converted into $CO_2$ and can be captured.[100]

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96 Including scrubbing processes, for example with amines, carbonate or methanol, physical absorption, and the oxyfuel process.

97 "Illinois Industrial Carbon Capture and Storage" project in Decatur, Illinois.

98 IIASA 2015.

99 Bauer et al. 2018.

100 Making extensive use of hydrogen in the energy system would entail putting appropriate infrastructure in place. On the basis of current knowledge, however, this infrastructure will be required irrespective of hydrogen being produced from biomass, since in the medium to long term there will be large surpluses of wind and solar power which can be converted into hydrogen by electrolysis, stored and used, among other things, in fuel cell vehicles (Ausfelder et al. 2017).

In contrast, in the production of carbon-containing energy carriers such as biomethane,[101] bioethanol or other biofuels, only some of the carbon from the biomass is converted into $CO_2$ and can be captured. The rest of the carbon remains in the fuel and is not converted into $CO_2$ until it is combusted. If the fuel is used in a vehicle or aircraft, capturing the $CO_2$ and supplying it to a $CO_2$ storage site would at best be highly complex and very costly. Realistically, therefore, it is only possible to collect and store the $CO_2$ which is captured during production and processing of the biofuels. The negative emissions in these processes are correspondingly lower. If biomethane is used in power stations or industrial plants, on the other hand, capturing the $CO_2$ arising during combustion would be possible.

On the other hand, biogenic fuels are of higher value to the future energy system than electricity from biomass because electricity is relatively simple to generate with wind and photovoltaic systems. Producing motor fuels from wind and solar power, in contrast, entails complex and costly power-to-X processes.[102] From a systems standpoint, the value of the $CO_2$ capture in relation to the value of the energy product depends on how much $CO_2$ has to be captured from the atmosphere to achieve climate protection targets and to what extent and at what cost other $CO_2$ capture technologies such as direct air capture are available. Which BECCS technology is capable of making the greatest contribution to the overall system is therefore also dependent on the development of these technologies.

## 3.4 Conclusion

On the basis of current knowledge it seems that if global climate protection targets are to be achieved, the $CO_2$ content of the atmosphere must be reduced at the latest in the second half of this century, i.e. more $CO_2$ will have to be removed from the atmosphere than is still being emitted. Using biomass for energy with CCS is one of several technologies which make this possible.

Considerable uncertainty remains regarding most $CO_2$ removal technologies in respect of potential, environmental impact, costs and the permanence of carbon sinks. There is therefore a need for further research in order to model technologies in future energy scenarios and to establish plausible volume frameworks as to how climate protection targets can be achieved. In all likelihood, a mix of different technologies will have to be used in order to be able to meet total $CO_2$ removal requirements. It must be borne in mind that all $CO_2$ removal technologies require long lead times before they are able to remove significant volumes of $CO_2$ from the atmosphere. Further research and development is first required for the technical processes and commercial plants would have to be built on a large scale. While it is indeed possible to make an immediate start with afforestation, ten years to a number of decades will elapse before trees planted today will absorb appreciable volumes of $CO_2$.

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101 Biomethane is upgraded biogas and mainly consists of methane. During upgrading, the $CO_2$ present in the biogas is captured. The gas is additionally dried, desulfurised and conditioned so that it meets the technical requirements to be fed into the natural gas grid. Biomethane can then be transported in the natural gas grid and used for various purposes instead of natural gas.

102 acatech/Leopoldina/Akademienunion 2018-1; dena 2017.

In addition, it will only be possible to develop a strategy for achieving long-term climate protection targets capable of obtaining consensus if there is social and political debate into the opportunities and risks of the various $CO_2$ removal technologies. Among other things, it must be clarified whether CCS is or is not to be used in Germany.

If BECCS is to make a contribution to climate protection on the order of magnitude required in global climate protection scenarios in the second half of this century, the first large-scale industrial plants would have to come on-stream as soon as within the next ten to twenty years. $CO_2$ transport and storage infrastructure would also have to be developed. BECCS should therefore be considered as one of the technological options in the debate around the future paths of development in bioenergy. Since $CO_2$ capture and connection to the necessary transport infrastructure is worthwhile only for relatively large plants, biomass streams might have to be diverted from the current decentralised pattern of use to larger, more centralised plants. The decision as to whether bioenergy is to be used in conjunction with CCS in the future could therefore have a major impact on the structure of bioenergy use in general.

# 4 Which bioenergy technologies are needed in the energy system of the future?

Bioenergy has in the past been viewed as one renewable energy carrier among many and has been associated with the goal of providing as much energy as possible, thus replacing fossil energy carriers. As a result, bioenergy use has been considered to have a positive effect on technological development and wealth creation in rural areas. At present, bioenergy is produced in over eleven million plants (see Table 5), which are appropriately connected to electricity, heat and gas grids. In parallel, processes for obtaining liquid biofuels from lignocellulose are the subject of intensive research.

Wet, fermentable biomass is currently used in Germany for generating power (mainly in combined heat and power systems) within the framework of the German Renewable Energy Sources Act (EEG) and for producing low-temperature heat. Government support here is primarily directed towards maximising energy production. In recent years, however, flexible power generation adapted to demand has become increasingly significant (Figure 4). A large proportion of the wood used for energy is burned in domestic fireplaces. This type of use receives no government support. The reason it nevertheless remains widespread is firstly, that many people consider a fire to be comforting, which probably means that cost sensitivity is low in many cases. Secondly, modern bioenergy plants provide an option to generate heat from locally available renewable energy sources at relatively low cost. Unlike in large parts of the world, efficient and low-emissions technologies are well established in Germany ("modern bioenergy" such as firewood gasification boilers, wood pellet boilers and stoves and woodchip heating systems).[103]

The new version of the Renewable Energy Directive (RED II), adopted in December 2018, provides tentative incentives for using waste- and residue-based fuels. The proportion of advanced biofuels in the transport sector should amount to at least 3.5 per cent by 2030.[104] At the same time, the use of conventional biofuels from food and feed crops is limited to at most 7 per cent of the final energy consumption of road and rail transport.[105] Endeavours will furthermore be made to progressively phase out the use of biofuels with a high ILUC-risk.[106] These stipulations, in particular, limit the use of biodiesel and bioethanol, and thus of conventional biofuels (first generation biofuels). The requirements applying to bioenergy use for mobility could therefore change considerably in future.

103 Cf. also Thrän 2015.
104 Article 25.
105 Article 26 (1).
106 EU 2018-1.

| | Type of plant | Number of plants | Installed capacity/ production capacity |
|---|---|---|---|
| **Biogenic solid fuels** | | | |
| **CHP**[107] | EEG-compliant biomass (district heating) power stations | 300 | 1.369 $MW_{el}$ |
| | EEG-compliant small-scale gasification plants (≤ 180 kW) | 400 | 45 $MW_{el}$ |
| **Heat**[108] | Biomass district heating stations | 1,000 | 2,000–5,000 $MW_{th}$ (extrapolation) |
| | Small-scale combustion plants: central combustion appliances (woodchips, firewood, pellets) (2014) | 1,153,300 | 36,372 $MW_{th}$ |
| | Small-scale combustion plants: single-room furnaces, fireplace stoves (2014) | 5,370,000 | 38,982 $MW_{th}$ |
| | Small-scale combustion plants: other single-room furnaces (2014) | 4,600,000 | 34,635 $MW_{th}$ |
| **Gaseous bioenergy carriers** | | | |
| **CHP**[109] (some biomethane used as motor fuels) | Agricultural biogas production plants | 7,640 | 4,379 $MW_{el}$ |
| | Small-scale animal slurry plants (≤ 75kW) | 560 | 40 $MW_{el}$ |
| | Fermenters for biowaste, food residues and other organic waste | 335 | no data |
| | Biogas to biomethane upgrading plants | 196 | 553 $MW_{el}$ |
| **Liquid bioenergy carriers** | | | |
| **CHP**[110] | Vegetable oil CHP plants (palm oil, rapeseed oil) | 690 | 79 $MW_{el}$ |
| **Motor fuels**[111] | Biodiesel plants (rapeseed oil[112], palm oil, used cooking oils/fats) | 30 | 4 million tonnes/year |
| | Bioethanol plants (sugar, starch) | 5 | 0.7 million tonnes/year |

**Table 5: Installed bioenergy plants in Germany in 2016 (some heat data from 2014)**

In the future, the focus should be on achieving the greatest possible contribution to Germany's energy transition from the limited biomass potential. The interplay between bioenergy and other renewable energy sources must be optimised accordingly. Bioenergy should primarily assume those functions in the energy system which cannot be performed by other renewable energy sources or only at very high cost. Many current energy scenarios therefore attach increasing significance to bioenergy in the production of fuel for aircraft and heavy goods vehicles and in the provision of industrial process heat.[113] On the other hand, decentralised heat and power generation from bioenergy will probably be carried out flexibly in the future in order to compensate the fluctuating feed-in from wind and solar power systems. However, the scenarios conflict with one another considerably in detail. In addition, as explained in the preceding section, combining bioenergy production with $CO_2$ removal from the atmosphere is thought to be necessary in climate scenarios. To this end, bioenergy plants would have to be equipped with CCS technology. Figure 4 shows how a system-beneficial use of bioenergy might evolve over the course of the coming decades.

107 DBFZ 2015. Unpublished analysis based on the master and movement data of the German Federal Network Agency BNetzA (conducted by DBFZ, 2018).
108 Lenz et al. 2018; Rönsch 2019.
109 DBFZ 2017.
110 DBFZ 2015.
111 DBFZ 2016.
112 Rapeseed oil as a pure fuel no longer has any relevance in Germany.
113 Szarka et al. 2017.

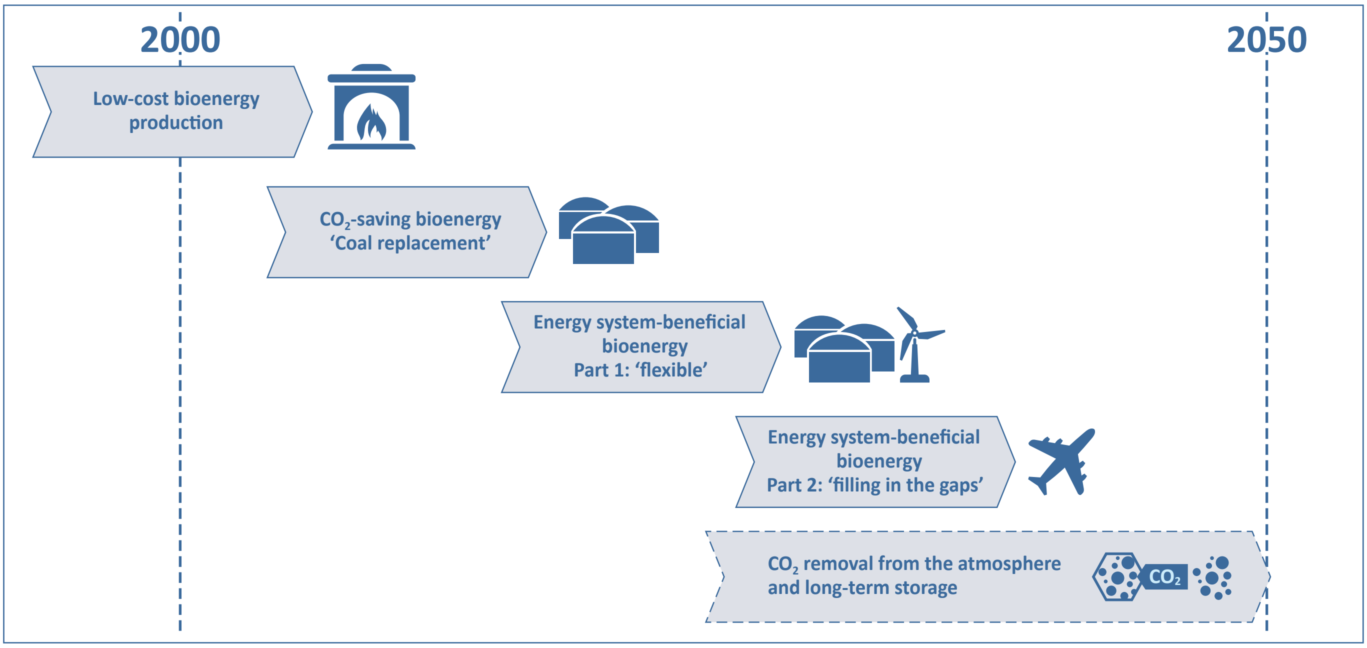


Figure 4: Stages in the bioenergy transition

Prior climate protection and energy scenarios have shown the role that might be played in future by bioenergy and "negative emissions" and what technical form future bioenergy use might take. They also provide an overview of anticipated costs. The models do not, however, generally include the necessary process of social transformation, ranging from the behaviour of various groups of stakeholders to specific market models.

These social processes may, however, crucially determine how feasible it will be to implement the technical concepts, in particular if the intention is to bring about a fundamental change to established bioenergy use. This is because the requirements of the energy system and of climate protection will probably mean that in future more complex processes for converting biomass (in particular lignocellulose) with correspondingly larger, more centralised plants will become increasingly important. This could, however, be an obstacle to social acceptance because the majority of the population prefers small, decentralised plants over large, centralised ones.[114] In addition, regional stakeholders, in particular agriculture and forestry, supply biomass to the decentralised plants and thus benefit economically. Wood, for example, is often supplied by self-harvesting[115] or by regional fuelwood dealers. If biomass is also to be used in larger, more centralised plants in the future, the biomass streams would have to be diverted accordingly so some of today's local wood use for heating might no longer be available. This could result in social resistance because providing and using bioenergy within a region by well-established local stakeholders is considered by much of the population as positive for regional wealth creation.[116] From the standpoint of the overall

114 Ohlhorst 2009; Wüste 2012.

115 Self-harvesting means that customers themselves harvest the wood by purchasing from the forest owner a right to harvest a specific quantity of fuelwood, or a particular area from which the customer can harvest is contractually agreed. The price for self-harvesting is usually distinctly lower than commercial wood prices.

116 In some technology pathways, biomass is processed in decentralised units into an energy carrier such as biomethane or pyrolysis oil which has a high energy density and is easy to transport. Further processing or use can then take place in large, centralised plants. Such approaches facilitate transport and some of the wealth creation remains in the region.

economy, however, it is not certain whether regional wealth creation is actually higher in decentralised patterns of use than in more centralised ones.[117]

In light of the challenges involved in achieving negative emissions, decisions about infrastructure developments, for instance $CO_2$ transport and storage, hydrogen and natural gas grids and heating networks, must be taken in good time. In this way, it is possible to avoid lock-in effects[118] which might perhaps bring short-term advantages but are inappropriate for achieving long-term climate protection targets.[119] A strategy designed for the long term would, moreover, help to reduce constant changes of course in bioenergy policy and increase planning certainty for developers, suppliers and operators of bioenergy technologies.

## 4.1 A comprehensive framework for evaluating bioenergy technologies

Transforming current bioenergy use towards technologies which, on the basis of current knowledge, will be of the greatest benefit to the overall system is a multifaceted task. To enable a comprehensive evaluation, the scientists of the interdisciplinary ESYS working group have drawn up an extensive catalogue of environmental, economic, social, technical, systemic and BECCS-related criteria and provided them with corresponding indicators.

Figure 5 sets out all the criteria. A traffic light scheme with five levels ranging from dark green to red has been developed for evaluating bioenergy technologies. Green in each case means that, in relation to the particular criterion, the technology makes a major contribution to achieving the target, while red means that the technology does not contribute to achieving the target. For many of the criteria, the bioenergy technologies are compared with a reference system which makes the same contributions to the energy system. In this case, red means that in relation to the particular criterion, the bioenergy technology makes a lesser contribution to achieving the target than the reference system, while green means that it makes a greater contribution and yellow that it makes roughly the same contribution to achieving the target as the reference system. Meaningful reference systems for bioenergy technology are not static, but instead develop along the time axis. In the short term, it may be fossil reference systems which are displaced by bioenergy technologies. In the long term, however, it will tend to be alternative technologies which are likewise based on renewable energy sources (e.g. power-to-gas) and may potentially also carry out the same functions in the energy system as the bioenergy technology in question.[120]

The traffic light scheme was applied to selected development pathways for lignocellulose and biogas (see section 4.2), with an analysis conducted for both the technology as it is today and as it expected to be in 2050. The evaluation was also carried out on the basis that the anticipated energy mix in 2050 will be largely renewable and will

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117 As part of the project "Energy Systems of the Future" (ESYS), one working group is comparing the effects of centralised and decentralised energy systems. The results are expected to be published in late 2019.

118 Lock-in effects describe hindrances which, once a development pathway has been entered into, make it more difficult deviate from it even if there were better alternatives. Such hindrances may include infrastructure which has been constructed or investments which have been made and have a long payback period.

119 See also Fischedick/Grunwald 2017 about handling path dependencies.

120 For example, an oil-fired boiler is used today as the reference for wood-fired heating, while the production of electricity-based synthetic motor fuels would be the reference for a wood-based biorefinery in 2050.

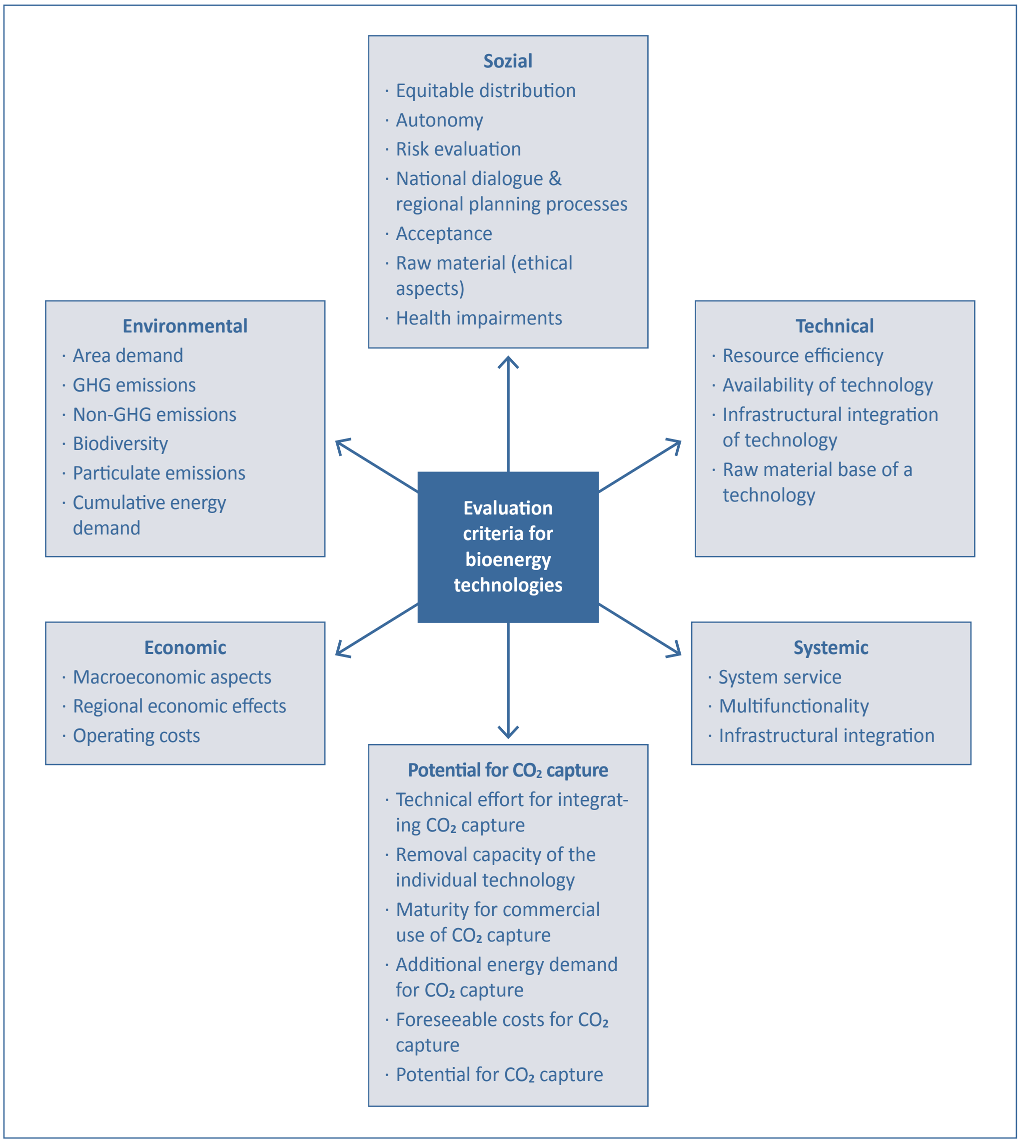


**Figure 5: Criteria for evaluating bioenergy technologies**

therefore, among other things, emit distinctly less greenhouse gases than in 2018. The greenhouse gas savings made by using bioenergy will thus be smaller in future. The evaluation, in particular of the technologies for 2050, is of course highly uncertain and reflects the judgement of the participating experts. The evaluation relates to the use of the respective technologies in Germany.

The analysis "Biomass: striking a balance between energy and climate policies. Potential – technologies – conflicts of interest"[121] provides a detailed description of the criteria and their indicators, the significance of the colour ratings for the individual criteria and presents the results of the evaluation.

The working group deliberately did not weight the criteria, which is a task that must fall to policymakers. It may thus certainly be questioned whether, for instance, a specific regional distribution of wealth creation, opportunities for as many stakeholders

121 Klepper/Thrän 2019.

as possible or perceived greater autonomy should in any way be taken into account in the evaluation of energy technologies. If, however, such issues are considered to be important by large sections of the population and the associated expectations are not met, there is a risk that any transformation of bioenergy will be delayed or prevented. The criteria can therefore be helpful in identifying possible obstacles at an early stage and developing strategies for overcoming them, for instance by providing additional measures to mitigate disadvantages for specific stakeholder groups. In this connection, a "red" evaluation of the traffic light system should not be taken to mean that the technology pathway in question should not be pursued. This rating should instead be taken to indicate that obstacles which will require additional effort to overcome may occur in a specific area.

The evaluation can also reveal how transformation pathways are modified when political priorities change and bring other criteria into the foreground.

## 4.2 Development pathways for lignocellulose and biogas

The ESYS working group has selected two bioenergy processes for its evaluation: technologies based on lignocellulose and wet fermentable biomass for biogas production. These materials constitute a substantial proportion of available raw materials both now and in future.[122] In terms of volume, wood constitutes the greatest proportion of lignocellulose. In the case studies examined, feedstocks which can be considered for lignocellulose plants in 2050 are primarily forest and industrial wood residues as well as some wood from short rotation coppices[123].[124] Biogas production is based on a mix of animal slurry and other wet waste and residues together with environmentally soundly grown biomass (e.g. grasses or legumes).

### Lignocellulose

Lignocellulose forms the cell walls of woody plants. Wood and straw largely consist of lignocellulose. Today's conventional processes for producing liquid motor fuels and biogas plants are incapable of processing lignocellulose or can only do so with considerable additional effort.

For the year 2018, typical plant designs for today's use of lignocellulose and wet biomass were defined. Two different development pathways were considered for the target year 2050: firstly, further development of currently used technology for generating electricity and/or heat and secondly, transformation towards other potential applications which enable the production of motor fuels. The possibility of $CO_2$ capture from each development pathway will also be taken into account and investigated. The technologies with potential for fuel production tend to require larger, more centralised plants, and as

122 Technologies for "first generation" biofuels, for example biodiesel and bioethanol from agricultural starch and oil crops such as oilseed rape and maize, were not considered here. In particular, in view of the current political debate, it may be anticipated that the use of biodiesel and bioethanol and thus of conventional fuels (first generation biofuels) will in future be restricted and so they will play a subordinate role in the long term (EU 2018-1).

123 In short rotation coppices, fast-growing tree species such as poplar or willow varieties are grown and harvested when only a few years old. They can be used for energy in the form of chips. Greenhouse gas emissions are low since almost no fertilisers are required and carbon accumulates in the soil. Thanks to the use of areas unsuitable for arable cultivation (degraded arable or pasture land), little land use competition is involved.

124 The case studies presented here examine a wood-based biorefinery; in principle, however, straw will in future also be usable in biorefineries.

a result, this tendency is much more pronounced for the use of lignocellulose than for processing wet biomass.[125] This is because wet biomass cannot readily be transported over long distances, among other things due to its low energy density. Table 6 provides an overview of the analysed technologies. The analysis[126] published in parallel to this document provides a detailed description of the plant designs.

| | 2018 | 2050 | |
|---|---|---|---|
| | **Current situation** | **Further development of currently used technology for electricity/ heat generation** | **Technology with potential for motor fuel production** |
| **Wet biomass** | Biogas plant with CHP for local electricity and heat generation | Flexibly-operated biogas plant with CHP plant for local electricity and heat generation | Biogas plant with upgrading of biogas to biomethane and feed-in into natural gas grid |
| **Lignocellulose** | Wood-fired boiler for generating low-temperature heat | Wood gasification plant for local electricity and heat generation | Synthesis gas biorefinery for producing fuels (including aviation fuel) |

**Table 6: Technologies investigated for using lignocellulose and wet, fermentable biomass for energy today and in 2050**

All the development pathways examined are in principle suitable for utilising residues and waste materials. This is an important criterion since residues and waste materials, unlike forest wood and agricultural commodities, offer a relatively readily predictable, sustainable potential (see section 2). From a technical standpoint, however, residues and waste materials are often more difficult to use than cultivated biomass. Firstly, their energy density is sometimes low, making collection and transport very costly. Secondly, they include very different and, moreover, varying components which complicate processing.[127] Treatment processing into defined intermediate products (by washing and drying, torrefaction, pelletisation) can facilitate transport and conversion but are not examined further here.

### Biorefineries

Biomass is a complex raw material from which it is possible to obtain not only foods and feedstuffs but also the most varied of materials and energy carriers and many chemical building blocks. "Biorefineries" link together different value chains by manufacturing a number of products in parallel (co-products). This makes it possible to make full use of the input biomass and to produce high-value products and intermediates from all the components of the initial biomass. Biofuels are already at present generally co-produced with other products.

Depending on plant design, biorefineries can process between 10,000 and several 100,000 tonnes of biomass per year. The carbon content of input biomass which is not bound in the products can be cap-

125 The biomethane plant processes only two to five times as much biomass as biogas plants with a CHP plant. The biorefinery, in contrast, each year requires approximately as much wood as 7,000 wood gasifiers or 100,000 wood-fired boilers. Bioenergy plants are here described as "decentralised" if they mainly use raw materials from the region and the plant is operated by regional operators or operating consortia. This is achievable up to an output of approximately 1 megawatt (electrical). A biomethane plant should therefore be classified more as a plant with decentralised production but a centralised use of the product.

126 Klepper/Thrän 2019, section 5.2.1.

127 For example, higher atmospheric emissions, low yields, formation of concretions in the combustion chamber, foaming in biogas plants.

tured as $CO_2$. If half of the carbon is bound in products, a refinery which processed half a million tonnes of wood per year would, for example, have a carbon capture potential of over 400,000 tonnes of $CO_2$.

There are various biorefinery concepts tailored to using different kinds of feedstocks (e.g. raw materials containing sugar and starch, oilseeds, lignocellulose or algae) as efficiently as possible.[128] *Lignocellulose biorefineries* convert woody and herbaceous biomass (for instance straw) via various separation methods into cellulose, hemicellulose and lignin which are preferably further processed by biotechnological processes (e.g. fermentation). In contrast, a *synthesis gas biorefinery* thermochemically converts the pre-treated lignocellulose into gases with high carbon and hydrogen contents. These are further processed in the next step into motor fuels and/or basic chemicals.[129]

Lignocellulose biorefineries are technically more mature than synthesis gas biorefineries. Irrespective of this, there is still some need for wide-ranging development and demonstration work, in particular in terms of integrating the different processes and reducing costs.[130] This applies in particular to advanced concepts such as synthesis gas biorefineries which are capable of processing a wide range of raw materials such as residues and waste materials, woody and herbaceous material and algal biomass and/or hybrid concepts involving power-to-X and greater diversification of the products. Important aspects here include:

- integrating innovative plant components in relation to up/downstream processes;
- increasing plant size and availability (scaling overall plants, provision of necessary quantities of raw materials of defined quality, large numbers of full-load hours simultaneously combined with flexibility in terms of raw materials and products, integration into appropriate infrastructure);
- falling capital expenditure thanks to plant designs adapted to local sites;
- appropriate raw material and product costs combined with suitably available and stable markets as well as high potential for greenhouse gas abatement.

The evaluation of the selected technology pathways on the basis of the 29 criteria is explained in detail in the analysis[131] published in parallel to this Position Paper and in additional online materials. The most important conclusions are summarised below.

**Technical criteria:** The examined technologies are largely technically mature and commercially available. Only the wood-based synthesis gas biorefinery has not yet been commercially implemented. All the examined technologies for 2050 permit efficient resource utilization with an overall efficiency of at least 80 per cent.

**Systemic criteria:** All the examined technologies can make a meaningful contribution to the future energy supply. In view of the 2050 perspective, fuel production in a biorefinery and the production of biomethane which can be put to flexible use in all sectors as a replacement for natural gas are probably of greater use to the system than the smaller scale electricity and heat generation plants. They produce products which are more difficult to replace with wind and solar power and are therefore of greater value to the energy system. This is because electricity and heat can be provided more

128 Various biorefinery concepts are described in the German government's biorefinery roadmap (Bundesregierung 2012).
129 Bundesregierung 2012; DBFZ 2016.
130 Mueller-Langer et al. 2017; Bundesregierung 2012.
131 Thrän 2019.

efficiently by wind power and photovoltaic systems and by heat pumps, while producing methane or motor fuels from wind and solar power is complicated. Moreover, biorefineries and biomethane plants can be combined with CCS and so in future will make a greater contribution to achieving long-term climate protection targets. In particular for CHP plants, the expansion of heating networks is vital to good system integration. If these paths are to be pursued, a higher-level heating strategy is needed to give impetus to the expansion of heating networks. In contrast, the infrastructure for biomethane and biofuels is already in place.

**Environmental criteria:** The environmental impacts are determined above all by the sourcing of raw materials and differ only marginally between the various pathways for expansion. A maximally sustainable raw materials mix was used as the basis for all the plant concepts for 2050. At least half of the input biomass is residues and waste materials and the remainder is biomass grown in conservation-oriented systems (such as grasses) and wood from short rotation coppices. Nevertheless, the examined bioenergy technologies for 2050 tend to be less favourable from an environmental standpoint than the renewable reference systems based on wind and solar energy, in particular for the criteria area demand, impact on biodiversity and greenhouse gas balance. This is mainly because producing the same products from wind or solar energy uses a smaller land area. If forest wood or cultivated biomass field crops are used, there is then an urgent need for environmentally compatible cultivation. Due to their harmful effects on health, particulate emissions are a major criterion for all technologies and can also be a decisive factor for acceptance.

**Economic criteria:** The economic viability of bioenergy plants in the future overall system is to a great extent dependent on trends in the costs for batteries and power-to-gas or power-to-fuel technologies. This is because these plants produce comparable products and will therefore in future compete directly with bioenergy plants. In current energy scenarios for 2050, biomethane is less costly to produce than synthetic methane from wind and solar power.[132] There is, however, considerable uncertainty about cost trends to 2050. In comparison with technologies which require no raw materials for operation, the operational risks in bioenergy technologies are greater due to the large proportion of costs accounted for by raw materials. Decentralised plant concepts provide potential for wealth and job creation in a comparatively large number of regions. In centralised plant concepts, these effects are concentrated on a smaller number of stakeholders and locations.

**Social criteria:** Sourcing of raw materials has a major impact on social effects. There is potential for conflict with regard to ethical aspects such as competition with food crops and the land area used by cultivation. A change to the landscape (for instance due to maize monocultures) is also viewed critically. Concerns about genetic engineering can likewise play a part in acceptance. In the case of wood, use at a regional level is associated with self-sufficiency and is viewed positively. In addition, in particular for low-income households, in rural areas there are virtually no alternatives to heating with fuelwood. Making large-scale use of bioenergy for producing fuel could, however, be inconsistent with the emotional significance of forests. All in all, lignocellulose biorefineries are to be expected to meet with the strongest resistance as “large-scale technology” with no relation to personal or regional self-sufficiency. With more decentralised plants,

132 Based on data from Erlach et al. 2018 and Elsner et al. 2015.

a larger number of different stakeholders (including small businesses) can benefit from plant operation and the supply of biomass. This can result in greater acceptance of decentralised concepts.

**Potential for $CO_2$ capture:** Biorefinery and biomethane plants are suitable for $CO_2$ capture and thus for producing negative emissions. How advantageous they are in each case depends on which energy carriers are preferable to be produced and how the plants can be integrated into CCS infrastructure. For the biomethane plant, the extent to which a connection to the $CO_2$ transport infrastructure is logistically feasible and economically viable would have to be investigated as the volumes of $CO_2$ which arise annually are relatively low. Neither of the decentralised concepts is suitable for combination with CCS.

## 4.3 Conclusion

How the raw materials are sourced is the most significant factor from an environmental standpoint. It is also of relevance to social acceptance and to the economic effects of bioenergy use at a regional level. Consistently further developing and establishing best practices in raw materials use is therefore a prerequisite for a sustainable bioenergy strategy. The energy system and land use need to be considered together.

From a systemic standpoint, the two more centralised concepts, biomethane plants and biorefineries, would appear to be superior to decentralised electricity and heat generation. They produce products which are more difficult to replace with wind and solar power and are therefore of greater value to the energy system. Moreover, they can be combined with CCS and thus will make a greater contribution to achieving long-term climate protection targets in the future.

For wet biomass, there are no fundamental differences in many criteria between the technology pathways. A gradual changeover from today's decentralised biogas plants to future, decentralised biomethane production is thus possible in a relatively straightforward manner. There are virtually no differences in the structure of raw materials sourcing and the stakeholders involved in raw materials sourcing and plant operation. The target should be to ensure that raw materials are supplied as sustainably as possible.

In contrast, the two technology pathways for using lignocellulose differ fundamentally. For a biorefinery, biomass streams would have to be extracted from regional patterns of supply and use and redirected into more centralized supply structures. This would fundamentally change the stakeholders involved, as result of which a relatively significant impact on and resistance from society would be anticipated. In light of the technical imponderables relating to wood-based biorefineries, it is not possible at the present time to make a meaningful decision in favour of one of the two technology pathways. This is all the more the case given the uncertainty about whether and to what extent BECCS technology will in future be accepted by society.

From today's perspective, it thus makes sense for the moment to continue pursuing both the decentralised and the biorefinery options for using lignocellulose. Efficient decentralised bioenergy use is only possible in combined heat and power plants. Heating networks are, however, required for operating CHP plants. Expansion of heating networks is therefore an important first step towards ensuring that efficient, decentralised bioenergy use can make a substantial contribution to the energy transition. Even without the use of bioenergy in the low-temperature range, heating networks will probably be required to ensure future climate-compatible heating. They increase the flexibility of the overall system since they make it possible to integrate large, inexpensive heat storage with various heat sources such as large heat pumps, electrode boilers, CHP plants, waste heat from industry and geothermal and solar thermal energy.[133] Should it subsequently be decided to prioritise the use of biomass in biorefineries, heating networks can be supplied from many other environmentally-friendly heat sources.

The decision between small-scale, more decentralised and highly centralised, large-scale bioenergy usage pathways depends firstly on further technical developments, in particular in relation to biorefinery concepts, to bring the technology to a successful commercial launch. Secondly, further development is dependent on a fundamental decision regarding the use of CCS technology. If it is decided to adopt CCS for industrial emissions sources this would prompt greater use of the centralised development pathway for energy biomass as well. This would create an opportunity to use BECCS to meet (at least in part) the requirement for negative emissions set out in climate protection scenarios. In the absence of a decision in favour of CCS, decentralised solutions are probably simpler to implement.

The working group's discussions of evaluation criteria and their application to the selected technologies have revealed that, in addition to uncertainties with regard to the definition and selection of the criteria and their interplay, there are still considerable knowledge gaps in the data on which the evaluation is based (in particular with regard to future technological development and the associated cost trends). The catalogue of criteria can only provide information about the many and varied aspects of using different technologies and bioenergy strategies and thus create transparency. Consideration as to which criteria enter into the evaluation and with what weighting remains a matter for society to decide and cannot be directly derived from the characterisation of different technologies on the basis of the catalogue of criteria. The catalogue and evaluation scheme can provide structured information as an input for participatory processes as a part of the public debate.

### Bioenergy costs

A national bioenergy strategy should have the aim of using the available bioenergy potential to achieve the greatest possible benefit for the overall system. This means from a cost standpoint that total energy supply costs should be kept as low as possible. To achieve this, bioenergy must be used in those fields in which alternative solutions are particularly costly and consequently, the greatest additional costs can be avoided by using bioenergy. While from a business management perspective it is sufficient to compare a bioenergy technology with alternative technologies for the same energy service (e.g. wood-fired heating with a heat pump or solar-thermal heating), from the perspective of the overall economy, the entire

133 Investigations into integrated energy systems have shown that up to one third of buildings could be connected to a heating network by 2050 (acatech/Leopoldina/Akademienunion 2018-1, p. 27).

energy system must be taken into consideration, including all potential fields of use for bioenergy for providing electricity, heat and fuel.

The costs of the future energy system will probably be heavily dependent on how the volatility of power generation from wind power and photovoltaics can be offset. “Flexibility technologies” such as standby power plants and storage systems will constitute a large proportion of total energy system costs.[134] As a storable energy carrier, bioenergy can reduce the need for other flexibility technologies and so reduce total system costs. This effect can only be quantified in model calculations with a high time resolution.

The results of such model calculations are heavily dependent on the assumed cost trends not only in bioenergy technologies but also in competing technologies. Different energy scenarios reveal very large differences in “cost-optimal” bioenergy use.[135] This indicates that, on the basis of current knowledge, it is not possible from a scientific perspective to provide an unambiguous evaluation as to the areas in which bioenergy should in future be used in order to minimise total energy system costs.

A further difficulty is that the costs of electricity, heat or fuel made from biomass are heavily dependent on the costs of the input raw materials. For example, biomass accounts for 43 to 56 per cent of production costs in a biogas plant generating electricity and heat from maize, for 34 to 50 per cent in a wood-fired power station and for 85 per cent in biodiesel production from oilseed rape.[136]

The prices of raw materials fluctuate greatly, however. In the case of internationally traded agricultural commodities such as cereals or plant oils, they are dependent on trends on international agricultural markets. In addition, the feedstocks, in particular for producing biofuels, are mainly co-products from agricultural processes in which a number of products and intermediates are produced from a single crop. Soya oil, for example, which is used for producing biodiesel, is a secondary product from feedstuff production; just one fifth of the input soya plant mass is obtained as oil and four fifths as high-protein cattle feed. Approximately equal parts of vegetable oil and feedstuff are produced from rapeseed. The costs for cultivating the plants cannot be unequivocally apportioned between the various co-products. Market prices for the individual products will therefore be strongly influenced by supply and demand for the co-produced products. Market prices for vegetable oils for obtaining biofuel accordingly depend on market prices for feedstuffs, for instance.

Last but not least, future cost trends in biogenic raw materials are crucially dependent on the extent to which external costs due to environmental impact and greenhouse gas emissions are factored into prices over the coming years and decades.

$CO_2$ avoidance costs are frequently stated as an indicator of the cost-efficiency of climate protection measures. Doing this would entail making assumptions about which technologies and energy carriers are replaced by bioenergy. However, this can only be reliably determined over a very short time horizon under known market conditions. For example, if a biogas CHP plant were to be built today, it would be possible to determine whether, under current electricity market conditions, it would displace coal-generated or natural gas-generated electricity from the market. Over the medium to long term, however, the entire conventional energy system will have to be replaced by renewable energies and flexibility technologies, the interplay of which will provide the required energy services. Market structures will likewise change over the course of this transformation. It is not possible to tell which fossil energy carriers will be replaced by bioenergy in this process and which, for example, by wind power in combination with battery banks or power-to-gas. Over the long term to 2050, $CO_2$ avoidance costs can only be stated on a scientifically well-founded basis for the overall system, but not for an individual technology.

134 Elsner et al. 2015; Ausfelder et al. 2017.
135 Szarka et al. 2017.
136 Hennig/Gawor 2012; DBFZ 2016.

# 5 Options for a sustainable bioenergy strategy

The described interrelationships suggest the following challenges for a bioenergy strategy:

Most risks arising from bioenergy use concern impacts on land use systems. The raw material base crucially determines environmental impacts and social acceptance. **Energy and land use systems must therefore be considered as an integrated whole**. This presupposes cooperation between energy, agriculture, forestry and environmental policy.

The greenhouse gas balance is also to a great extent dependent on the raw materials used. A **coherent climate protection policy** which includes and regulates all greenhouse gases is required in order to achieve the greatest possible climate gas savings by using bioenergy. In particular, greenhouse gases from land use must also be taken into account.

Residues and waste materials provide considerable potential for bioenergy where the risks arising from interactions with alternative land uses do not occur or only to a greatly reduced extent. This potential could rise still further in the future as a result of greater material use of biomass with subsequent energy recovery from the products at the end of their service life (cascade use). The **interface between the energy and waste management sectors** will therefore become more significant in the future.

However, due among other things to their higher pollutant contents, waste materials are usually complicated feedstocks which are costlier to process than, for example, forest wood. **Bioenergy plants will have to be adapted to these feedstocks**. Conversion technologies for using residues have so far only been developed in part. There is a need for further **research and development** in this area.

The way in which bioenergy can achieve the greatest benefits for the overall system varies as a function of how the remainder of the energy system develops. From a systemic standpoint, producing motor fuels would appear to make sense in the medium to long term, since producing these energy carriers from wind and solar power entails considerable effort and high costs. The biorefineries required for this purpose would, however, mean large industrial plants and to some extent a move away from the decentralised bioenergy use which is currently society's preferred option. Flexibly operated decentralised CHP plants can even in the short-term assist with stabilising supplies of electricity and heat. It is not possible at present to assess when and to what extent changing over to biorefineries might be advantageous. This depends, among other things, on developments in biorefinery technology as well as in electricity-based synthetic motor fuels. This results in **major uncertainty for stakeholders**, which has a dampening effect on innovation, ongoing development and capital investment.

In addition to bioenergy's functions in the energy system, the **production of negative emissions**, i.e. the removal of $CO_2$ from the atmosphere, may in the long term become a more significant requirement. In addition to bioenergy with CCS (BECCS), there are various other methods such as afforestation and direct air capture with which $CO_2$ can be removed from the atmosphere. It is therefore unclear whether and to what extent bioenergy should provide the negative emissions which will be required in the future. Since not all bioenergy technologies are equally well suited to $CO_2$ removal, the decision as to whether bioenergy should be used in conjunction with CCS has a major impact on the future nature of bioenergy use. CCS technology is very controversial in Germany so it is difficult to tell whether the population would accept the use of BECCS. This increases uncertainty for stakeholders in the bioenergy sector. Moreover, there is a need for $CO_2$ transport and storage infrastructure which would have to be put in place in the near future. This is because if BECCS is to make a significant contribution to climate protection within a few decades, the first large-scale plants will have to come on stream shortly. There is therefore an urgent need for **a social and political debate around CCS technology, BECCS and alternative $CO_2$ removal technologies**.

**There is a lack of system knowledge when it comes to evaluating different bioenergy transformation pathways**. A comprehensive evaluation including environmental, economic, social, technical and systemic criteria could provide some guidance for bioenergy stakeholders and increase the predictability of developments in the medium term.

## 5.1 Coherent climate protection policy

The purpose of using bioenergy in the energy system is climate protection. Bioenergy should accordingly be used in such a way that greenhouse gas savings of the magnitude required by the Paris Climate Agreement are actually made.[137] Account must be taken here of the entire bioenergy life cycle, whether for biomass cultivated in Germany or for imported energy carriers.[138]

### 5.1.1 $CO_2$ pricing as a key instrument

In the long term, setting a uniform and sufficiently high $CO_2$ price can be an efficient and well targeted way of contributing to achieving climate protection targets. This pricing can be achieved either by extending the European Emissions Trading System (EU ETS) or by taxation.[139] In the case of emissions trading, the European Emissions

137 The EU Renewable Energy Directive specifies minimum requirements as to what proportion of greenhouse gas emissions must be saved by biogenic fuels relative to fossil fuels.

138 It must furthermore be borne in mind that biomass (in particular wood) will in future probably primarily be used as a material and energy use will only occur in a second stage (cascade use). The environmental impact of an increased need for biomass in the forestry and agricultural systems occurs irrespective of whether the harvested biomass is initially put to use as material or directly used for energy. Appropriate sustainability criteria for material use should therefore also be defined in good time.

139 acatech/Leopoldina/Akademienunion (2017-1) summarises the advantages and drawbacks of the two instruments (p. 56–63); apart from the general differences between them, it is not to be anticipated that they will act differently on the production and use of bioenergy. Pricing is therefore discussed below without considering the specific instrument applied. According to legal experts, a direct $CO_2$ tax might be contrary to the constitution in Germany (Rodi 2017; UBA 2017; Kahl/Simmel 2017), but options are being discussed to enable taxation by linkage to an excise duty (e.g. for fossil combustion and motor fuels). It would have to be examined how the various greenhouse gas sources from agriculture can be taxed. An EU-wide $CO_2$ tax would have to be unanimously adopted by member states.

Trading System would have to be extended to all GHG emissions from all sectors in order to provide incentives for efficient avoidance of greenhouse gases.

Since nitrous oxide emissions from the cultivation of energy crops have a major impact on the overall greenhouse gas balance of bioenergy, it is essential to include them in the pricing scheme. In the long term, all greenhouse gases in all sectors including agriculture should ideally be priced. The advantage is that setting a price for all greenhouse gases from agriculture would provide an incentive for climate-friendly land use, including in food production. If a $CO_2$ price could be established worldwide, it would also solve the problem of greenhouse gas emissions by "indirect land use changes" (cf. section 2.2). This is because if greenhouse gas emissions, for example caused by forest clearance, were to generate costs, there would be less incentive to make such land use changes. In the energy system, an effective $CO_2$ price would result in bioenergy being used where it is of greatest benefit to climate protection. However, even a globally uniform $CO_2$ price does not reflect environmental impact such as reduced biodiversity. Such impact must therefore be considered separately.

Extending $CO_2$ emissions pricing to methane and nitrous oxide from the whole of agriculture will increase food production costs and thus also food prices. The effects can be positive on the climate, environment and health.[140] For instance, increased costs and prices could reduce meat consumption. In relatively poor countries, this could result in poor households, in particular, being more severely affected by increased staple food prices. While such an effect would be less pronounced in Germany and Europe,[141] the impact on lower-income households should nevertheless be investigated and, if need be, mitigated.

A sufficiently high $CO_2$ price is, moreover, needed so that the capture of $CO_2$ from the atmosphere which is necessary in order to achieve climate targets can be funded (cf. section 3). Specifically, the following mechanisms are conceivable for this purpose:

1. **Integration of negative emissions into an extended European Emissions Trading System (EU ETS)**. This ensures that the remuneration for $CO_2$ removal is identical to the price for emissions. If, for example, the $CO_2$ price is 80 euros, the cost for emitting one tonne of $CO_2$ would be 80 euros and the remuneration for removing one tonne of $CO_2$ from the atmosphere would be 80 euros. In this system, one tonne of removed $CO_2$ would always be worth exactly the same as one tonne of avoided $CO_2$. This would be economically efficient. Such an approach could, however, result in $CO_2$ removal technologies only being developed if the price is very high. In this case, the technologies would not be available in time for large-scale use. It should therefore be investigated whether government support is required for research and development into BECCS and other $CO_2$ removal technologies. The same applies when it comes to constructing the necessary infrastructure to enable carbon dioxide transport and storage.

2. **Tendering process for a fixed amount for $CO_2$ removal**. In this way, $CO_2$ removal technologies can be nurtured and trialled from an early stage. Costs

140 The German Nutrition Society (DGE) recommends cutting meat consumption (DGE 2015).

141 A $CO_2$ price of 50 euros per tonne would, for example, increase the cost of one kilogram of beef by 66 cents and the cost of one kilogram of potatoes by one cent (based on data from Fritsche/Eberle 2007).

would indeed initially be distinctly higher than the $CO_2$ prices in emissions trading. However, even today, $CO_2$ avoidance costs in the transport sector, for example, are distinctly higher than in the ETS sector. It is to be expected, however, that $CO_2$ prices will rise in future while costs for $CO_2$ removal will tend to fall as the technologies become more mature. Prices would equalise over time and once appropriate infrastructure is in place.

The advantages and drawbacks of specific regulatory and incentive instruments for $CO_2$ removal by BECCS have not yet been investigated. There has, in contrast, already been discussion in the specialist literature of various policy instruments by which $CO_2$ removal in the EU could be regulated by the restoration of degraded forests.[142]

### 5.1.2 Alternative support mechanisms

At present, there is no expectation that it will be possible to implement a global $CO_2$ price for greenhouse gas emissions in the framework of an international agreement. Therefore, feasible alternative measures should be put in place in the short term in order to bridge the gap until a global agreement is reached. The aim of these measures would be to ensure that in those countries pursuing ambitious climate targets, bioenergy is produced and used in a climate-friendly manner. Another aim of these policy instruments should be avoiding unwanted social and environmental side effects of expanding bioenergy production, for example the restriction of food production due to increased cultivation of energy crops or the loss of biodiversity due to land use changes. The measures described here could also be used for this purpose as a supplement to a $CO_2$ price. It is important for alternative support mechanisms to always include any impacts which are caused outside of the country applying the mechanisms. This applies in particular to countries and confederations of countries which purchase a large proportion of their biomass from foreign countries, for instance the EU and in particular Germany.

The prerequisite is firstly that incentives for using bioenergy as a means of climate protection are put in place within the EU or Germany. In the case of domestically produced biomass, statutory provisions at the national or EU level should ensure that bioenergy is produced sustainably and makes a specified contribution to abating emissions. In contrast, more complex policy instruments are required for imports of biomass or bioenergy carriers. These measures are currently under discussion or are already in use:

- imposing a border tax adjustment in the amount of the GHG emissions present in imported products;
- integrating imports into national or European climate policy instruments such as a GHG tax or the European Emissions Trading System;
- certifying imported products with regard to their GHG emissions and their environmental and social effects in the framework of quota systems[143];
- prohibiting the import of specific energy carriers.

142 Meyer-Ohlendorf/Relih-Larsen 2017.

143 A quota system stipulates that a specific proportion of the sales volume of an energy carrier must originate from renewable energy sources. One example is the biofuel quota in the context of the implementation of the EU Renewable Energy Directive (RED) in Germany.

Border tax adjustments[144] and certification schemes are intended to promote the use of imported biomass or bioenergy, but only to the extent that they also make a contribution to climate protection. In this case, imports have a charge applied to them in relation to the GHG emissions involved in their production but can then participate on the market under the same conditions as domestically produced bioenergy. A prerequisite for this is that Germany should have corresponding economic incentives for using bioenergy, for instance a price on GHG emissions or quota systems of the kind in existence for biofuels in the EU.

The proposal to tax the GHG content of imports by means of a **border tax adjustment** has not yet been implemented. Such regulation would have to be introduced by the European Union since, for the purposes of the internal market, the EU is the external border for all member states. In addition, care must be taken to ensure that any border tax adjustment arrangements which are made are compatible with World Trade Organization rules. Practical implementation would require complex measures, depending on whether the border tax adjustment is to be applied only to imports which are directly used for energy or converted into bioenergy, or whether it is to cover all imports. Furthermore, the environmental and social aspects of the production of the imported goods are difficult to include in the framework of a border tax adjustment.

**Integrating imports into a GHG taxation system or into an Emissions Trading System** is one option for treating domestic and imported biomass or bioenergy identically. A prerequisite for this is that the GHG emissions arising outside Germany are treated in the same way as those arising in Germany. The information required for this purpose must be available and verifiable. It could, for example, be provided by a certification system. Alternatively, exporters could be obliged to submit this information in verifiable form. A further option would be to calculate the GHG content of imports using standard values and to take account of them in climate policy instruments in a corresponding manner to domestic goods. For example, in the case of an Emissions Trading System, importers wishing to introduce products onto the European market would have to hold emission rights for the GHG emissions arising outside Germany.

The third option of recording, regulating and **certifying** the GHG content of imports (and likewise of domestically produced biomass) is already applied to the use of biofuels in the EU and, despite some implementation challenges, has now become established. The obligation specified in the EU Renewable Energy Directive (RED)[145] to provide sustainability certification for all biofuels is the prerequisite for it to be possible for these fuels to count towards the biofuel quota and so achieve a price premium when sold to the petroleum industry. In this case, it has to be proven that the imports achieve specified greenhouse gas savings, currently set at 60 per cent, in comparison with fossil fuels. Biofuels which do not meet this specification cannot be certified.[146] This excludes *inter alia* biofuels which are produced on land which has been deforested since 2008. This is because the resultant emissions have such a negative impact on the GHG balance

144 In the case of a border tax adjustment for GHG emissions, imported goods have a duty imposed, the level of which is determined by the GHG emissions present in the imported goods multiplied by the prevailing $CO_2$ price in the importing country.

145 EU 2009.

146 While RED only applies to liquid bioenergy carriers, the upcoming RED II is set to extend sustainability requirements to biogas and solid energy carriers as well.

that the minimum savings cannot be achieved.[147] At the same time, unwanted environmental side effects are reduced as a result.

Certification achieves three fundamental aims: it provides information about the contribution made by bioenergy to climate protection, it states clear requirements for exporters as to the conditions they must meet in order to be able to offer bioenergy or biomass for sale in the EU, and it creates incentives for producers in exporting countries to make their output more climate friendly. The information provided by certification can, for example, be used for determining border tax adjustment import duties. At present, it is used with biofuels for the RED quota system. The information from certification could, however, also be of use for integrating domestic and imported bioenergy carriers into the EU ETS. It would be used to determine how many emissions rights for a specific bioenergy carrier have to be held so that it can be used in the EU.[148]

The certification of biofuels within the framework of RED has been widely criticised and debated. One criticism was that it was unable to stop deforestation of areas outside Germany in particular for the cultivation of vegetable oils such as palm and soya oil for biodiesel production. Since the certified vegetable oils used for producing biodiesel made up only a small proportion of the entire output, 'cherry-picking' would occur. The vegetable oils from areas which meet certification criteria are certified for the production of biodiesel, while the great majority of output continues not to meet the requirements for certification and is used for other purposes for which certification is not mandatory. All biomass imports, including foods and feedstuffs, would have to be subject to the same criteria to solve these problems. An additional incentive for climate-friendly production could thus be provided at least for EU imports. The volumes exported to other countries, however, remain unaffected thereby.

The companies affected initially criticised certification as being administratively cumbersome and too costly. Objections were also raised that the standard values set for drawing up the greenhouse gas balance were too pessimistic and discriminatory. In practice, however, bioenergy certification has turned out to generate only very low costs. The possibility for producers to have actual greenhouse gas emissions which are lower than the standard values verified by certification bodies has led to more transparency and greater efforts on the part of many producers to improve GHG balances.

Indirect land use changes will remain problematic until greenhouse gas emissions from agriculture and forestry are controlled globally and regulations are applied to all agricultural products. "ILUC factors" for including this effect when drawing up biofuel balances are under discussion. These indicate the volume of emissions arising from indirect land use changes. The ILUC effect is driven by globally rising prices for agricultural raw materials as a result of the support provided for first generation biofuels, namely motor fuels produced from agricultural raw materials such as vegetable oils or cereals. As a consequence, there are also greater incentives to extend cultivated areas, which leads to greenhouse gas emissions. The magnitude of these effects is disputed and cannot be directly measured. All that is possible is to make an estimate using

147 However, RED only controls biomass for bioenergy use. However, since, for example, over 90 per cent of global palm oil production is used in the food and feedstuffs sector, conserving forest areas solely on the basis of the proportion used for energy purposes is largely ineffective.

148 Integration of the transport sector into the EU ETS is the subject matter of a request submitted to the German Parliament by the FDP parliamentary group (Deutscher Bundestag 2018).

numerical simulation models, the results of which are in turn dependent on disputed assumptions. One alternative under discussion is to certify 'ILUC-free' products. In this case, the producer must ensure that no food production is displaced by the production of biomass for use as energy.[149] Furthermore, the RED retains sustainability certification while more vigorously supporting the use of residues and waste materials in order to reduce the risk of indirect land use changes.

In the negotiations regarding RED II, the European Parliament demanded the introduction of **import bans** for palm oil used for energy.[150] This proposal is controversial, firstly because it would exclude manufacturers who are already producing bioenergy sustainably from the market. Secondly, an import ban would lead to substitution effects: instead of palm oil, other vegetable oils such as soya or rapeseed oil, which are subject to similar ILUC risks, would come onto the European market. And finally, a ban would merely shift palm oil use elsewhere because the palm oil previously put to use as bioenergy would be used to a greater extent in the food processing industry where it would displace other vegetable oils which would then be used for bioenergy production. In a nutshell, an import ban might do almost nothing to curb deforestation in the main vegetable oil exporting countries. Controlling deforestation by regulating bioenergy ultimately has only a slight effect because only a small proportion of agricultural production is actually used for producing energy. Forests ought instead to be protected by direct political measures at a national and international level. One of the necessary measures which should, for example, be investigated is an extension of existing approaches to certification into all areas of biomass use.[151] It is primarily the task of all nation states also actually to implement existing and future bans on deforestation. This could also be supported by compensation payments within the framework of the Paris Climate Agreement.

## 5.2 Energy, agriculture, forestry and environmental policy as components of an integrated bioenergy policy

The many and varied sources from which biomass is supplied mean that there are aspects of bioenergy which relate to agriculture, forestry and waste management policy as well as nature conservation. These interfaces make it a special case in comparison with other energy sources. In addition to its functions in the energy system, bioenergy also makes further systemic contributions: possible positive effects in the land use system,[152] a disposal or utilisation function at the end of cascade processes[153] and, in the case of BECCS, removal of $CO_2$ from the atmosphere. Figure 6 brings together the various sectors with bioenergy impact. In the long term, it would therefore be desirable to have a bioenergy policy which takes a holistic view of the energy system, greenhouse gas emissions, waste management strategies and land use as an integrated system.

149 This may, for example, be the case if residues and waste materials are used, the biomass is cultivated on previously unused land or it can be proven that the biomass for energy use is cultivated in addition to the crops previously cultivated on the area.

150 EU 2018-2.

151 Majer et al. 2018.

152 Examples include making crop rotations more flexible in arable farming areas, water-conserving cultivation, provision of organic fertiliser, cultivation of bee-friendly energy crops (e.g. cup plant).

153 Including avoidance of greenhouse gas emissions by residues and waste materials (e.g. in biogas production from animal slurry and solid manure).


**Figure 6: Sectors with potential impacts from bioenergy[154]**

This requires interaction between the many policy portfolios with responsibility for bioenergy-related fields and **coordination or harmonisation of the various funding or governance mechanisms**.

To date, producing energy with biomass in Germany has, for the most part, been controlled by energy sector incentive systems and regulations. These include in particular the German Renewable Energy Sources Act, the market incentive programme for promoting measures for the use of renewable energy sources in the heating market (MAP) and the German Biofuel Quota Act. Effects outside the energy system are, however, not addressed sufficiently. On the one hand, pressure on the operators of bioenergy plants is increasing because bioenergy is in competition with other renewable energy sources, and raw material costs have a major influence on whether and to what extent it is economically viable to make use of bioenergy. On the other hand, energy-sector payments today are already funding services which are of benefit to other sectors, thereby cutting costs in these sectors.

154 Based on IZES et al. 2018-1.

One example is biogas plants which make use of animal slurry and solid manure and so contribute to greenhouse gas savings in the agricultural sector. Processing into biogas results in the avoidance of emissions which would otherwise occur during conventional storage and the spreading of animal slurry and solid manure.

If bioenergy is measured solely on the basis of its economic effects in one area (e.g. electricity price trends), external costs and benefits in other areas are usually insufficiently taken into account. However, an **awareness and inclusion of these external costs and benefits** would be necessary in order to decide whether a policy instrument for promoting the competitiveness of sustainably produced bioenergy makes macroeconomic sense.[155]

Even comprehensive climate policy measures such as a $CO_2$ price cannot alone reasonably control the complex interplay of alternative land uses and bioenergy use; they must be coordinated with instruments for achieving other policy goals. **Water quality, nutrient cycles and biodiversity** are of particular relevance here.

There is still a considerable need for debate, which goes beyond bioenergy, around the **economic effects of these "ecosystem services".** While there are indeed approaches which attempt to classify and shed light on the interrelationships between ecosystems and human well-being[156] , they have not yet been transferred to specific funding and incentive models. Isolated approaches to ensuring better remuneration for biomass from near-natural ecosystems (e.g. in EEG 2012) rapidly fell victim to a debate around costs and do not provide sufficient experience.

At present, there are virtually no **incentives to ensure biomass is supplied in as environmentally friendly a manner as possible**. For instance, investigations have shown that using environmentally sound rotations and cultivation methods is barely economically viable under the current funding mechanisms. Additional or alternative instruments are therefore necessary.[157]

Market-based instruments such as, for example, emissions trading are generally more cost-effective than regulatory measures. Including external costs relating to water resources and soil quality, nutrient cycles and biodiversity in prices is, however, substantially more complex and difficult to implement than pricing greenhouse gases. Macroeconomic harm caused by impairment of ecosystem services may therefore in many cases be more effectively prevented by regulatory provisions (e.g. legal limits on pollutants or restrictions on the use of environmentally valuable areas).

There is still a considerable need for research into the possible impact of future biomass use in some areas and not just in relation to energy production. For example, there is **major uncertainty about the medium-term effects which might possibly arise from making greater material use of cultivated biomass**. In the past, biomass has primarily been used as a raw material for producing derived timber

155 The German Bioeconomy Council accordingly recommends developing a uniform evaluation framework which takes account of external costs and can be used to compare bioenergy options and alternatives to bioenergy (Bioökonomierat 2015).

156 For example in the UFZ "Naturkapital Deutschland – TEEB DE 2016" project (https://www.ufz.de/teebde/).

157 For example IZES et al. 2018-2.

products, paper and pulp and in the packaging industry. Applications in which it is a replacement for polymer-based products and chemicals (in a move towards a bio-based economy) are, however, becoming increasingly significant. Should this development be left to the market or, as has been called for by various parties[158], should funding models be put in place here as well? In the absence of corresponding restrictions from sustainability criteria, both mechanisms may possibly lead to similar land-use effects as in the case of expanding biogas plants.

If bioenergy is to be ranked and supported in a way that makes macroeconomic sense, as far as possible, all the contributions to the system made by bioenergy should be evaluated and weighed against one another. The contributions to the system made by alternative forms of land use (e.g. afforestation) and biomass applications (e.g. material use, biochar) should also be compared. **An evaluation system including indicators for all relevant contributions to the system ought to be developed** to permit the evaluation of the various contributions.[159] Energy system models, which have previously only taken account of the contribution made by bioenergy to the energy system, should be extended into **integrated models of the energy and land use systems** or make use of the insights from existing energy/land use models. To this end, various scenarios could initially be calculated in a land-use model, for example with more or less energy crop cultivation, afforestation or biochar use. On that basis, *inter alia* the greenhouse gas emissions from land use in the various scenarios could be determined. The resultant quantity of bioenergy which is available in the respective scenario and the associated greenhouse gas emissions and $CO_2$ removal by biochar and afforestation could then be used as input variables in the energy system model. This would make it possible to compare different scenarios while taking account of effects in the overall system.

### 5.2.1 Agricultural and forestry policy measures

The fact that biomass is in part produced on agriculturally used arable and pasture areas gives rise to interfaces between agricultural policy and a policy for supporting bioenergy. EU agricultural policy applies measures which already have an influence on land use today and could therefore in principle also be used to promote the production of sustainable bioenergy.

EU agricultural policy is generously funded: annual expenditure on the “first pillar” of the agricultural policy is approximately 40 billion euros for direct payments to farmers, some 5 billion of which is paid out in Germany alone. These direct payments are justified firstly as income support for farming households and, since 2013, additionally as payments for environmental services in the context of “greening”. It has, however, repeatedly been shown that both effects are achieved only to a very limited extent.[160] There is therefore a broad consensus that a considerable proportion of the EU agricultural budget could be spent in a more targeted manner than in the past. Among other things, it is conceivable that a policy for supporting sustainable biomass production could be devised using EU agricultural policy measures and funds.

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158 UBA 2014.

159 The evaluation tool developed in the working group provides some approaches for achieving this (Klepper/Thrän 2019).

160 For example, the European Court of Auditors 2016, Pe’er et al. 2016 and EU Commission 2017.

Agricultural policy decisions are taken at the EU level. Majorities in the Council of Ministers and in the EU Parliament would be required in order to appreciably reallocate direct “first pillar” payments to the promotion of sustainable biomass production and use. However, some 12 billion euros annually are available for promoting rural development in the “second pillar” of EU agricultural policy. Individual member states such as Germany can use these funds for specific national and regional measures. It has accordingly been possible in Germany since 2018 to promote the cultivation of specific energy crops such as miscanthus (elephant grass) and cup plant.[161]

Agricultural policy measures and funds could be used as described to promote the sustainable production of biomass for use as energy. By applying stringent sustainability requirements, it could in this way be ensured that energy crops are cultivated in a more climate-friendly and environmentally sound way than in the past. It is, however, uncertain whether the greatest climate protection effect per euro of expenditure could be achieved in this manner. Instead of subsidising the production of bioenergy, agricultural policy funds could therefore be used to promote land use changes which increase carbon sinks in vegetation and soil, for example by afforestation and rewetting of wetlands. These changes are generally accompanied by a loss of profits for farmers which could be offset by support payments. In both alternatives, possible direct and indirect land use changes with climate impact in Germany and abroad would have to be taken into account. Further effects on ecosystems should also be included in the evaluation.

**Forestry policy** in Germany is not anticipated to change substantially due to the use of bioenergy. Wood will in future primarily initially be used as a material, and only be used for energy at the end of the use cascade. When regenerating forests, it should therefore be taken into account which tree species are suitable for which kind of material use. In Germany, short rotation coppices provide the most noteworthy additional wood potential for energy as well as materials production. Such plantations are grown on cultivated areas and are thus governed by agricultural policy rather than by forestry policy. When it comes to using forest wood, the focus should be on making use of the limited potential in the most beneficial way possible for the energy system. It should therefore be used in more efficient plants (e.g. CHP) rather than in open fires as in the past.

The **extension of sustainability criteria for biofuels** to all bioenergy in the context of the revised version of the Renewable Energy Directive[162] is a necessary and correct step towards ensuring a sustainable raw material base. The greatest risks associated with bioenergy, however, involve above all indirect effects, such as indirect land use changes or other displacement effects. These can only be reduced by applying **sustainable land use policies and sustainability requirements to agriculture as a whole**. There are only very limited potential land areas on which competition with food production and serious environmental impacts can be ruled out. Strictly speaking, only using residues and waste materials is completely free of ILUC risks. However, depending on the situation, ILUC risks for cultivated biomass vary considerably. Sustainable cultivation involving low ILUC risk would, for example, be possible on degraded land on which competing uses can be ruled out or minimised, but the data used as the basis for estimating these areas are uncertain. If, for example, the productivity of a

161 Neumann 2017.

162 EU 2018-1.

cultivated area can be increased by improved management, the ILUC risk for the additional produced biomass is likewise low. While approaches to quantifying and certifying the risk of ILUC have already been developed,[163] they have not yet been demonstrated to be robust, effective and generally implementable in RED certification systems.

ILUC models are nevertheless helpful instruments for describing risks. A statement of the effects of bioenergy use on global land use made on the basis of these models does, however, firstly have clear limits and secondly, it does not necessarily provide approaches for avoiding the risks. Other disciplines or a suitable combination of methods could be of assistance here in developing appropriate policies and strategies. ILUC models can act as an early warning system for policy scenarios. For instance, ILUC models could be used to investigate the extent to which different climate protection strategies are associated with an ILUC risk. Further research is required.

When it comes to using forest wood for energy, there is not yet any scientific consensus about whether and under what circumstances such use saves greenhouse gases (carbon debt debate, see section 2.2). Should it in future prove possible to establish effective global protection of ecosystems and of forests as carbon sinks, a cautious expansion of cultivated biomass and forest wood for energy production can be considered. Priority here should be given to biomass with the least possible ILUC risk. The extent to which sustainability can be ensured and whether less risky alternatives (e.g. other renewable energy technologies) are available will then, however, have to be carefully examined. Ensuring a sustainable raw material base can also alleviate social conflict around the use of cultivated biomass (e.g. “maize monoculture” and “competition for food production”).

**Measurement programmes for nitrous oxide emissions** in agriculture could assist with more accurately recording greenhouse gas emissions caused by the use of nitrogen fertilisers (see also section 2.2). The more accurately the greenhouse gas balance is determined, the more readily can a $CO_2$ price contribute to reducing emissions.

Making sustainable use of biomass from agriculture and forestry requires **nutrient cycles** to be closed. Each time biomass is removed, plant nutrients are also taken out of an ecosystem. These nutrients should be returned to the system. If biomass is burnt, the mineral substances remain in the ash. Using ash for fertilisation could contribute to closing nutrient cycles.

#### 5.2.2 Measures in the waste management sector[164]

Plants which recover the energy content from waste already use more than 50 per cent biobased waste[165] as feedstock today. Due to the increasing material use of biomass, the quantity of biogenic waste will in future probably continue to rise in both percentage and absolute terms. Particularly for lignocellulose, **use cascades** in which cultivated biomass and wood[166] are initially put to material use and, at the end of the product’s lifetime, used to produce energy, facilitate an efficient form of biomass use.

163 For example ECOFYS 2016, Ernst & Young 2011 and RSB 2018.

164 Reference to organic residues and waste materials as defined in Germany’s Waste Management and Product Recycling Act.

165 i.e. biomass; according to Dehoust et al. 2010.

166 See German Charta für Holz 2.0 scheme.

However, pollutants can accumulate over the stages of the cascade, for example, due to treatment of the wood with impregnating agents or colorants. This can be avoided by **low-pollutant, readily recyclable design of biobased materials** and products. Bioenergy plants using residues and waste materials must be adapted to their respective feedstocks (in particular pollutant contents).

As explained in section 2, there is further **residue and waste material** potential involving only slight risks to the environment and food security. In excess of 100 terawatt-hours of forest wood residues, cereal straw and animal excrement could additionally be put to use as energy in Germany. If greater volumes of these materials are to be used as feedstock in bioenergy plants in the future, **economically dependable funding models** which permit a gradual changeover from using energy crops or forest wood to residues and waste materials will be required. Policy measures which provide an incentive for greater use of residues and waste materials should only result in existing residues and waste materials being used more efficiently. Incentives which lead to the generation of additional residues and waste materials should be avoided.

At present, energy-sector funding mechanisms (in particular EEG) make a significant contribution to meeting the requirement for high-quality recovery[167] in the waste management sector set out in Article 8, paragraph 1 of the German Resource Cycle Management Act (KrWG). Using biowaste in biogas plants achieves greenhouse gas savings in comparison with other waste management methods. Generating energy from waste wood allows greenhouse gas reductions to be achieved with very low levels of financial support. In the past, however, inadequate requirements for the efficient use of energy and excessively high subsidy rates led to the construction of waste wood plants, the generated heat from which was not always used completely. Establishing approaches which make sense in energy terms is therefore an important prerequisite if waste wood is to be put to use efficiently.

As a consequence of 2017's revised version of the German Renewable Energy Sources Act (EEG), some of the waste and residue streams (e.g. animal slurry and waste wood) currently put to use in producing energy could become available again over the coming years. Firstly, EEG support for bioenergy plants, which currently use these material streams, will come to an end over the next few years. Secondly, additional construction of new bioenergy plants and the ongoing operation of existing plants through participation in EEG calls for tender are limited by current legislation. Accordingly, the current version of the Biomass Ordinance *inter alia* no longer lists waste wood among recognised biomass,[168] and no claim for payment can therefore be made pursuant to the EEG (Article 19, EEG 2017).[169] The existing landfill prohibition does indeed mean that waste wood would then increasingly be put to material use. However, material use is mainly only possible for uncontaminated waste wood.[170]

167 This legislation requires implementation of the utilisation measure which is the best option for protecting humans and the environment.

168 German Ordinance on the Generation of Electricity from Biomass (Biomasseverordnung 2016).

169 German Renewable Energy Sources Act (EEG 2017).

170 Waste wood categories I and II.

If it is to be possible to continue putting these waste and residue streams to use for producing energy in the future, appropriate short-term legislative measures would have to be put in place. One option would be a comprehensive recognition of residues and waste materials as biomass as defined in the Biomass Ordinance.

In the medium to long term, however, the waste management sector will require an overall strategy which takes account of the following factors:

- Pursuit of an integrated funding approach in support of a circular economy. At present, the existing regulatory and funding landscape is highly fragmented and does not enable the efficient use of organic residues and waste materials.
- Creation of a genuinely circular economy by closing material cycles.
- Cascade use in the circular economy should be rigorous, i.e. involving numerous stages with a high degree of material use and considerable value creation. The organic waste and residues from the cascade should then be used for producing energy (taking into account the emissions limits of the 17th Federal Pollution Control Ordinance (BImSchV)).
- Pollutant levels should be kept low within the circular economy. There is therefore a need for an additional route for utilising severely contaminated or polluted organic residues and waste materials.
- Improvement of the collection of biogenic waste (including implementation of segregated collection of biogenic residual household waste).

## 5.3 Political and social dialogue

Biomass use is a recurrent theme of social dialogue. Feelings do not infrequently run high when the focus is on odour nuisances, changes to the landscape or the “food-versus-fuel” debate. Issues such as CCS or BECCS, which are currently the subject of scientific investigation in connection with biomass use, have not yet reached the general public and are also very largely unresolved in the wider political and social debate. Experience has so far revealed a wide range of responses and activities in society: when increasing use of bioenergy began to be made in the context of developing renewable energy sources, attitudes among the population tended towards neutrality. As bioenergy became more widespread, local resistance sometimes increased. For instance, local residents have been strongly critical of biogas plants which have actually been built due to the odour nuisance and noise caused by plant operation. This has also had a negative impact on acceptance.[171] At the same time, however, acceptance of bioenergy plants has grown in connection with bioenergy villages which obtain a large proportion of their electricity and heating requirements from regionally produced biomass.[172]

171 Kabasci et al. 2011.
172 Wüste et al. 2011.

Central stakeholders, residents or entire ‘bioenergy regions’ have been coming together and jointly creating active acceptance of the energy transition at a local level.[173,174] In the mobility sector (blending with petrol, ‘E10 fuel debate’), however, there has been a collapse in acceptance.[175]

Using fuelwood is commonly thought to be “environmental” and a “good thing”, while expert opinion would tend to call this into question. However, even the experts are not in agreement in every area (e.g. regarding the climate protection contribution made by bioenergy). As a result, given current scientific knowledge, it is not possible in some cases to make unambiguous recommendations. Coming to a well-founded decision, however, precisely requires a careful weighing of advantages and drawbacks, of various social demands and possible “impositions”. If society is to be successfully transformed, the population must play an active part in shaping the future.[176] A broad-based social dialogue, further opinion making and establishing links with society’s values will also be required. There would also appear to be an urgent need for backup from the social sciences to bring into play not only more recent technical approaches but also behavioural measures which assist in meeting society’s “major challenges”. The results from climate protection scenarios which demonstrate the necessity for negative emissions would appear to be virtually unknown to the wider public. There is an almost complete absence of any new scenarios which both weigh all possible technical options (including BECCS and other $CO_2$ removal technologies) and combine them with social interests (values) and possibilities (changes in behaviour).

Discussions must be carried out with broad participation of the most varied stakeholder groups and political decision makers, using adequate formats for discussion process. They should involve various levels (local, regional, national and international) and help to integrate cross-sectoral issues such as the energy transition, climate protection and agriculture (and hence associated dietary habits). It must be borne in mind that opportunities for involvement differ between technological options: technologies for producing biofuels and capturing $CO_2$ often require relatively large plants. These therefore have distinctly less potential for involvement on the part of different stakeholders, and for wealth creation and employment effects at a regional level than, for example, smaller CHP plants do. Similarly, conflicts of interest at different levels would have to be reflected and made transparent while policy objectives would have to be clearly communicated and set out as a guiding framework. For example, possibly dispensing with BECCS means that it may be impossible or at least substantially more difficult and costly to remove $CO_2$ from the atmosphere. In that case, climate protection targets would have to be achieved to a greater extent via other strategies, for example via a significant change in individual consumer behaviour with regard to eating meat or travelling by air. Such interrelationships should be clearly explained, debated and weighed.

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173 Active acceptance means not only having a positive attitude towards the issue in question but also behaving accordingly, i.e. being personally committed to and supporting a specific plant or, in this case, moving towards a bioenergy village (cf. Hildebrand et al. 2018).

174 Kortsch et al. 2015.

175 Schütte et al. 2011.

176 Lutz/Bergmann 2017.

If the debate in society is to be constructive, all relevant aspects must be comprehensively and transparently disclosed. Only in this way will it be possible to have a well-founded discussion around social values (what is particularly worthy of protection, desirable, etc.) and the options for action and their consequences.

**Wide-ranging debates at various levels and with different stakeholders** are vital to the development of a sustainable bioenergy strategy which is embraced by society. Participatory processes should firstly involve higher-level social themes relating to major social transformation and provide a deeper discussion of values. Secondly, however, they should also address specific regional and local planning procedures. It is also essential for participatory processes to be carried out professionally. Only those solutions which are built on a broad consensus will in the long term also be acceptable to the majority of the population. Knowing the room to manoeuvre is very important here and this should be explained as specifically and transparently as possible. This relates not only to goals and measures but also the extent to which joint decision-making and participation is possible. It must always be clearly communicated where there are limits to joint decision-making. This is a matter of explaining that there are different levels of responsibility and that the decisions taken should always be of assistance to the major social transformation which is required.

The extent to which society explicitly desires a decentralised energy supply in future will play an important role in the **debate in society as a whole**.[177] Climate protection and agriculture must definitely be included in this debate if a holistic perspective is to be obtained. In addition, **stakeholder-specific dialogue** should throw light on possible future trends and associated consequences in manufacturing, transport and use (and also storage in the case of BECCS). This concerns many and varied issues, from competition for land through raw materials and grid capacity to safety and consumer behaviour. Options for economic participation by different stakeholder groups should also be addressed. These issues relate to various criteria which are of relevance to acceptance, such as risk evaluation, autonomy, costs and perceived equitable distribution.[178]

The effort which must be made to include bioenergy sector stakeholders and the general population differs depending on the transformation pathway. In the case of biogas, a transformation from local biogas use to biomethane provision would appear relatively straightforwardly possible in light of the evaluation criteria taken together. Effects on stakeholder structures are comparatively slight. In terms of possible operators and raw material supply chains, a biomethane plant hardly differs from a biogas plant. Stakeholders and the population must, however, be fully involved, in particular with regard to the raw materials used, in order to ensure a sustainable raw material base and counter any reservations on the part of the population. A development towards wood-based biorefineries for fuel production is a more fundamental decision with greater impact on the stakeholders involved.

177 The strength of the trend towards energy supply decentralisation in the future depends on many factors, including the development of smaller scale digital business models. The ESYS working group "Centralised vs. decentralised power supply" is investigating this bundle of issues.

178 Equitable distribution is a measure of the subjective balance of tangible and intangible costs and benefits. It is thus of significance not only to financial benefits but also certainly to other aspects such as attitudes toward life, pride or identity. Perceived costs include aspects such as landscape changes and a reduction in quality of life. These evaluations should be taken to be subjective and mainly relate to the local or regional level.

In this case, more issues of equitable distribution, autonomy and regarding raw materials use would be raised for the wide variety of stakeholders involved than in the case of changing over from biogas to biomethane production.[179] Intensive discussions would therefore be essential.[180]

One decision which has far-reaching consequences for the future shape of climate protection options is whether CCS technology should or should not be used. If the decision is against, not only BECCS but also direct air capture will not be usable as a $CO_2$ removal technology, which has major climate protection potential and involves little demand for land. There is therefore a need for **a debate in society as to whether and for what purposes CCS should be used**, since CCS is currently highly controversial in Germany. In Germany, CCS has in the past been discussed in particular in connection with lignite-fired power generation. Further research should *inter alia* address the question of the acceptability of this technology if the $CO_2$ did not originate from the power generation sector (coal and gas), but instead from BECCS or DAC plants. While it was indeed not least the storage aspect of CCS which was criticised, some of the unease would also appear to be due to the fact that low-emission alternatives in the form of wind and photovoltaics are available in the power sector. A critical discussion about $CO_2$ removal technologies with CCS will therefore always also include the alternative $CO_2$ removal technologies without CCS. There is a need for research into the conditions under which CCS would be accepted. For example, one conceivable approach would be to require that it be plausibly ensured that all other climate protection options are exhausted first and CCS is only used as a final fallback solution. Another conceivable approach would be to require that it be ensured by law that CCS is used only for bioenergy and unavoidable industry emissions, but not for coal-fired power stations.[181]

**The potential and risks of alternative $CO_2$ removal technologies** such as DAC, wetland restoration, afforestation and biochar should be investigated accordingly and communicated from the outset because above all, the environmental impact, long-term carbon balance and costs of these technologies are currently still very uncertain. More wide-ranging research should also be carried out into the perceived social risk and acceptance of the various technologies.

In the debate in society, new technologies are in some cases detached from the context of possible alternative future developments. The implicit reference scenario for the use of BECCS is thus assumed to be a world "like today's". The risks of BECCS are considered in absolute terms but are not compared with the risks of dispensing with BECCS (use of alternative $CO_2$ removal technologies or less climate protection). Such arguments can only be countered by clearly explaining the urgency of taking action on climate policy. Policy objectives should be clearly communicated and emphasis placed on the accompanying obligations. **Political agreement about a zero emissions target** (for the purposes of national implementation of Article 4 of the Paris Climate

179 Imported biomass for biorefineries in the form of woodchips and timber residues could be addressed here because they are relevant to the issues at hand and also raise issues of justice at a global level.

180 This is the result of applying the traffic light scheme presented in section 4 to the development pathways and is described in detail in Klepper/Thrän 2019, section 5.

181 Such aspects were mentioned by the participants in the consultation 'Energy transition trialogue: correctly evaluating and using bioenergy potential and curbing side effects. What form should a long-term bioenergy strategy take?', which was carried out on 23.02.2018 by the 'Energy Systems of the Future' project and the HUMBOLDT-VIADRINA Governance Platform.

Agreement) would be a very promising milestone.[182] The focus would then continue to be on conventional emissions abatement strategies. Any "residual" emissions (for instance from aviation or agriculture) would, however, have to be offset by initially limited use of $CO_2$ removal technologies. The **complementary nature of the various measures should be clearly emphasised**: $CO_2$ removal, for instance by BECCS, does not in any way replace other climate protection measures. Energy savings, the expansion of wind and solar energy, energy efficiency and sufficiency are also necessary. Dispensing with $CO_2$ removal options reduces the likelihood of achieving widely accepted climate protection targets. **The risks posed by $CO_2$ removal technologies therefore stand in opposition to the risks of climate change**. Even political stakeholders have so far not focused on this trade-off.

It would be helpful to create various scenarios with consistent volume frameworks for achieving climate protection targets. For instance, how many additional wind and photovoltaic installations would be necessary if bioenergy use continues to be decentralised and the necessary negative emissions are provided by direct air capture? Could the use of CCS be substantially reduced or even made unnecessary by bringing about a root-and-branch transformation of consumer behaviour, for example with dietary habits?[183] **Comparing different scenarios** could help to create clarity and transparency about the consequences of using or dispensing with specific technologies. Such a comparison could serve as a basis for decision-making in the social dialogue. Finally, it must be emphasised that a social dialogue is not inconsistent with the need for immediate action on the part of political stakeholders, but can, in a complementary and ongoing process, instead have a corrective effect.

## 5.4 Developing signposts for transformation pathways

The available sustainable biomass potential will in future decisively determine the extent to which bioenergy use is possible. The greatest potential is anticipated to be in lignocellulose biomass, followed by wet, fermentable waste and residues. The technologies will have to adapt to these more difficult and unconventional feedstocks.

The way in which biomass is used primarily depends on **three developments**:

1. Will combined heat and power generation be a mainstay of the energy transition?

2. Will liquid biofuels made from lignocellulose (wood, residues and waste materials) be commercially introduced?

3. Will society come to terms with using CCS as part of the climate protection strategy?

182 Geden 2017.

183 Investigation of this issue shows that even in the case of very wide-ranging changes in consumer behaviour (lower meat consumption, use of more environmentally friendly means of transport, less use of heating and air conditioning, introduction of cultured meat as a food) and very optimistic assumptions about progress with climate-friendly energy technologies for achieving the 1.5°C target, $CO_2$ removal technologies will still be necessary to some small extent (Vuuren et al. 2018).

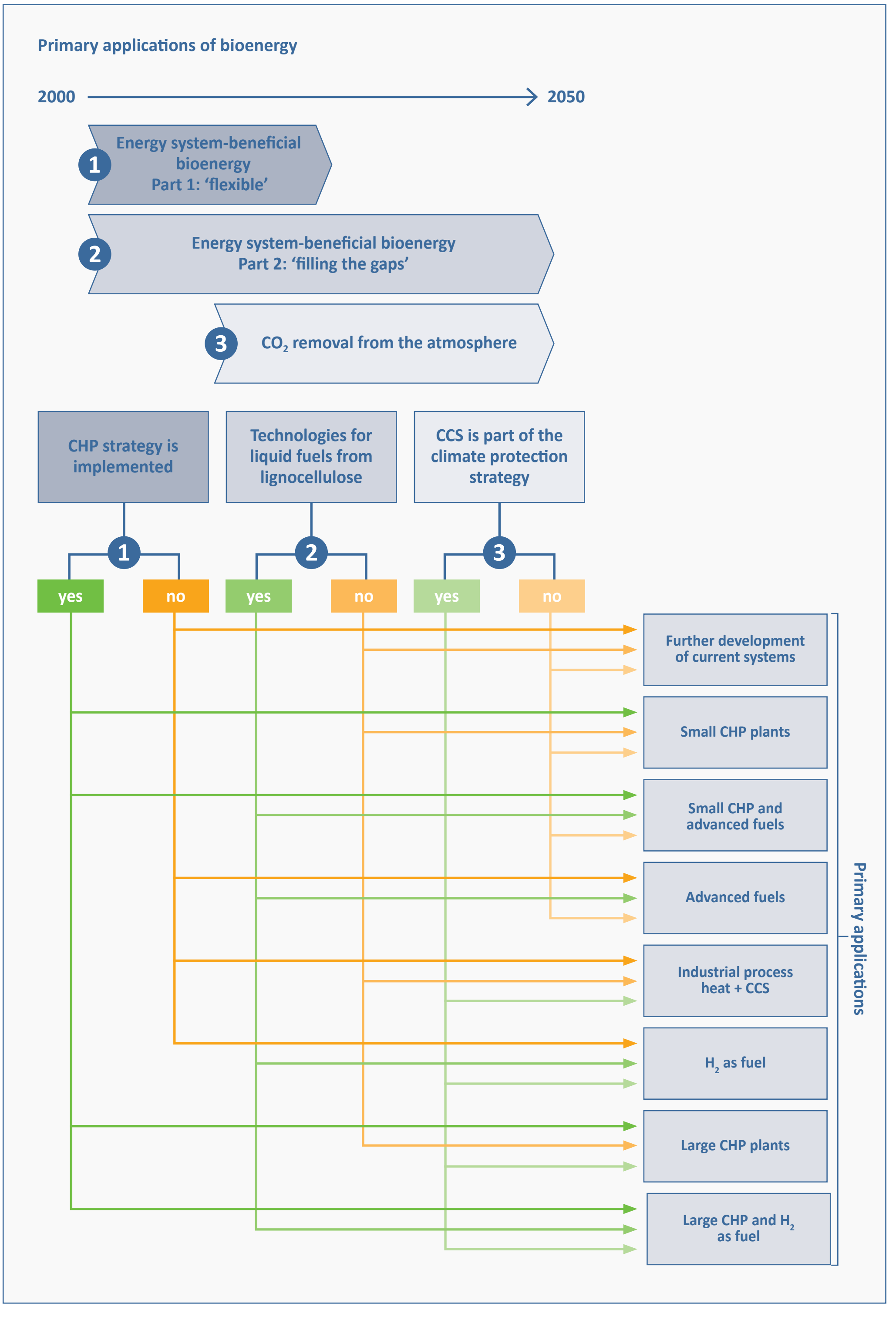


Figure 7: Prioritisation of bioenergy use options

The outcome of these developments will determine which bioenergy technologies are put to priority use. Figure 7 sets out the dependencies between the three higher-level developments and the technologies.

**Flexible CHP technologies** based on natural gas, biomass or other renewable energy sources will already in the near future be able to contribute to stabilising the fluctuations in power generation from renewable sources and at the same time substantially assist the energy transition in the heating sector. Industrial plants or urban areas can be supplied here not only by small, decentralised plants but also by larger ones. This presupposes the expansion of modern gas-fired power stations and heating networks. At present, investment in combined heat and power generation is not being systematically supported, despite this technology playing a major part in many energy scenarios. Should CCS become part of the climate protection strategy, large biomass CHP plants can be equipped with $CO_2$ capture and contribute to producing negative emissions. While today, biogas can already be upgraded to **biomethane** and used both in combined heat and power generation and as motor fuel, it is unclear whether and when liquid motor fuels will be commercially available if lignocellulose (in particular timber residues) is used as feedstock.

**Liquid biofuels from lignocellulose** can make a valuable contribution to the energy system both with and without CCS. For biorefineries with CCS, it would be expedient to produce hydrogen instead of carbon-containing motor fuels since higher negative emissions could be achieved in this way. The extent to which hydrogen will be used in the energy system of the future depends on whether appropriate infrastructure is put in place.

Generating **process heat in industry** with biomass could serve as an initial trial for BECCS, if **CCS** is to be used in the future. If CCS does indeed become part of the climate protection strategy, from today's perspective many industrial plants will in any event be connected to CCS infrastructure in order to capture process-related emissions.

If **CCS technology** is rejected by society, there is no breakthrough in the production of motor fuels from lignocellulose and biomass CHP cannot be expanded over a sufficiently large area due to the absence of heating networks, further development aiming at a system-beneficial use of bioenergy will primarily focus on decentralised systems. In this case, while bioenergy will indeed be able to contribute to climate protection and energy supply, it will be less readily able to meet other requirements for ensuring a greenhouse gas-neutral energy supply such as motor fuel applications or BECCS. Contributions to the energy system would then, for example, be possible by means of gaseous biofuels (biomethane or biomass gasification products), while biochar could contribute to negative emissions. If the answer to at least one of the above-stated questions is positive, various development pathways will be available for a system-beneficial transformation of bioenergy use.

The sustainably usable biomass potential is not sufficient to meet total demand in the fields of application under discussion. Table 7 provides an overview of anticipated final energy demand in 2050. Using bioenergy would appear to be primarily of interest in applications which will remain dependent on combustion and motor fuels in the long term. These include, in particular, aviation, shipping and heavy goods transport, together with the generation of high-temperature heat in industry. However, there are also specific power and heat generation applications in which biomass is an attractive energy carrier.

| Application | Annual final energy demand 2050 (TWh) |
|---|---|
| Aviation[184] | 100–120 |
| Shipping[184] | approx. 140 |
| Long-distance road transport | 90–130 |
| Local road transport | 160–250 |
| Rail transport and public service buses | 15–20 |
| Medium- and high-temperature heat demand in industry | approx. 320 |
| Low-temperature heat demand (heating, hot water in the buildings sector and low-temperature heat in industry, commerce, trade and services) | approx. 400 |
| Original electricity applications[185] (including network and storage losses) | approx. 450 |

**Table 7: Final energy demand in Germany for various applications in energy scenarios in 2050[186]**

Traffic forecasts assume that transport volumes in aviation, shipping and heavy goods transport will rise sharply over the coming decades, possibly more than doubling by 2050. Despite considerable gains in efficiency that could cut the specific energy requirements of the various vehicles, aircraft and ships by a quarter to a half, total energy demand in these areas will remain at least at the current level and may even rise further.[187] An energy requirement of 300 to 400 terawatt-hours per year will therefore remain in the long term, the majority of which will have to be met by motor fuels. The approximately 300 terawatt-hours of residues and waste materials which would be available to Germany each year if it tapped previously unused potential could, allowing for conversion losses, meet around half of this future fuel demand. A considerable additional fuel requirement would arise should it not prove possible to convert the great majority of local transport to electromobility.

Ensuring greenhouse gas-neutral energy supply will therefore in any event also require the development of electricity-based synthetic fuels (power-to-gas, power-to-fuels) in addition to biofuels. Apart from liquid fuels, hydrogen or methane (from biomass or electricity) can potentially be used at least in shipping and road transport.

In industry, bioenergy can above all be used to meet demand for medium- and high-temperature heat. Low-temperature heat can be efficiently provided by means of heat pumps or waste heat. Demand for process heat at temperatures of above 100°C up to in excess of 1,000°C is today approximately 420 terawatt-hours per year. If demand can be reduced by a quarter by 2050, 315 terawatt-hours will still have to be supplied.

184 including Germany's share of international traffic.

185 "Original electricity applications" are those fields which are also today to a great extent supplied by electricity, such as lighting, ICT, domestic appliances, refrigeration equipment, pumps, ventilation and air conditioning. Electricity demand from "electrified applications" such as electric cars or electrical heating systems is not included.

186 Based on acatech/Leopoldina/Akademienunion 2018-1, Ausfelder et al. 2017, UBA 2016-2, UBA 2015 and BMWI 2017-2 (reference scenario with 85 per cent greenhouse gas savings).

187 UBA 2016-2.

At an efficiency of 85 per cent, available biogenic residues and waste materials can be calculated to meet approximately 80 per cent of this demand. However, their technical suitability, in particular for high-temperature processes, must be checked. A proportion of process heat could in the long term also be produced with electricity (e.g. electric steel production).[188] If bioenergy is primarily used in other applications (e.g. fuel production or CHP), electricity-based energy carriers (hydrogen or methane) or fossil fuels with CCS would probably have to be used to ensure climate-friendly process heat generation.

A large proportion of the heating demand in the building sector will in future probably be met by heat pumps. Nevertheless, in some energy scenarios, over 100 terawatt-hours of combustion fuels will still be being used for heating buildings in 2050.[189] Bioenergy could make a contribution here. However, use in CHP plants with the input of the generated heat into local or district heating networks is more efficient. By 2050, one third of buildings, corresponding to the heating demand of approximately 180 terawatt-hours, could be connected to heating networks.[190]

Power generation will probably rise sharply because, in addition to the original applications for electricity, increasing levels of supply will have to be provided for electric vehicles, heat pumps and power-to-gas plants. As a result, total electricity demand could rise to 700 to 1,000 terawatt-hours by 2050. In power generation, bioenergy is above all attractive as a flexibility technology for compensating fluctuating feed-in of wind and solar power. The level of demand for combustion fuels for power generation in the future depends to a great extent, among other things, on how far it is possible to utilise compensating effects in the European integrated grid. Various scenarios indicate that in 2050, some 10 per cent of power could be generated in load-following combustion power plants (in part in CHP plants).[191]

If all the unavoidable emissions from agriculture and industry are to be handled with BECCS, from around half to the entire volume of biomass previously put to use producing energy would have to be processed in bioenergy plants with CCS.[192] Since $CO_2$ capture consumes energy, the possible contributions to the energy supply would reduce.

The preceding observations show that the total energy demand in the fields of use in which bioenergy in principle appears to be attractive is far greater than the anticipated bioenergy potential. Applications will therefore compete for biomass potential. Some current biomass streams will have to be diverted to new applications, resulting in changes to the stakeholders involved, the necessary business models and local integration. Both science and politics often focus on the "world" of today and the one which is desired for 2050. The intervening period which is of importance to the stakeholders on the ground is often neglected, which potentially gives rise to acceptance problems. The primary concern for the affected stakeholders is their ability to plan. This means that policymakers must state climate, energy and environmental goals in binding terms,

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188 The "Greenhouse gas-neutral Germany" study reveals, for example, how demand for combustion fuels in industry could be reduced to 200 terawatt-hours by a fundamental transformation of many production processes (UBA 2015).

189 BMWI 2017-2.

190 Ausfelder et al. 2017.

191 Ausfelder et al. 2017; BMWI 2017-2; acatech/Leopoldina/Akademienunion 2016-2.

192 See Klepper/Thrän 2019, table 5, estimated with unavoidable emissions of 60 million tonnes per year on the basis of UBA 2016.

and that measures for achieving these goals must be implemented transparently and consistently.

However, policymakers face the challenge here that it is uncertain whether implementation of the stated bioenergy development pathways will be successful. Accordingly, despite huge research and development efforts, there is no guarantee that there actually will be a breakthrough in the production of fuels from lignocellulose. The use of BECSS may be thwarted by social resistance to CCS. If a firm commitment is made to one of these development pathways too early on, there is a risk of going up a "blind alley". Subsequently pivoting to a CHP strategy is very time-consuming due to the long investment cycles in the buildings sector. The use of CHP technology is associated with less technical or social uncertainty. Deciding to follow this development pathway reduces the risk of failure. However, from a systemic standpoint, CHP systems make a limited contribution to ensuring an energy supply which is climate-neutral, reliable and as inexpensive as possible. Bioenergy cannot then contribute to fuel production and $CO_2$ removal. The technological and social risk is thus merely shifted from bioenergy to other technologies and energy carriers, given that there is just as much uncertainty about the commercial introduction of the electricity-based production of synthetic fuels as about biorefineries. It is likewise uncertain what potential alternative $CO_2$ removal technologies have and whether they will be more readily accepted by the population than BECCS.

However, if all development pathways receive equal support and it proves possible to bring all the technologies successfully into service, they will compete for biomass because the sustainable biomass potential is insufficient to cover all development pathways to their full extent. This therefore gives rise to the risk of supporting technology pathways for which there will ultimately be little or no biomass available.

When formulating a bioenergy strategy, a balance must therefore be struck between committing too early to a path dependency and the greater effort involved in keeping additional options open. Given that the energy system must be virtually climate-neutral in just three decades, time is too short to permit a sequential approach in which one development pathway is initially investigated and, in the event of failure, another one is pursued.

In order to ensure that bioenergy makes the greatest possible short- and long-term contribution to the energy system and to climate protection, existing concepts for bioenergy use should be progressively further developed. This includes making increasing use of environmentally friendly raw materials such as waste and residues and environmentally soundly grown cultivated biomass instead of conventional energy crops. The contribution to the energy system can be increased firstly by making more efficient use of input biomass (full utilisation of the heat in biogas plants, efficient wood-fired CHP instead of pure heat generation), and secondly by flexibly generating electricity and heat in order optimise the interplay with wind power and photovoltaics.

In parallel, concepts for future biomass use in a GHG-neutral economic system should be developed and trialled because not only the energy system but also the industrial sector will have to be very largely GHG-neutral by 2050. Production processes using biomass or $CO_2$ (carbon capture and utilisation, CCU) as the carbon source will have to be established for carbon-containing products and materials which are currently made from fossil resources. Biorefineries for manufacturing motor fuels (in particular for aviation) in combination with other products (e.g. basic chemicals) may play a key role here. If solutions which will be dependable in the long term are to be developed, it is vital to coordinate thinking about the energy system and industry of the future, biomass and CCU and to develop integrated concepts.

In addition, there is an urgent need to clarify the extent to which BECCS can and should play a role in climate protection strategy. This entails comparing BECCS with alternative technologies that can remove $CO_2$ from the atmosphere (*inter alia* afforestation, biochar, direct air capture). However, there has so far been major uncertainty with regard to the potential, costs and risks of the various $CO_2$ removal technologies. Further research should be carried out to create a better knowledge base for this comparison. Options for substantially reducing the use of CCS or even making it unnecessary, for example by root-and-branch changes in consumer behaviour, should be investigated with regard to their potential and included in the comparison. On this basis, there should be renewed debate as to whether and under what conditions CCS is acceptable to society in combination with bioenergy or direct air capture. A technical trial of BECCS in particular in industry would be useful. Synergies between CCU and CCS could also be exploited here because they differ only in how they use $CO_2$ but not in how they obtain it.

The following measures can progressively improve the sustainability and benefits of bioenergy for the overall system.

### 5.4.1 Making the sustainable raw material base usable

An analysis of biomass potential has shown that increasing use should be made of residues and waste materials for producing bioenergy in the future. These are produced in other sectors (see section 5.2), but are of lower and less stable quality than, for example, conventional energy crops. Technologies for upgrading the residues and waste materials must therefore be developed and bioenergy technologies adapted to handling a wider range of raw materials. In addition, technologies and infrastructure will be required to enable the tapping, storage and transport of the residue and waste streams.

### 5.4.2 Developing and introducing technologies

*Biofuels from residues and waste materials.* Changing over from established biofuel technologies, for example using maize and oilseed rape, to advanced biofuels based on residues and waste materials throws up major challenges. Securing an ongoing supply of resources is distinctly more difficult at the level of the market participants. In addition, with the exception of biomethane, most technology concepts are not yet established on a commercial scale. The necessary medium-term research and development work is costly and requires ongoing funding and a stable framework.

*Parallel development of lignocellulose-based, integrated CHP technologies and lignocellulose-based biorefineries for fuel production.* Since a decision in favour of one of the two technology pathways cannot sensibly be made at the present time, development should continue on both concepts. These include, in particular, for biorefineries, R&D efforts to improve technologies, reducing costs and obtaining industry involvement for commercial introduction, and ongoing reductions in emissions. At the same time, clear decision-making points should be defined for prioritising biorefinery concepts with CCS or flexible CHP technologies (e.g. commercial introduction of refinery technology and establishment of CCS). A synthesis gas biorefinery in particular provides the possibility of large-scale $CO_2$ capture. Relatively little development effort is required to allow flexible CHP plants to contribute substantially to climate protection in the near future, whereas biorefineries will be ready for service at best in the medium term. Even if biomass were to be primarily used for biorefineries at a subsequent point in time, CHP plants can make a major contribution to achieving shorter-term climate protection targets.

*Finalisation of a national biomethane strategy* which builds on installed biogas capacity and is an important building block of the overarching bioenergy strategy. Possibilities for BECCS biomethane plants should also be investigated. The issue of path dependencies arises less frequently in biomethane production than in the processing of lignocellulose. This is because the technology is already commercially established, fundamental acceptance problems are not to be expected and biomethane can be put to flexible use in any sector.

#### 5.4.3 Shaping the technological environment

*Expansion of heating networks*. Heating networks need to be expanded for the energy transition irrespective of bioenergy use. It is a necessary prerequisite if the CHP transformation pathway is to be pursued further. Should it subsequently be decided to prioritise the biorefinery use of biomass, the heating networks can be supplied from many other environmentally friendly heat sources.

*Social consequences of putting biomass to new uses*. If it is decided to redirect biomass streams into more centralised usage pathways (e.g. biorefineries), biomass will be taken away from previous users. Those affected should be offered acceptable alternatives for their energy supply.

*Eliminating legal obstacles to transformation*. Existing legal stumbling blocks must be removed in order to improve the interplay between bioenergy and other renewable energy sources. These include the provisions of the German Renewable Energies Heat Act (EEWärmeG), which call for an individual renewable energy carrier for heat production and do not permit a combination of different renewable energy sources which might be able to bring about a greater reduction in climate gases. In addition, the incentives provided by EEG for establishing gasifier technologies capable of flexibly generating power and heat in the short term are currently too low.

#### 5.4.4 Creating system knowledge

*Development of a platform for discussing transformation pathways*. In parallel to the further development of bioenergy technologies, the associated effects on stakeholders must be taken into account. Given that bioenergy today is predominantly used in comparatively decentralised plants, the biomass supply chain is generally located regionally and plants are funded and operated by regional stakeholders. Local stakeholders, in particular in the agricultural and forestry sectors, benefit economically from this existing use. In the future, if bioenergy tended to be put to centralised rather than decentralised use, this would have an impact on stakeholders and would lead to a redistribution of the economic effects. When participants are selected for the national discussion platform, it should be ensured that they are representative of every group in the relevant sectors (*inter alia* climate protection, energy industry, agriculture and forestry) and everyone whose day-to-day life is affected. This includes, for example, industry and agricultural interest groups, consumer advice centres, environmental interest groups, local representatives and representatives of various areas of civil society. Since the pending decisions, once consistently implemented, will have a significant impact on people's day-to-day lives (e.g. consumption behaviour), care should be taken to ensure that the circle of participants is as disparate as possible and therefore represents different segments of the population (e.g. differentiated by age, gender and background).

*Developing a monitoring system.* A comprehensive, standardised and regular evaluation of different transformation pathways could make a wide range of influencing variables more transparent, reduce constant changes of course in bioenergy policy and so increase planning certainty for developers, suppliers and operators of bioenergy technologies. So far, however, the system knowledge for permitting a full evaluation of different bioenergy pathways has been absent. The effects of bioenergy use on land use are sometimes difficult to record or are the subject of controversy (for instance in relation to carbon debt and indirect land use changes, see section 2.2). What the attitude of the population and stakeholders actually is towards new technologies such as BECCS in particular is, moreover, uncertain. An improved awareness of such aspects of evaluation is necessary to ensure comprehensive monitoring. The evaluation scheme developed and applied by the working group can be seen as a first step in this direction. The monitoring system could be further developed in the context of the discussion platform.

*Comparing different biomass scenarios.* Firstly, energy scenarios should take the entire range of bioenergy options into consideration, both with and without BECCS, so ensuring that the optimum contribution is revealed from various standpoints.[193] Moreover, integrated models of energy and land use systems should be further developed. In this way, alternative possible uses for land and biomass (e.g. afforestation, biochar) could be compared with bioenergy. This is also of relevance *inter alia* for the comparison of different $CO_2$ capture technologies. In order to ensure that the approaches of the different scenarios are both meaningful and comparable, the input parameters and assumptions for the scenarios could be developed in the context of the discussion platform. Models and results should be transparently disclosed and comprehensibly explained for the debate in society.[194]

#### 5.4.5 Enabling $CO_2$ capture

*Bioenergy use in industry as a possible BECCS application.* Current energy scenarios indicate that process heat generation in industry is an important application for future bioenergy use. The use of CCS is currently also primarily being considered for the industrial sector.[195] If the outcome from trials here is positive, this could also be the first field of application for BECCS. Plant concepts for BECCS in industry should, however, be investigated more closely for this purpose, *inter alia* by process simulations in order to estimate efficiency and costs. The implications of different feedstocks (*inter alia* their chlorine content) for $CO_2$ capture should also be investigated.

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193 Millinger/Thrän 2018.

194 acatech/Leopoldina/Akademienunion 2016-1 discusses the requirements which apply to energy scenarios for policy advice.

195 For example, BMWI 2017-2, PCG/Prognos 2018 (95% scenario) and acatech 2018.

*Development of infrastructure for $CO_2$ transport and storage.*[196] If CCS technology is to be used for industry emissions and BECCS in order to achieve the climate protection targets for 2050, work on developing the transport and storage infrastructure would have to be started in the near future. The extent to which capture from small plants (for instance the biomethane plant considered here) can make macroeconomic sense and be logistically feasible should also be investigated. Direct air capture, one of the few $CO_2$ removal technologies which does not compete for cultivated area for biomass, also requires this infrastructure.

*Embedding BECCS in a coherent climate protection policy.* Trialling and the establishment of BECCS must be embedded in a politically convincing package of measures and mandatory targets for emissions abatement. Using BECCS must in no event result in a decline in efforts to avoid emissions. Only a combination of stringent measures for reducing emissions with $CO_2$ removal technologies is capable of ensuring that climate targets are met and climate damage minimised. If CCS capacity is limited, the CCS technologies used should primarily be those which store $CO_2$ from bioenergy and direct air capture and any unavoidable emissions from industry.

196 acatech 2018 sets out detailed considerations regarding the development of CCS infrastructure.

# 6 Conclusion

Today, bioenergy covers around ten per cent of Germany's energy demand and thus makes a greater contribution to the energy supply than do all other renewable energy sources put together. **Two conditions** must be met if bioenergy is to be able to make the energy system climate-friendly in the future: firstly, the **biomass must originate from sustainable sources**. Secondly, it must be used in such a way that it makes an effective contribution to the overall system of **reliable and affordable energy supply.**

Important defining criteria for the **sustainable provision of biomass** are the resultant **greenhouse gas emissions** and environmental impact on **soil and water quality and biodiversity.** Careful consideration must also be given to the proportions of biomass which should be used for **food production, material use** and obtaining bioenergy.

The increasing global population means that demand for biomass for food and feedstuff production will continue to rise. Bioeconomy strategies also mean that greater future use will be made of biomass as a climate-friendly alternative to fossil resources for producing materials and products. **Competition for land** will thus intensify. A bioenergy policy which provides strong incentives for the energetic use of biomass must therefore ensure that the increased demand for bioenergy has **no negative social and environmental impacts. Indirect, market-driven repercussions on global land use** cause major difficulties with evaluation. Indirect land use changes can only be reduced if sustainability requirements are established worldwide for all forms of land use. If sustainability criteria only apply to bioenergy but not to other agricultural and forestry products, it is in many cases not possible to ensure that the use of **forest wood and agricultural biomass** is free of harmful social and environmental effects. One exception is cultivation on degraded arable or pasture land but the potential of such land is disputed.

When tapping additional bioenergy potential, the focus should therefore firstly be on **residues and waste materials.** Subject to the 2050 energy efficiency targets being achieved, putting hitherto unused potential from forest wood residues, cereal straw and animal excrement to use in producing energy could mean that residues and waste materials will meet around 13 to 17 per cent of Germany's primary energy requirements in the future. Bioenergy technologies which are capable of processing lignocellulose will, however, be required.

If greater volumes of biomass are used in the future for producing products, increasing volumes of waste wood and other biogenic residues for producing energy will thus be available at the end of a product's lifetime. A **low-pollutant, readily recyclable design of bio-based materials** can facilitate such **cascade use**.

As a result of the **interfaces not only with agriculture and forestry but also with waste management,** bioenergy is a special case in comparison with other energy sources. To date, using biomass to produce energy in Germany has for the most part been controlled by energy-sector incentive systems. However, this does not take sufficient account of effects outside the energy system. In the long term, it would therefore be desirable to have a bioenergy policy which takes an overall view of the energy system, greenhouse gas and carbon balances, waste management strategies and land use as an integrated system. This requires cooperation between the many policy portfolios with responsibility for specific bioenergy-related fields and **coordination of the various funding and governance mechanisms**.

One effective instrument for regulating the greenhouse gas emissions from bioenergy over the entire life cycle would be a **uniform and sufficiently high $CO_2$ price**. It is essential to price nitrous oxide and other greenhouse gas emissions during the cultivation of energy crops, since they have a major influence on the greenhouse gas balance of bioenergy. Ideally, all greenhouse gases should in the long term be priced in every sector of the economy, thus also including food and feedstuff production. Establishing a $CO_2$ price for all greenhouse gas emissions worldwide would result in the climate-friendly use of land and energy. It would also make forest clearance less economically attractive. This would reduce the risk of bioenergy use leading to deforestation and thus ultimately to an increase in greenhouse emissions. For the foreseeable future, it would seem to be difficult to implement a global $CO_2$ price for greenhouse gas emissions within the framework of an international agreement. An increasing number of countries and regions have, however, begun to introduce emissions trading systems or $CO_2$ taxes which cover around 20 per cent of worldwide greenhouse gas emissions.

Further instruments are conceivable as an alternative or in addition to a $CO_2$ price. They can be used in the short term and bridge the gap until a comprehensive $CO_2$ price can be established.

In the case of domestically produced biomass, **statutory provisions** at the national or EU level can ensure that bioenergy is produced sustainably and makes a specified contribution to abating emissions. More complex policy instruments are, however, required for **imports of biomass** or bioenergy carriers.

One versatile instrument is **certification**. Biofuels which are imported into the EU are already certified with regard to various sustainability criteria. Only if defined minimum greenhouse gas savings over fossil fuels are proven can they count towards the biofuel quota. In addition to greenhouse gas emissions, a certification system can also help to verify social and environmental sustainability criteria. However, if only the biomass which is used for energy production is certified, the problem of indirect land use effects still remains. All biomass imports, including foods and feedstuffs, would have to be subject to the same criteria to solve this problem.

The greenhouse gas emissions of imports could be subject to a **border tax adjustment**. Because of the European internal market, the border tax adjustment would have to be introduced by the European Union. Another alternative for ensuring equal treatment of domestic and imported biomass is to **integrate the greenhouse gas emissions present in imports into the European Emissions Trading System.**

In this case, importers would have to purchase emissions rights for the greenhouse gas emissions which arose outside Germany in order to provide the biomass. The magnitude of the "imported" GHG emissions could be demonstrated by certification, as in the case of the border tax adjustment.

The described instruments provide a selection of well-developed methods, some already tried and tested, for regulating greenhouse gas emissions. Including **ecosystem services** in specific funding and incentive models, in contrast, is far more difficult. Effects on **water quality, nutrient cycles and biodiversity** are of particular relevance to bioenergy use. Although theoretical approaches for evaluating ecosystem services do exist, there is virtually no experience of implementing them in practical policy instruments. **If incentives are to be provided for raw materials sourcing which makes environmental and macroeconomic sense,** instruments which take comprehensive account of the effects of bioenergy use in land use systems would have to be developed.

The nature of bioenergy use will probably undergo major changes over the coming decades. Firstly, rising levels of residue and waste material processing will require **technical adaptations**. Secondly, combustion and motor fuels from biomass as storable, easily transported energy carriers should as far as possible be used in applications in which electricity from wind power and photovoltaics cannot be used or only at very high cost. The **most important future fields of use** are currently considered to be the **provision of industrial heat and motor fuels.** Combustion and motor fuels from biomass can moreover be used to fire **standby power plants** over extended spells with little wind and sun and to supply heat to **difficult-to-insulate buildings.**

Climate protection scenarios indicate that bioenergy will in the future also be able to carry out another task, producing **"negative emissions"**. If the global climate protection targets set out in the Paris Agreement are to be achieved, on the basis of current knowledge, $CO_2$ will have to be removed from the atmosphere in the second half of this century at the latest. Producing **bioenergy with downstream CCS** (BECCS) is one possible technology for doing this. Another alternative involves extensive afforestation of unused areas. BECCS plays a major role in IPCC's global climate protection scenarios. However, not all bioenergy technologies are equally well suited to $CO_2$ capture. Whether bioenergy is to be used in the future with or without CCS will therefore have a major impact on the further development of bioenergy use.

Whether **CCS is accepted as part of the climate protection strategy** has wide-ranging effects on the energy system and land use. If the decision is against, not only BECCS but also direct air capture, which facilitates $CO_2$ removal with little demand for land, will not be usable. Since time is pressing, there is an urgent need for a **debate in society as to whether and for what purpose CCS should be used.** If the decision is in favour of using CCS, **infrastructure for $CO_2$ transport and storage** would have to be put in place in the near future. **Industrial** process heat generation using biomass, the production of biofuels or biomethane plants **are suitable applications for trialling BECCS**. The latter have the advantage that the $CO_2$ is in any event already captured in order to achieve the specified gas quality. Instead of discharging it into the atmosphere as in the past, it could be compressed and transported to a storage site. However, a biomethane plant produces only relatively small volumes of $CO_2$. The logistical effort and transport costs per tonne of captured $CO_2$ would therefore probably be higher than in large industrial plants or biorefineries.

However, apart from the significance of CCS, the commercial introduction of liquid biofuels from lignocellulose and the expansion of CHP infrastructure place decisive constraints on where biomass will be able to make an efficient contribution to ensuring a reliable and affordable energy supply in the future.

**Liquid biofuels from lignocellulose** can make a valuable contribution to the energy system both with and without CCS by providing alternatives to fossil fuels, for example in aviation and shipping. Instead of carbon-containing fuels, biorefineries can also produce hydrogen, in which case greater negative emissions could be achieved. Producing fuels from lignocellulose is, however, very technically complex and costly. Further **development** is required to make them ready for commercial launch. Dispensing with this option would entail using electricity-based fuels to a greater extent in aviation and possibly in other areas of the transport sector. The production of such fuels is likewise complex, costly and research-intensive.

Lignocellulose has previously above all been used in small heat and heat and power generation systems (CHP). In contrast, using biomass for producing fuel requires **technologies** which are only economically viable employing larger plants. This means a partial move away from **decentralised bioenergy use** as is currently put into practice and preferred by society. Integrating CCS would boost the trend towards industrial bioenergy production. The transformation of bioenergy use therefore requires **new participants and business models**, and thus sometimes means major changes for local stakeholders.

**The contribution of CHP systems** using different energy carriers is in particular being discussed with regard to the energy transition in the heating sector. Flexible biomass CHP technologies are technologically well developed. Both small, decentralised plants as well as larger plants for supplying industrial plants or urban areas could be put to greater use, the latter in the long-term also in combination with CCS. If CHP is to be able to make an appreciable contribution to stabilising renewable electricity supplies and accelerating the energy transition in the heating sector, there will have to be systematic support for the necessary investment in the **expansion of heating networks.** While flexible CHP plants could indeed even in the short term make a substantial contribution to climate protection, the bioenergy carriers used would then no longer be available for producing liquid fuels.

When it comes to using wet waste, upgrading biogas to **biomethane** is one option for using bioenergy in various applications. This technology is commercially mature and is already in use today. Biomethane can be transported in the existing natural gas grid and can be used flexibly for electricity and heat generation and as a motor fuel. A gradual changeover from today's local use of biogas to biomethane production could be set in motion by an appropriate legislative and economic framework.

The acceptance of CCS, the commercial introduction of liquid biofuels based on lignocellulose and the expansion of heating networks for the use of CHP are thus **three important signposts** towards different development pathways for a system-beneficial transformation of bioenergy use. If all three options are rejected, there will be less major change, particularly in lignocellulose use, and this material will continue to be used more in relatively small plants for heat and CHP. In this case too, $CO_2$ capture is possible, for example in association with biochar.

A comprehensive **bioenergy strategy** should ensure that bioenergy assists in both the short and the long term in the energy transition and in achieving climate protection targets, is embedded in a well-balanced system of land and biomass use and is supported by society. It must be borne in mind that the total energy demand in the fields of use in which bioenergy in principle appears to be attractive is far greater than the anticipated bioenergy potential. **Different applications will therefore compete for biomass**. Some current biomass streams will have to be diverted to new applications. It should therefore be the aim of a national bioenergy strategy to adjust the legislative and economic framework such that biomass is primarily directed into those applications which, having considered all relevant criteria, are most advantageous. As has been described, however, it is as yet not completely possible to foresee which these might be.

**The uncertainty about future development pathways** in combination with **limited biomass potential** and the **urgency for climate policy action** are a major challenge for energy policy, developers of bioenergy technologies and biomass users. For policymakers, the issue particularly arises as to whether various development pathways should receive equal support, despite its being foreseeable that ultimately sufficient biomass will not be available for all potential applications.

If bioenergy is to make the greatest possible contribution to the energy system and climate protection in both the short and the long term, it would appear to be necessary both to **develop further the bioenergy technologies in use today** and to **research and trial prospective technologies** with potentially high benefits for the overall system, in particular transport fuel production and BECCS.

**In the short to medium term,** the greenhouse gas balance and environmental footprint of biogas production in particular can be improved by making greater use of residues and waste materials and environmentally soundly grown cultivated biomass (e.g. grasses). The contribution to the energy system can above all be optimised by **increasing the flexibility** of bioenergy plants (e.g. by gas or heat storage) which permit **demand-based generation of electricity and heat.** If **biomass were more efficiently converted into useful energy** (e.g. by better utilisation of the generated heat in biogas plants or by using efficient wood-fired CHP instead of pure heat generation), the same volume of input biomass could replace more fossil fuels and consequently make a greater contribution to climate protection.

In the **long term,** not only the entire energy system, but also the industrial sector will have to be made greenhouse gas-neutral. Achieving this will mean replacing fossil resources not only as a source of energy but also as a source of carbon, with biomass and $CO_2$ being potential carbon sources. In this context, concepts for making optimal use of biomass which go beyond the incremental further development of currently established bioenergy technologies will have to be developed, trialled and debated in society. **Biorefineries,** which produce fuels (in particular for aviation) in combination with other products (e.g. basic chemicals) and can so contribute to **closing carbon cycles,** may play a key role here. **BECCS** could play another key role as a technology which links energy production to $CO_2$ removal from the atmosphere and can so help to offset unavoidable emissions, for example from agriculture. Further research and trials of these technologies could in future provide substantial extra **room to manoeuvre** for fulfilling important functions in the energy system and in climate protection with biomass.

It is important **to communicate the limited nature of biomass potential clearly** and, in good time, **to develop acceptable alternatives** for applications for which little or no biomass may ultimately be available. These efforts can be assisted by ensuring that the goals and effects of bioenergy strategy are transparently explained to all stakeholders.

Creating more **system knowledge** is an important prerequisite for a good bioenergy strategy. In order to compare different **biomass scenarios,** energy scenarios in the future will have to take BECCS technologies into account. There is still a need for research in order to further develop **integrated models of energy and land use systems.** Alternative options for using biomass and alternative $CO_2$ removal technologies (e.g. afforestation) could also be compared in this way. Further research into the **potential and risks of the different $CO_2$ removal technologies** will, however, be necessary first.

A systematic **monitoring system** could be established in order to avoid constant changes of course in bioenergy policy and increase planning certainty for stakeholders. The aim is to evaluate all the contributions made to the system by bioenergy against suitable indicators. The evaluation system could also be applied to different development pathways in order to support the system-beneficial development of bioenergy. The evaluation should be regularly adapted to new insights. For example, there is a further need for research into the **greenhouse gas emissions caused by indirect effects** (indirect land use changes, dynamics of carbon storage in vegetation and soil).

A **platform for discussing transformation pathways** could ensure that different development pathways are thoroughly evaluated from different viewpoints. Participants in the national discussion platform could *inter alia* include interest groups from the energy sector, agriculture and forestry, environmental interest groups, consumer advice centres, local representatives, and representatives of various areas of civil society and of affected segments of the population. The results could be input into the monitoring system in order, in particular for new technologies such as BECCS, to take into account as many aspects of evaluation as possible.

In this discussion, it is vital to always focus on the **urgency for climate policy action.** If, for example, the risks of $CO_2$ removal technologies are being discussed, it should be borne in mind that dispensing with such technologies could reduce the likelihood of achieving climate protection targets. The risks presented by new climate protection technologies therefore always have to be balanced against the risks of climate change.

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# The Academies' Project

With the initiative "Energy Systems of the Future", 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 impulses for the debate on the challenges and opportunities of the German energy transition. In interdisciplinary working groups, some 100 experts from science and research develop policy options for the implementation of a secure, affordable and sustainable energy supply.

## "Bioenergy" working group

This interdisciplinary working group has addressed three key themes: firstly, providing an estimate of available bioenergy potential; secondly, evaluating the possible role of bioenergy with carbon dioxide capture and storage (BECCS); and thirdly, developing a comprehensive tool for evaluating development pathways for using biomass to produce energy from technical, environmental, economic and social standpoints.

The results of the working group's efforts have been made available in three formats:

1. The **Analysis** *"Biomass: striking a balance between energy and climate policies. Potential – technologies – conflicts of interest*" comprehensively documents the state of scientific knowledge about global bioenergy potential, bioenergy technologies and BECCS and other $CO_2$ removal technologies. It also presents the evaluation tool for bioenergy technologies developed by the working group and uses it as the basis for outlining the challenges facing German energy and climate policy.

2. The **Position Paper** "*Biomass: striking a balance between energy and climate policies. Strategies for sustainable bioenergy use.*" presents the results in compact form and indicates options for a sustainable bioenergy strategy.

3. The online **Materials** "*Interdisciplinary evaluation tool for bioenergy development pathways*" contain a detailed description of the evaluation methodology developed, including the criteria and evaluation scales and the results of their application to selected bioenergy technologies.

## Members of the working group

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