

THE ROLE OF BIOGENIC WASTE AND RESIDUES IN A CLIMATE NEUTRAL WORLD

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ABSTRACT

The paper discusses the role of biogenic waste and residues in a climate-neutral world, highlighting their potential for sustainable energy production, climate protection, and resource conservation. The authors conclude that a significant amount of biogenic waste and residues can be utilized to produce biofuels, biomethane, and other bio-based products, contributing substantially to greenhouse gas reduction and a circular economy (Carrillo-Rodríguez et al., 2025). In Germany, the use of bio-fuels from waste and residues already prevented emissions of 11.6 million tonnes of CO₂-eq in 2022. The paper also emphasizes the importance of a National Biomass Strategy (NABIS) to steer biomass flows and ensure the optimal use of this valuable resource.

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1. INTRODUCTION

Against the backdrop of current wars and other violent conflicts, climate and environmental issues appear less important in the public eye.

Nevertheless, it is not a new insight that we are to change our utilization of raw materials into sustainable consumption on long term. Earth overshoot day in 2025 was July 24th, when globally more resources are consumed as these could be regenerated.

The share of renewable energies in Germany's energy system is around 20% (Umweltbundesamt, 2024), and the circularity rate (CMU), i.e. the proportion of waste and residual materials generated in production processes, is only around 14% (Eurostat, 2024).

International comparison shows that Germany remains one of the leading countries in waste management and recycling, and makes a significant contribution to resource and climate protection. For example, waste management has been the most successful sector in reducing CO₂ emis-

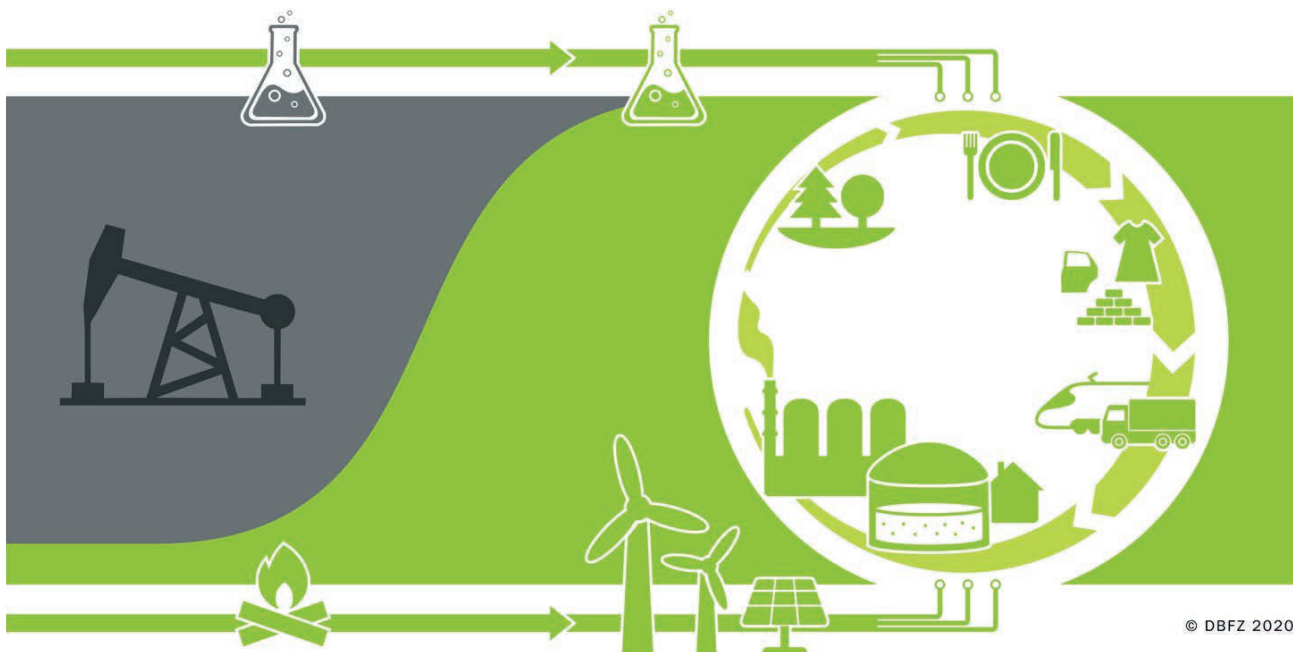
sions since 1990. In addition, other positive effects are not attributed to waste management, but to the energy industry or other sectors to which the waste management industry supplies secondary fuels and resources.

Over the past years, the German government has created a so-called 'intergenerational climate contract' (Bundes-Klimaschutzgesetz vom 12. Dezember 2019) with several amendments to the Climate Protection Act (Bundesregierung, 2022). This aims to reduce German greenhouse gas emissions by at least 65% by 2030 and by 88% by 2040, compared to 1990 levels. From 2045, the Federal Republic of Germany is to become climate-neutral, i.e. there should be a balance between greenhouse gas emissions and sequestration. After 2050, the German government aims to achieve negative emissions by naturally sequestering more greenhouse gases than are emitted. The new government remains committed to these goals, but has so far failed to publicly define and implement enough of the necessary measures (Figure 1).

What is required to achieve climate neutrality in Germany by 2045 is, to increase further optimised interaction of wind, solar and geothermal energy, bioenergy, and hydro-power for electricity, heating/cooling and mobility.

In Parallel, a development from a 'linear' economic system into a true circular economy is required, where used materials are further recycled and at last, the energy remainders shall be recovered. And for the supply of raw ma-

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FIGURE 1: Highly simplified representation of future energy supply and (bio-based) circular economy as central building blocks for a climate-neutral society © DBFZ.

materials to the industry, petroleum-based raw materials shall be replaced step by step with biobased materials.

Biomass will therefore be the basis of the bioeconomy and an integral part of a sustainable energy system. This can only be achieved if biomass is produced sustainably and used efficiently, in an environmentally friendly manner and with the greatest possible economic benefit. A sustainable bioeconomy therefore optimises the material and energy recovery of biogenic waste and residues, as the current production technologies are optimized for the conversion of fossil raw materials. This requires new technological concepts and coupled and cascading use. But also 'negative' emissions that can be generated through the storage of 'green' carbon. Biomass is thus increasingly coming into focus as an important 'green' carbon carrier, on the one hand to reduce and bind CO₂ emissions, and on the other hand, as the carbon carrier for the future bioeconomy. This will significantly increase the demand for biomass and the need for sustainable cascade and coupled use in the future.

As an essential basis for the transformation process towards a sustainable, circular bio-based economy and society, the last German federal government undertook in its 2021 coalition agreement to develop a National Biomass Strategy (NABIS). The development of NABIS was led by the Federal Ministry for Economic Affairs and Climate Action (BMWK), Federal Ministry of Food and Agriculture (BMEL) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), with the original goal of adoption by the Federal Cabinet by the end of 2023. Against the backdrop of climate and biodiversity protection and food security, NABIS aims to steer biomass flows in a targeted manner so that this valuable resource is used in the best possible

way (Bundesumweltministerium, 2025). Such a long-term strategy is certainly necessary and helpful in order to make the best possible use of the limited biomass available in Germany in terms of materials and energy in the future.

However, it is clear that the transition to the desired circular bioeconomy can only succeed if the utilisation of biogenic waste and residual materials is given the priority. This applies to both material and energy recovery, which are also the main areas of focus of the cooperation between the DBFZ and the Chair of Waste and Resource Management at the University of Rostock. Against this background, the potential and current use of biogenic waste and residues will first be presented below. This will be followed by an explanation of the current status and necessary developments in the areas of "waste wood and residual wood", "biogas technology", "biofuels and biorefineries" and "negative emissions".

2. POTENTIAL AND USE OF BIOGENIC WASTE AND RESIDUES IN GERMANY

In order to take into account, the availability of biogenic resources as a decisive factor in assessing the opportunities and risks of existing and potential uses, the DBFZ develops raw material monitoring systems for various geographical regions, implements them and makes them available in standardised formats.

Currently, 77 different biogenic residues from numerous sectors are considered. All results, including documentation, are available for individual data analysis in an online database in the DE Biomassemonitor, which can be accessed at <https://datalab.dbfz.de>. The database includes by-products from agriculture and forestry, municipal waste, sewage sludge, industrial residues and residues from other areas. On this basis, the German theoretical potential (bi-

ophysical maximum) ranges from 185.2 to 232.2 million tonnes of dry matter (tDM) in 2020. The annual technical biomass potential, which is defined as the potential that includes further limiting restrictions of technical, structural and legal nature (Brosowski et al., 2019), amounts to around 91.7 to 128.9 million tonnes of dry matter (tDM) in 2020 in Germany (Wilske et al., 2025) (Naegeli de Torres et al., 2024). Between 68 and 83% is already being used for material and/or energy purposes. The DBFZ assumes that, in addition to optimising existing use, a further 15.7 to 41.8 million tonnes DM can be mobilised for further applications. A material flow aggregation of the annual biogenic waste and residues is shown in Figure 2 for 2020 and the average values of the ranges described above. Regarding the overall average theoretical biomass potential of 208.7 million tonnes DM, the largest contribution sectors are agricultural by-products (77.6 million tonnes DM), forestry by-products (74.4 million tonnes DM), municipal waste and sewage sludge (34.1 million tonnes DM), followed by industrial residues (15.4 million tonnes DM) and residues from other areas (7.2 million tonnes DM). Including the further above outlined restrictions regarding the technical potential, the order of the largest sectors changes, municipal waste and sewage sludge now contributing 33.8 million tonnes DM, forestry by-products 30.2 million tonnes DM and agricultural by-products 27.2 million tonnes DM. Finally, industrial residues and residues from other areas provide 15.3 and 3.8 million tonnes DM respectively.

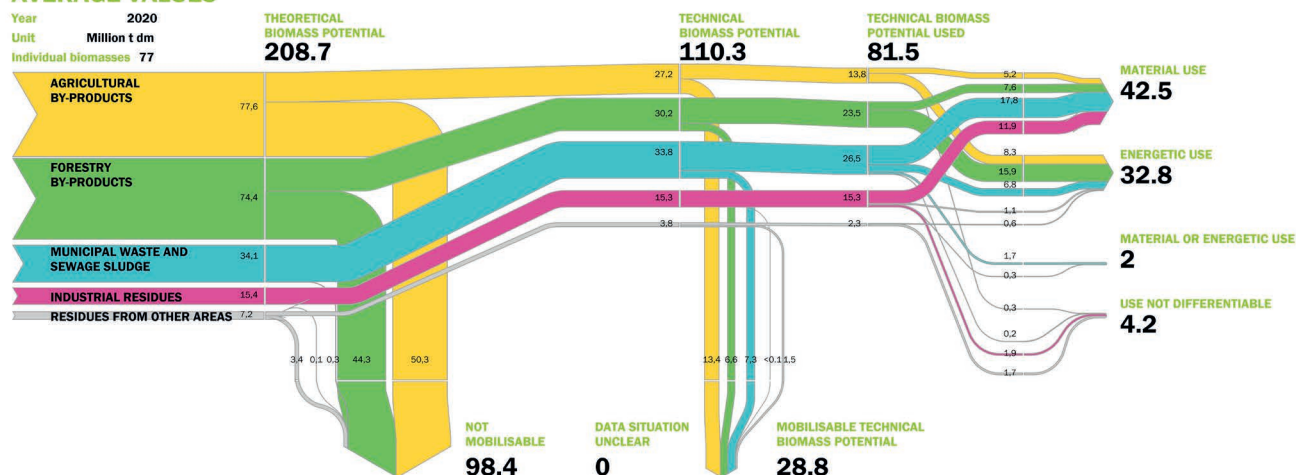
It should be noted that the quantities are given as dry matter (DM). This means that the quantities actually available for recycling are significantly higher. For example, in animal husbandry in Germany alone, an average of 17.6 million tonnes DM per year are produced in the form of cattle and pig solid manure, cattle and pig slurry, dry chicken manure, etc., whereby the wet mass (WM) is much high-

er (up to a factor of 7) depending on the DM content of the respective animal excrement. Low dry matter contents (e.g. 4-8% in pig slurry) pose particular challenges for the exploitation of still available feedstocks due to their low transportability (Krause et al., 2020).

Biogenic waste and residues comprise a very broad spectrum of different material flows, and resource management is already being implemented in a highly differentiated manner, especially outside waste legislation. The very large quantities of biogenic residues mentioned above, which are already collected separately from municipal waste generated from private households and businesses, are recycled in a variety of ways. For example, there are highly differentiated recycling processes for slaughterhouse waste, which end up in the pharmaceutical, feed and food industries and contribute to the substitution of so-called primary raw materials. Large quantities also arise in agriculture and fisheries and in their processing stages of the value chain. Production residues from the food industry are also reused in a similar way for animal feed production or as a basis for further production processes.

Especially if material flows cannot be used in applications with higher economic and environmental added value (e.g. material use), they can be used either for thermochemical, biological or mechanical conversion into biogas, solid or liquid biofuels, electricity or heat (cascading principle REDIII) (EU, 2023). In order to mobilise additional potentials for those applications, municipal biowaste from households, gardens and parks account with a technical potential of around 14 million tonnes of dry matter (average) for a significant but by no means dominant proportion of total biogenic waste and residues. They are of particular importance within municipal waste, both for sanitation and for meeting specific recycling and recovery targets.

BIOGENIC RESIDUES IN GERMANY AVERAGE VALUES



Monitoring of the bioeconomy Resource base and sustainability

Arbeitsgruppe Biomassereststoffmonitoring (AG BioRestMon)
Source: DBFZ Resourcendatenbank 12/2020



FIGURE 2: Aggregated material flow of biogenic residues, by-products and waste as average values in millions of tonnes of dry matter (Million tDM). Source: DBFZ resource database, <https://datalab.dbfz.de>. © (Wilske et al., 2025, p.18).

Other individual biogenic wastes and residues relevant in terms of quantity are shown in Figure 3. In 2020, the total technical biomass potential mainly consists of 15 types of biomasses, which together account for 93.7 million tonnes of dry matter (DM) or 85% of the total technical potential of biogenic waste and residues of 110.3 million tonnes DM. In terms of quantity, waste paper (14.5 million tonnes DM), green waste (11.2 million tonnes DM) and cereal straw (9.7 million tonnes DM) are particularly noteworthy.

However, in addition to animal excrement, wood-based residues and by-products are particularly well represented among the top 15 biomasses. The five biomasses from the wood and forestry by-products sector, i.e. sawmill by-products and wood shavings, waste wood, coniferous forest residues, deciduous forest residues and black liquor, account for a total of 27.9 million tonnes DM or 29% of the technical potential. However, it should be noted that relevant quantities of this potential are already in use. For example, 76% (average) of the five biomasses from the wood and forestry by-products sector are already being used for material or energy purposes. Additional mobilisable potential exists only for forest residues (coniferous and deciduous), as sawmill by-products and wood shavings, waste wood and black liquor are already fully utilised. However, greater use of forest residues should be examined, particularly in view of future sustainability requirements (e.g. EU biodiversity and sink targets (LULUCF)), which could limit the amount that can be extracted in the future, depending on the location. However, there is also considerable potential for sawmill by-products and wood shavings, waste wood and black liquor, as these could be used in alternative pathways. In particular, due to the expiry of EEG subsidies for waste wood, large quantities (~ 50% of the volume covered by EEG subsidies) could potentially be used for other

material or energy purposes (Matschoss, 2020). Due to increasing cascade factors for wood and rising material use of wood, e.g. through bans on single-use plastics and by timber construction initiatives, it can be assumed that the volume of waste wood will continue to rise until 2030 (Mantau, 2023).

3. RECYCLING OF WASTE WOOD AND RESIDUAL WOOD

In practice, it is not always easy to distinguish between primary wood and residual and waste wood. While there is at least a formal legal classification for waste wood, the situation is much more complicated for residual wood. Ultimately, the practical application makes the distinction by wood fractions (logs) that are processed in a sawmill, whereby, depending on the processing method, 30 to 50% of bark, slabs and splinters, offcuts, sawdust and wood shavings are produced as production residues. In addition, further wood fractions are produced in the forest and during landscape maintenance as part of clearing, thinning, timber harvesting and the partial removal of calamity wood. These fractions cannot be used in the sawmill industry, but have so far been mainly used for energy purposes and assigned to the category of residual wood. Primary wood is mainly used for energy when sawable wood from the forest is processed into firewood for end customers – either privately or by commercial wood processors. In principle, however, all the quotas listed here in Germany are characterised by the fact that there has been no economically advantageous demand from material use to date. It should be noted that funding incentives (e.g. the Renewable Energy Sources Act or investment subsidies for wood-fired heating systems) can distort the economic situation between material and

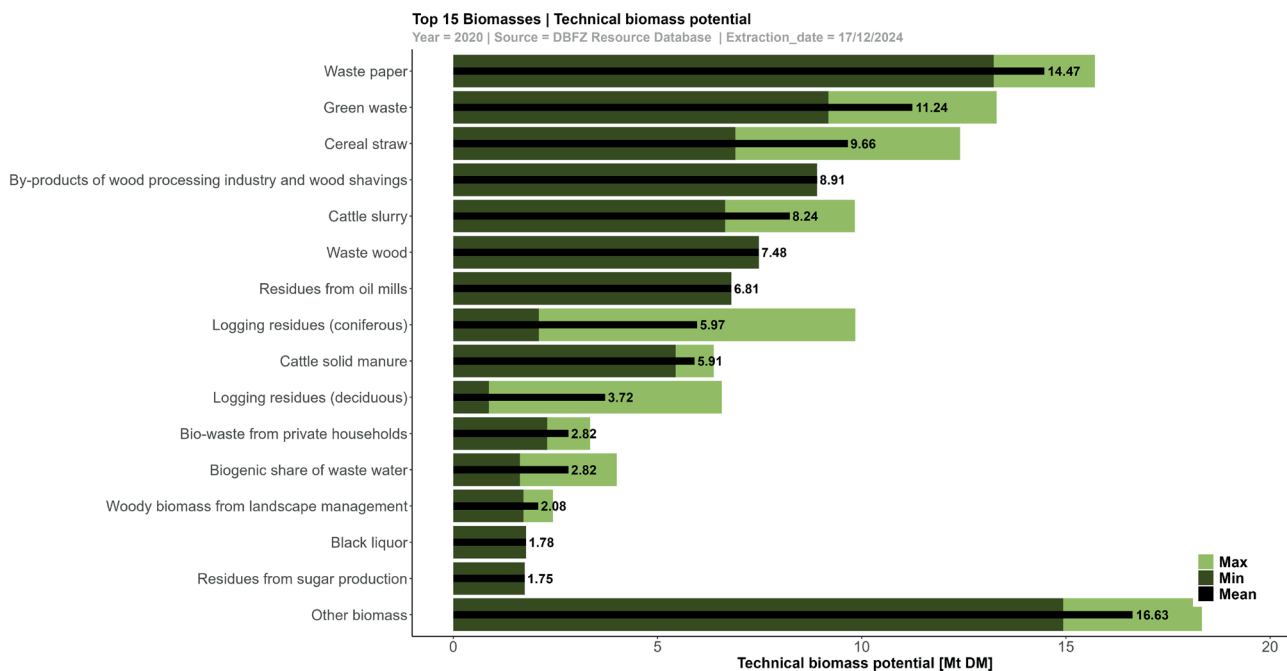


FIGURE 3: Top 15 biomasses with technical potential in 2020 according to minimum, maximum and average values in million tonnes of dry matter (Million tDM). Source: DBFZ resource database, <https://datalab.dbfz.de> © (Wilske et al., 2025, p.20).

energy use. Conversely, it has also been observed in the past that without financial incentives for energy use, prices in the timber sector fall to such an extent when material and energy use are linked that timber supply is reduced. Although this would lead to an increase in the amount of carbon stored in forests in the short term, it would increase the risk of climate-damaging total loss through forest fires with high soot emissions in the foreseeable future as a result of climate change and the resulting delay in forest conversion.

Until now, residual wood and waste wood have mainly been used for energy purposes to provide full or base load heating and, in case of waste wood, to generate electricity in waste wood power plants within the EEG. The combustion plants are more expensive than gas or oil-fired plants, both in terms of heat and electricity and in the CHP sector. It is therefore important to recoup the higher investment costs by ensuring that the plant is utilised as much as possible with cheaper wood fuels. Apart from wood pellets (over 90% of which is wood from wood processing residues in Germany), bark, wood chips from sawmill by-products or waste wood and black liquor are mainly used in larger plants (over 100 kW_{thermal}, in some cases significantly over 1 MW). In addition, the use of waste wood and scrap wood for energy purposes has become established in industry, particularly where these fuels are produced during the manufacturing process, i.e. in sawmills and the wood-processing industry, including paper manufacturing. Due to the demand for electricity and heat for cooking and drying processes, temperatures required are usually below 200°C. In German speaking countries, wood pellets are mainly used in the end customer sector for space heating at a maximum temperature of 90°C. Overall, waste wood and scrap wood are mainly used for energy in the lower temperature range, with the result that the available capacities are only sufficient for a limited number of combustion plants. At the same time, the development of the legally

required municipal heating plans shows that many heating networks rely on significant proportions of wood for defossilisation, which in total amounts to much too high wood consumption for the future in Germany.

In this respect, the use of residual and waste wood must be re-thought and transformed from a systemic perspective.

(1) Material cascades must be extended. Sawdust, wood shavings and wood chips are suitable raw materials for chemical base materials, as they are a very homogeneous biomass with significantly less than 1% impurities (mineral ash). Bark can be used as a proven raw material for peat substitutes (Fachagentur Nachwachsende Rohstoffe, 2022), as can wood chips from various tree species with and without treatment in biogas plants (Fachagentur Nachwachsende Rohstoffe, 2022). For these natural biomasses, processing into disposable food packaging and disposable tableware is also standard. In the area of waste wood, classes AI (wood without any additions despite very small ones) to AIII (waste wood with colours, ceilings and so on including halogen organic ingredients, but without wood protection poisons) are suitable for the production of building components which, depending on waste wood class (occupational health and safety), can be used either for free distribution to craftsmen or restricted to industrial use. Last but not least, there are approaches to further utilise black liquor for chemical raw materials instead of directly recycling it thermally (Fraunhofer-Gesellschaft, 2025). Figure 4 provides an overview of these options.

Besides these main utilization pathways there are also some innovative concepts for reusing wood waste e.g. for nanocellulose production to be used in advanced materials (Ghamari, 2025).

(2) Wherever energy use still appears advantageous for technical or economic reasons, care must be taken to generate maximum system benefits. This means that biomass should primarily be used in peak load applica-

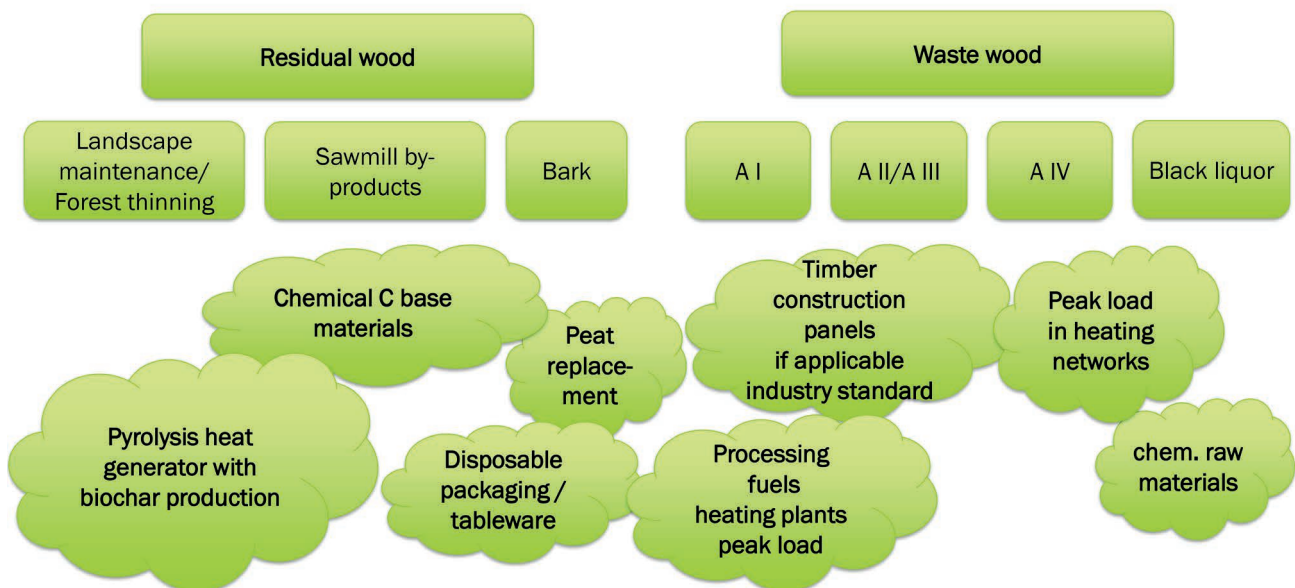


FIGURE 4: Development options for innovative utilisation concepts for residual and waste wood. © DBFZ.

tions in combination with other renewable heat generators (hybrids, especially with heat pumps) and in high-temperature applications for industrial process heat (Jordan et al., 2019). Hybrid concepts should be designed in such a way that the proportions of biomass and electricity (ambient heat) can be flexibly adjusted depending on the price situation and the availability of renewable electricity. In the medium term, options for negative emissions should be integrated. For example, materials from landscape management, which are often very heterogeneous and tend to occur locally in small quantities, could be used in small-scale pyrolysis plants for heat supply and biochar production as a future option (Thrän et al., 2025). In addition to covering any necessary peak heat loads, this would also produce stable biochar for material applications (e.g. soil improvers, additives for road construction, concrete, etc. (RWTH Aachen, 2024) (Vaupel, 2023) (Wollnik et al., 2023). The use of AIV waste wood (waste wood contaminated with wood protection poisons) in waste-fired heating plants remains interesting, although in future, the focus here should also be on the storability of the biomass and combustion to supply heating networks during winter. In addition, CO₂ capture (BeCCS) should also be planned for these rather large plants in the medium term. In this context, use in the cement industry is likely to be particularly promising, as this industry will not be able to avoid CO₂ capture due to process-related CO₂ emissions. In addition, AI and, if necessary, All waste wood (glued and/or painted wood without halogen organic ingredients), provided it cannot be used for other purposes, can be processed for peak load heating plants in local heating networks. Here, pyrolysis heating plants with simultaneous biochar production should also become more relevant in the medium term. Besides these established thermochemical conversion routes, research worked on process to produce hydrogen from wood residues by thermos-catalytic conversion (Jelschow, 2024).

In a glance, due to legislation in Germany all wood residues and wastes are already used, either for material purposes or for energy supply. Up to now, this is oriented very much on cost efficiency and not on climate efficiency. That means, for a full renewable material and energy world, limited wood potentials have to be redirected in a much more climate efficient way, like prolonged material cascades, energetic uses for peak loads and higher temperatures and combined with negative emission generation, perfectly.

4. BIOGAS TECHNOLOGY FOR THE UTILISATION OF BIOGENIC WASTE AND RESIDUES

Biogas technology plays an important role in the sustainable utilisation of biogenic waste and residues, particularly from agriculture and food production (IEA, 2020; Weinrich & Nelles, 2021). Anaerobic digestion involves the breakdown of organic materials by microorganisms in the absence of oxygen. The resulting biogas consists mainly of methane and carbon dioxide. This technology not only provides an environmentally friendly source of energy, but also helps to reduce greenhouse gas emissions associ-

ated with conventional storage and disposal, especially of agricultural residues (Fachagentur Nachwachsende Rohstoffe, 2022). To date, energy crops (such as silage maize) and farm manure (primarily slurry) have been the main inputs used in biogas plants (Rensberg et al., 2023). In 2023, the energy-related input of renewable raw materials was approximately 68% from cultivated biomass and 19% from farm manure. Municipal biowaste accounts for approximately 4% and other waste materials from industry and commerce for approximately 9% of energy-related consumption. From 2010 to 2023, the energy-related share of renewable raw materials has decreased slightly in favour of farm manure and industrial residues (Figure 5) (Rensberg et al., 2023).

The cultivation of energy crops is generally considered to compete with food production and to have negative environmental consequences (e.g., land-use competition and biodiversity trade-offs) (IEA, 2020; Theuerl et al., 2019). Using biogenic waste and residues as input materials reduces these negative effects, and is therefore increasingly supported by politics and public opinion alike (IEA, 2020). Residual materials produced in agriculture include manure, slurry, harvest residues and landscape conservation materials. However, landscape conservation materials can have waste characteristics, especially roadside vegetation, which is decisive for the legal status of a biogas plant and has an impact on requirements and permits (Bundesgütegemeinschaft Kompost e.V., 2014). Slurry and manure are particularly suitable substrates for biogas production because they are continuously available and their fermentation reduces emissions of methane, a potent greenhouse gas (Umweltbundesamt, 2019). Crop residues such as straw offer further potential but are often underutilised, mainly due to the high cost of harvesting and pre-treatment. Physical, chemical or biological pre-treatment processes can break down the structure of these materials, making them more accessible to microorganisms (Yu et al., 2019). This improves both the biogas yield and handling during the process by improving mixability and reducing layer formation in the fermenter (Yu et al., 2019). In the case of straw, there is also competition for material uses such as bedding in animal husbandry, meaning that, depending on the region, straw is a very cost-intensive substrate with an average purchase price of €120/t (top agrar., 2024). This example shows that biogenic waste and residues can be very expensive, which contradicts the often-held assumption that they are always cost-neutral. This needs to be examined on a case-by-case basis.

Waste from food production and the processing industry for agricultural raw materials often has a high energy content and is therefore well suited for biogas production (IEA, 2020). This sector generates significant amounts of biogenic waste and residues, including production waste or unsaleable products and calamity batches, such as grain contaminated with mycotoxins. However, residues that previously had other sales markets but are now disappearing, such as the use of residues from starch production for pig fattening, are also of interest. Stagnating livestock numbers require new utilisation solutions in this area. Depending on the starch factory, quantities of residual materials

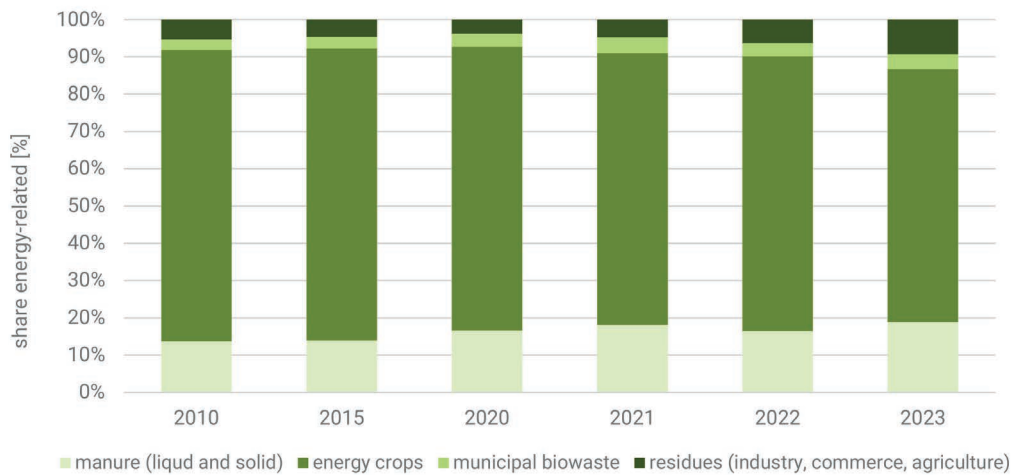


FIGURE 5: Energy-related substrate input in German biogas plants. Source: Non-public database: DBFZ operator surveys from 2011, 2016, 2021-2024 (reference value for the previous year). © (Daniel-Gromke et al., 2025, p.55).

ranging from 100,000 to 500,000 tonnes per year (based on fresh mass) may be available at a single location. The low dry matter content of approximately 20% poses economic challenges in terms of logistics. Direct discharge into the wastewater system without pre-treatment is not possible due to the high organic load (Umweltbundesamt, 2019). To add value to wastewater treatment, biogas can be produced by integrating anaerobic fermentation (IEA, 2020). Furthermore, added value can be generated by processing and recycling the fermentation residues, either as fertiliser or as substances that can be isolated from the fermentation residues as basic chemicals (Drosg et al., 2015). New input streams from the manufacturing industry in particular require the adaptation of biogas technology, which has mainly been used in the agricultural sector to date. The fermentation of homogeneous individual substances poses particular challenges in terms of supplying the microorganisms with micronutrients, for example, or regulating the pH value in the process (Weinrich & Nelles, 2021).

Technological innovations play an important role in the efficient use of these heterogeneous waste streams. Modern biogas plants are capable of processing a wide range of substrates while maintaining optimal process conditions (Theuerl et al., 2019). Advances in process monitoring and control make it possible to dynamically adapt fermentation to the properties of the materials used, thereby maintaining process stability with heterogeneous substrate streams. This is crucial for biogenic waste and residues, as their composition and quantities can vary greatly depending on the season.

In addition to energy production, biogas technology offers further advantages. The fermentation residues produced during fermentation are nutrient-rich fertilisers that can be used in agriculture, thereby reducing the use of mineral fertilisers (European Biogas Association, 2024). Furthermore, the use of biogenic waste and residues contributes to closing material cycles and reduces the amount of waste to be disposed (IEA, 2020). However, the environmental performance of biogas systems increasingly depends on (i) minimising methane slip along the chain and

(ii) managing digestate to avoid nitrogen and phosphorus losses to air and water (IPCC, 2021; Umweltbundesamt, 2019).

Innovative utilisation of digestate is therefore a key future priority. Solid digestate can be upgraded via solid-liquid separation followed by composting, drying and pelletisation to produce transportable organic fertilisers and soil improvers, or it can be converted into biochar via (co-)pyrolysis/hydrothermal routes to stabilise carbon, reduce odour, and create sorbent/soil-amendment products (Drosg et al., 2015; Fu et al., 2024; Dincă et al., 2025). In parallel, the liquid fraction (often rich in readily available ammonium) requires careful treatment and application management to prevent contamination of water bodies (e.g., nitrate leaching and runoff), consistent with water-protection requirements such as the EU Nitrates Directive (EU, 1991). Promising approaches include ammonia stripping/scrubbing (e.g., ammonium sulfate), membrane filtration or evaporation/concentration, and phosphorus recovery as struvite, thereby turning the liquid fraction into standardised, marketable fertiliser products and reducing nutrient surpluses in vulnerable regions (Drosg et al., 2015; EU, 2019). Application methods that increase nutrient use efficiency (e.g., injection or trailing-shoe/band application, adapted timing and rates) further reduce emissions and leakage risks (Korba et al., 2024).

Despite the advantages mentioned above, there are challenges involved in integrating biogenic waste and residues into biogas production. The heterogeneous composition of the substrates requires flexible plant technologies and careful process monitoring (Weinrich & Nelles, 2021). Logistics such as the collection, transport and storage of the materials must also be taken into account. In addition, legal aspects of the joint use of biogenic waste and residues often stand in the way and are a major obstacle (Bundesgütegemeinschaft Kompost e.V., 2014). In the future, it will be crucial to further increase the efficiency of biogas technology and tap into new, previously unused waste and residual material streams. Research and development must focus on optimising process control, developing new

pre-treatment methods and integrating biogas production into existing agricultural and industrial systems.

Overall, biogas technology can make a robust contribution to the energy transition and circular economy if it prioritises residues over dedicated crops, reduces methane slip, and couples energy services with nutrient recovery and safe digestate management as central design goals (IEA, 2020; IPCC, 2021; European Biogas Association, 2024).

5. BIOFUELS AND BIOREFINERIES BASED ON BIOGENIC WASTE AND RESIDUES

In 2022, the use of biofuels in Germany prevented emissions of 11.6 million tonnes of CO₂-eq. Of the total 140 PJ, 46% came from biofuels from waste and residues and 54% from cultivated biomass (Bundesanstalt für Landwirtschaft und Ernährung, 2022). The legal framework for bio-based fuels has already been adapted in recent years to significantly increase the share of waste and residues as feedstock for production. Based on the requirements of the EU Renewable Energy Directive (RED II), the following biomass classes for biofuels can be distinguished (Bundesanstalt für Landwirtschaft und Ernährung, 2025):

1. Conventional biomass: so-called food and feed crops;
2. Advanced biomass: raw materials in accordance with Annex IX A of RED II that are not suitable for food or feed;
3. Waste-based biomass: raw materials in accordance with Annex IX B of RED II;
4. Biomass with a high risk of indirect land use change: palm oil;
5. Other biomass: raw materials not explicitly assigned to any of the other categories.

In a comparative meta-study of sustainable biomass and substitution potentials, the amount of biogenic waste and residues available for processing into biofuels in Germany and Europe was investigated (Naumann et al., 2024). Relevant studies were identified based on the following

criteria: transparent methodology, recency (no older than ten years) and potential levels considered (at least bioenergy potential or mobilisable potential). Furthermore, the focus of all studies was quantifying the potential of biogenic by-products, waste and residues. The comparison of the thus identified five studies – (Fehrenbach et al. 2018), (Panoutsou & Maniatis 2021), (Brosowski et al., 2019), (Ruiz et al., 2015) and (Searle & Malins 2016). In addition to quantifying biomass potential, its mobilisation potential is also of central strategic importance. This means that suitable production technologies that are sufficiently developed for market establishment are also required. In the best-case scenario, processing capacities are already available or existing facilities from the fossil resource processing sector can be converted or upgraded.

Based on the five studies the possible production quantities of biobased diesel, kerosene, naphtha, ethanol, methane and methanol were calculated. The analysis was made for Germany and Europe, to determine the quantity of biogenic substitutes that could be produced. According to these calculations, 7-28% of current refinery output could be substituted in Germany and 10-45% in the European Union (Figure 6). Looking at sufficiently mature conversion processes, there is substitution potential resulting primarily from the conversion of biogenic by-products, waste and residues into biomethane and biomethanol.

The wide range of the estimated substitution potentials is due to differences between the biomass potential studies. These arise from the potential levels considered, the number of biomasses considered, the assumptions made about the mobilisation and use of biomasses, the data used and the reference year. However, assuming a significant reduction in demand for liquid and solid fuels in the future, mainly due to electrification, the substitution shares determined would be even higher. The use of biogenic waste and residues for the production of biofuels therefore already makes a significant contribution to climate protection in the transport sector. Further biogenic waste and residues can also be used to produce fuels for the combustion engines that will remain in use in the medium term.

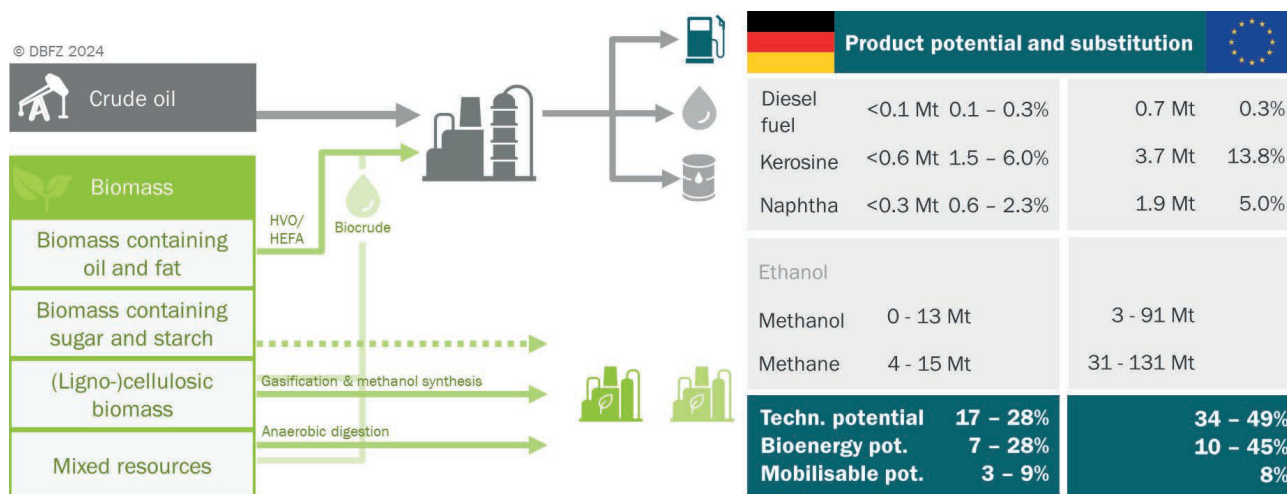


FIGURE 6: Substitution potential for mineral oil-based fuels by bio-based alternatives, for Germany and the EU. © (Naumann et al., 2024, p. 3).

For example, the DBFZ is investigating the efficient conversion of agricultural and urban residues into biomethane for transport (Röder et al., 2024). In an integrated pilot plant (Pilot-SBG), modules for biomass pre-treatment, anaerobic digestion, digestate processing and catalytic methanisation of CO₂ are being developed. Parallel to the ongoing experimental campaigns on developing the mentioned techniques, techno-economic assessments and sustainability assessments were already conducted. The costs for a commercial scale plant for the conversion of straw and manure to liquified biomethane were estimated for an exemplary plant concept with all of the mentioned modules. One of the findings is, that the catalytic methanation of the CO₂ in the biogas could double the methane production. However, the catalytic methanation module significantly adds to the costs, both to the CAPEX (33% of the entire investment) and to the OPEX (hydrogen would make 51% of the entire consumption related costs) (Röder, et al., 2024). A more thorough techno-economic assessment of benefits and drawbacks of the different modules and their combinations will be elaborated, when the experimental campaigns are completed.

The production of hydrogen from biomass is another approach to substitute fossil fuels. While competition with large-scale electrolysis is seen difficult, bio-hydrogen was found particularly promising through routes like steam reforming of biomethane and thermochemical gasification to serve as a decentralized pillar in the transition to a climate-neutral energy system (Dögnitz, 2022). Hydrogen could then be used to meet regional demands in transport and municipal fleets or be part of integrated concepts, where biogenic carbon is coupled with green hydrogen to create high-value synthetic fuels. Conversely, direct applications for the heating market or injection into the national gas grid are deemed inefficient, suggesting that the role of biogenic hydrogen is best realized in localized, circular value chains where it can provide high greenhouse gas reduction potential from otherwise underutilized waste streams.

The production of basic and fine chemicals from bio-based waste and residues is also increasingly being pursued (Nitzsche et al., 2021). In principle, higher specific revenues can be achieved with these products, but at the same time the quality requirements for product purity are significantly higher and usually require longer processing chains. Since often only parts of the biomass can be processed into the desired products, the concept of biorefineries plays an important role in the production of bio-based raw materials for material use in the chemical industry. In biorefineries, the raw biomass is processed into various products as well as biogenic waste and residues through a combination of conversion and separation processes (Bundesregierung, 2012).

Another example of producing chemicals from regional biomass residues is the production of medium chain carboxylic acids by fermentation. The fermentation process has successfully demonstrated that caproic and caprylic acid can be produced from moist residues such as fruit pomace, harvest residues or other residues from the food industry or even mixed organic waste (Xu et al.,

2018), (Chen et al., 2017). The entire process, including the purification of the carboxylic acids, has been demonstrated on a pilot scale (Braune et al., 2021). Sample quantities of the products were produced for application tests in the lubricant sector. The processing method is designed to be integrated into biogas plants so that, in addition to the carboxylic acids, biomethane is produced and the nutrients in the remaining digestate can ultimately be returned to agriculture as secondary fertiliser. This turns biogas plants into biorefineries that can process biogenic waste and residues with high added value (Braune et al., 2021).

6. NEGATIVE EMISSIONS

BECCS stands for Bioenergy with Carbon Capture and Storage. Bioenergy is based on biomass, the formation of which involves CO₂ capture from the air through plant growth. BECCS involves the technical conversion of biomass into bioenergy products (e.g. biofuels, heat/cooling, electricity) while simultaneously capturing carbon in the form of carbon dioxide or solid carbon products, including its permanent storage. This makes BECCS one of the better-known technologies in the field of carbon dioxide removal (CDR).

What contribution can BECCS options make to CO₂ capture in Germany in the coming years? The focus here is primarily on biogenic waste and residues, the utilisation of which is associated with a high climate protection contribution.

The significant bioenergy flows (> 10 PJ) shown in Figure 7 are converted into CO₂ flows. To this end, the CO₂ potential that would be released if the biomass were completely converted into CO₂ is calculated. This calculation is based on the carbon content of the biomass and the bioenergy products, as well as the efficiency of the associated bioenergy plant. In total, the CO₂ potential fed into the bioenergy system by biomass is approximately 150 million tonnes of CO₂/year (based on 2021 figures). Of this, just under 50 million tonnes of CO₂/year comes from biogenic waste and residues.

However, one restriction applies: not all bioenergy supply is equally suitable for expansion with BECCS components. The most promising routes are as follows:

CO₂ captured from biogas and biofuel production: around 2 million tonnes of CO₂ are already being captured each year from the processing of bioethanol and biogas. However, CO₂ capture could be doubled if large biogas plants that use waste and residual materials switch to biomethane production and set up appropriate processing with CO₂ capture. Around 3 million tonnes of CO₂ per year appear to be possible (Rensberg et al., 2023).

CO₂ that can be captured from the use of solid fuels in large-scale plants: 25-35 million tonnes of CO₂ per year could be captured from the combustion of waste and residual materials (e.g. waste wood, industrial wood residues) in existing waste incineration plants and large biomass heating (combined heat and power) plants. Assuming a capture rate of 80% (Markewitz et al., 2018, own estimates

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